Dear Editor,

We are grateful for the additional round of comments on our manuscript from both yourself and an anonymous referee. These comments have helped to improve several sections of the manuscript. In particular, we feel that the focus of the manuscript is far clearer. Below we respond to the major comments by the referee, in each case including and noting the editor's guidance on each matter, as well as the specific line edits suggested by the referee. We also include a revised manuscript with changes tracked. Once again we thank the editor and the additional third referee for their constructive comments on the manuscript.

Thank you for considering this manuscript for publication.

Emily Hill

Response to major comments made by anonymous referee 3 (in each case including the moderated revisions by the Editor)

Referee #1 Only including velocity changes between 1995/96 and 2015/16 might alias important velocity changes on shorter timescales that could be linked to discrete terminus perturbation events. As such, the link between terminus position and dynamics might not be fully appreciated. Perhaps finding trends across all years would provide a more complete context and links to the terminus position changepoint analysis? The same could be said for surface elevation changes; why not look at shorter-term trends?

Editor #1 This point on considering more detailed temporal trends/resolution of velocities and elevation changes has already been risen in the first round of reviews and explained but the authors why they did not change this. I agree with the re-reviewer that for the explanation of some of the dynamic changes the detailed timing of acceleration or thinning is crucial (see major comment #3) but I understand that calculating continuous rates is with the given dataset very challenging. I suggest at least in the discussion to include a more detailed/temporally resolved consideration of temporal variations (even though in the presented spatial variations of rates (in figures and tables) this is not explicitly done).

Our initial reason for including long-term trends in velocity and surface elevation change (Table 1) was to enable comparison to our longer-term decadal changes in frontal position, and provide a broad overview of any major changes. We agree that by not providing a continuous record there may be some oversimplifications in our interpretation of short-term timescales. However, the focus of the manuscript is on the long-term dynamic changes at outlet glaciers in northern Greenland, rather than a short-term analysis of individual calving events and velocity changes. Indeed, this may even require seasonal resolution for velocity and elevation change datasets, which are not available. We agree that short-term velocity/elevation changes are likely to be relevant and we present data on shorter time-scales (Figures 6 and 7) and briefly discuss these in the revised manuscript, as the Editor suggests. However, we refrain from a lengthier detailed analysis simply because our main focus in this paper is on longer-term trends from a broad sample of glaciers. Undoubtedly, future work could look at this on some of these selected glaciers, but it would be difficult for us to do this across all glaciers in a clear and consistent manner and without adding substantially to the length of an already long manuscript.

Referee #2 The introduction of terminus types – grounded or floating – is a great distinction and worthy of investigation. However, it should be made explicit up front and not part way through the results. Furthermore, I find it hard to follow the results section for frontal position change. What is the main point you want to make? It seems redundant to go through so many different periods and classifications of change; net from 1948-2015; decadal; changepoint time periods; based on terminus type. I would change to 1) briefly note trends and variability over the entire study period, 2) introduce terminus types (grounded vs floating), and 3) differences in frontal positions between terminus types at decadal (i.e. fig. 4) and/or changepoint time periods (i.e. fig. 5).

Editor #2 I would also welcome a clearer introduction of 'terminus types' in the introduction which would allow a more focussed and clearer presentation in the results.

A discussion of the terminus types already exists in the introduction (lines 15 to 21) and we also introduce which glaciers have floating ice tongues or are grounded in Section 2.1 (Study region). However, we have followed the advice of the referee comment and restructured the first section of the results. We now have a brief overview at the start of Section 3.1 of region wide long-term changes. Then we have brought the introduction of terminus types (from Section 3.2) before the decadal changes. We agree that this gives better context for interpreting the decadal changes that are presented in Figure 4 and Table 2. We have left the decadal discussion in this section, rather than splitting by terminus type, but we have added additional focus based on terminus type in this paragraph. The section is concluded with a summary sentence that was previously at the end of Section 3.2, and states that 'based on terminus type, we treat these as separate categories for the remainder of the results, during which we discuss short-term trends'. Finally, we have removed Section 3.2 as it was surplus and was largely brought into this section, and instead go straight into individual sections on grounded and floating termini. We have changed the numbering of the subheadings accordingly.

Referee #3 The discussion introduces several triggers for enhanced terminus retreat, including "initial thinning at the glacier terminus." While possible, I do not think that these suggestions are well supported within the data analysis and results. The authors note in the methods section that thinning rates were averaged over the entire glacier centreline, so do we have the spatial resolution to test this hypothesis? Does retreat lag thinning in the time series? Is thinning dynamic or SMB driven? Furthermore, if large thinning rates cannot be explained solely by SMB, wouldn't terminus retreat be required to produce the observed thinning rates? The authors present a multitude of descriptive data in the results section, however, I feel there are gaps in logic within the discussion in attempting to explain the observed trends.

Editor #3 improve and clarify the argumentation and line of thought for the discussion of the causes of enhanced dynamic changes (retreat). Relating to point #1 the more 'continuous' time series of thinning and velocities could be better used in discussion.

We appreciate the concerns about the current dataset and absence of climate forcing for inferring the specific triggers for enhanced terminus retreat. We also appreciate that by averaging over the centreline that we cannot comment on spatial elevation changes and instead can only comment on the general trend of annual changes in thinning and acceleration shown in Figures 6 and 7. We try to make sure that the focus of these sections of the discussion is instead on the dynamic changes (acceleration and thinning) during periods of rapid retreat. For this reason we have removed any reference to 'initial thinning at the termini' from the discussion. We also appreciate the concerns that we do not have the spatial resolution of elevation change data to determine if it is dynamic of SMB driven. We have responded to specific line comments that have helped address this comment (e.g. comments to lines 23/2 and 23/31) as well as some confusion about the extent of the glacier centreline (in the methods). Following the Editor's suggestions on

Section 4.1 we have improved the argumentation for thinning rates being the initial forcing for dynamic retreat, by referring to previous studies that have invoked dynamic thinning at glaciers in northern Greenland (Khan 2014, Pritchard 2009) and have made better references to the figures that show the more continuous time series of thinning and retreat (Figures 6 and 7). In addition, by following specific comments by the referee (23/31), we have revised Section 4.2 paragraph 2 in which we also previously invoked the cause of terminus change. Instead we refer back to Section 4.1, briefly mention that dynamic thinning may have initially caused retreat, but add a caveat to our coarse resolution dataset. We then clearly focus the rest of the section on changes in velocity and thinning after the onset of rapid retreat (no matter what the cause).

Referee #4 Throughout the manuscript the authors invoke climate forcing as a possible trigger of terminus retreat and dynamic glacier adjustments, however, the authors do not include time series of climate and ocean conditions. I certainly appreciate that climate forcing is not the main focus of the study, but perhaps it is worth including some available data in the supplementary information for readers and reviewers to look at. If not, the authors should consider more careful and direct references to pertinent published datasets and studies

Editor #4 this is a tricky point, as the authors removed the extensive presentation and discussion related to climatic and oceanic forcing in order to address the first round of reviews. I support the much clearer focus on the terminus types and geometry factors improved the paper substantially but of course the observed changes are not fully independent of climatic/oceanic forcing I somewhat agree with the re-reviewer that presenting no evidence of climatic/oceanic forcing and which makes it somewhat difficult to relate the observed changes to potential triggers (timing…). I leave it open to the authors whether they address this point but perhaps just showing for context some simple well established time series of atmospheric and oceanic (the latter being already tricky though) temperatures maybe useful.

We appreciate the concerns of reviewer 3 on the absence of climate forcing data from the manuscript. As the editor summarises, these data were included in the original submission, but we removed this to improve the focus on terminus types and geometry. We too feel that the paper was improved by removing it. We acknowledge that there are some points in the manuscript that we invoke climate forcing as a possible trigger of terminus retreat. However, we feel that these references to climate forcing are not extensive enough to warrant adding an assessment and time-series of climate-ocean forcing that would detract from the main focus of the manuscript. Some of the instances at which we inferred climate forcing have now been removed (i.e. when referring to Ryder Glaciers behaviour). Revisions have also been made to Section 4.1 following the specific comments to this section so that at all points at which we invoke climate forcing, we reference recent work in northern Greenland (e.g. Khan et al., 2014), and other regions of the ice sheet that suggested that climate forcing is a trigger of recent retreat. The referenced study also suggests that climate forcing may have triggered dynamic thinning. We feel that by making these changes we have alleviated some of the points at which referee 3 may have had concerns about the absence of climate/ocean forcing data.

Referee #5 Where is the calculation of the force balance, longitudinal stretching and driving stress that is referenced in the discussion Please make it explicit if we are supposed to deduce these from the velocity time series alone.

Editor #5 regarding the force balance I assume no explicit calculation has been done, if so rephrase this sentence somewhat to avoid confusion (if it has been done then explain it clearer).

We have now reworded this section to avoid confusion, following the specific line edit comment made by the referee.

Referee #6 Is the discussion of surge-type glaciers relevant to the main conclusions of the paper? It seems to confound the main points: behavior of grounded vs. floating termini and importance of bed topography controls.

Editor #6 I guess the fact that some surge-type glacier occur should be included but perhaps this can be shortened a bit to avoid loss of focus on the main important points.

We understand the concerns of referee 3 on the surge-glacier section. However we feel that it is worth briefly recording how surge-behaviour may cause glaciers to behave independently of terminus type. We have therefore followed the editor's suggestion to shorten this section of the discussion. We have done this by removing the previous fourth paragraph which provided a very brief (and thus potentially unnecessary) overview on glaciers that have been previously referred to as surge-type but are not found to be the case in this study. We have also made an effort to substantially shorten the paragraphs discussing likely surge-type glaciers. Another way we have improved this section is by providing better links to our main conclusions of the paper. Examples of this are on lines 31/7, 31/20-21, 32/19-25 in the tracked changes manuscript.

Referee #7 Perhaps most important --- the manuscript writing should be more clear and concise. The main point within individual sentences or paragraphs is often convoluted and, as a result, the content suffers significantly. I've tried to offer some specific improvements in my line edits, but was unable to address everything. Ultimately, these problems can be addressed with careful and collaborative editing by all authors.

Editor #7 please try to further make the writing in general more concise and clearer (simpler). Partly this will be solved by addressing the listed minor points by the editor. And further address list of minor points (which to some degree will make the manuscript more focussed and concise, see point #7

We have addressed the list of minor points made by the referee below, and feel that this has significantly improved the clarity of several parts of the manuscript. In each case we refer to line numbers in the tracked changes manuscript where changes have been made. We have also made an effort to make the writing more concise and clearer in several other places in the manuscript (e.g. Sections 3.2 and 3.3).

Specific comments by page/line number and figure number:

1/16. No need for parenthesis, just "was"

Deleted parenthesis.

1/19. "adjustment" not "re-adjustment"

Changed to adjustment.

1/21. Delete comma before suggests

Deleted.

1/29. Should be Carr, 2017a

We are unsure whether this comment is suggesting that we should be referencing Carr2017's paper on Novaya Zemlya, or if this is because it should be lettered a, based on the pan-arctic retreat paper being referred to first in the manuscript. If the former, 2017b (pan-arctic retreat) is a more appropriate reference for this sentence. If the latter, the lettering has been done automatically by using The Cryosphere's referencing style. This bases the lettering on the time of year during the year that the paper was published. As this is the automatic referencing style, we assume we should just leave it as it is.

2/5. Delete "surface"

Deleted.

2/10. This paragraph is longwinded – considering stripping down to the main points, i.e., terminus retreat can initiate dynamic adjustments independent of climate and modulated by local outlet geometry and associated resistive stresses. The last two sentences seem most important.

We have made an effort to shorten this paragraph as suggested in an attempt to better highlight the main points (lines 2/8 to 2/22).

2/12. I suggest using "slow", "long", or "gradual", but best not to use two adjectives.

Changed to just 'slow periods of advance'.

2/17-19. Is this sentence necessary? If so, perhaps it should have a reference.

This sentence has now been removed when shortening this paragraph.

2/27. Delete "Most"

Deleted.

2/30. Create a new sentence…"Dynamic changes at Jakobshavn are linked to the gradual collapse of its floating ice tongue."

Changed as suggested.

2/31. Is there anything specific that can be added here to demonstrate the importance of northern Greenland ice dynamics to sea level rise? Important to let the reader know the region is important to study for reasons other than it's underrepresented in previous investigations.

We have added extra context to the importance of northern Greenland ice dynamics for sea level rise (lines 3/8-11).

2/33. Delete "far"

Deleted.

3/1. "Consequently, few long-term records of frontal positions exist in the region. As a result, their potential impact on inland ice flow remains unclear."

Changed as suggested.

3/5. The sentences in this paragraph seem redundant. I would suggest combining sentences 2-5 into something like, "We couple a multi-decadal annual terminus position record between 1948 and 2015 with recently published surface elevation and ice velocity datasets. We use these datasets to evaluate dynamic responses (i.e. acceleration and thinning) to frontal position change and examine disparities in the context of glaciers with floating or grounded termini."

We have included this as suggested which has shortened and improved the clarity of this paragraph.

3/10. Would recommend changing slightly to, "Finally, we assess local topographic setting (ie fjord width and depth) as a control on glacier behavior."

Changed as suggested.

3/16. Is this true? There are other, albeit smaller floating tongues elsewhere, such as Rink Isbrae and Helheim?

To clarify we have changed 'extant' to 'long'.

3/13-20. This seems like introduction or nonessential methods material. What is the point of this paragraph? Seems like most important information is the characterization of floating vs grounded termini… then quickly note that there are large and changing tongue systems.

This study area section was added in the last round of revisions after it was suggested by one of the reviewers. Their idea was that it would be good to have some background on the region and which glaciers still have floating ice tongues or are grounded across the region. We would like to at least introduce the region we are covering, but realise we can remove some of the excess detail to focus on the characterization of floating vs grounded termini. As such we have simply removed sentences 2 and 3 to shorten and remove nonessential material.

5/2. Are there any gap years?

We are unsure exactly what this point means. There are ortho-photos available for 1978 for most glaciers (excl. NW Greenland) and 1985 for glaciers in NW Greenland, so in some sense there are gaps, but it doesn't seem necessary to mention this.

6/7. To what end? Do you use changepoint analysis between glaciers, over a single record, etc.? What is the point? This paragraph needs a topic sentence that makes this clear up front for the reader to understand the value in this approach.

We have now rewritten the first couple of sentences of this section (see lines 6/22 to 7/7).

6/10. This sentence is redundant and could be more concise. Just cite Bunce and Carr in the first sentence after clarifying.

See above.

6/18. Within what range?

We have removed this sentence and just refer to the method used by Carr et al., 2017 to avoid confusion.

6/17-22. This explanation is confusing to the reader. What is the reason for a threshold penalty? What is a threshold penalty? If this method is following Carr 2017, then simply reference their method, give a brief overview with an emphasis on portraying what the main point is and why it's valuable. The main point seems to be articulated in the last sentence of the paragraph, perhaps this could be a topic sentence?

We have now explained more clearly what the threshold penalty value is, and how it assists in the automatic detection of the changepoints (7/11-18). While the method we use here is similar to that used by Carr et al., 2017, it does have some differences (i.e. our approach uses a function in Matlab rather than R), so we feel that some of the detail needs to remain. We have also added a topic sentence to this section which gives a better overview on the main point of using this method.

8/9. It is unclear why Euclidean distance is necessary – to draw centerlines? What if fjord walls are not parallel?

We have added some clarity to this section of the methods. In all cases the fjord walls were parallel, but we're not sure if there would be an issue if not, because this would still produce a maximum distance within the centre of any two lines. We still feel this method is more robust than drawing a centreline freehand.

8/11. I would think averaging elevation change over the entire centerline (to the ice divide as the manuscript suggests) would significantly skew your results. Would it also be better to mask elevation changes seaward of the grounding line on floating tongues?

We acknowledge that using 'to the ice divide is misleading' as the centreline profiles stop at the point at which the glaciers are no longer within a fjord rather than much further inland. When we mask out elevation changes seaward of the grounding line, the averaged elevation change values along the time series are the same in most cases. This suggests that including these data does not significantly skew the results. However, at a few glaciers by masking out changes along the tongue, we omit a lot of the data points from the earlier years of the elevation change record, when the data is generally sparser. For this reason we would like to keep the continuous trend averaged along the centreline. However, we do change the terminology in the methods to 'to the inland end of the glacier fjord' instead of the to the ice divide.

9/4. This sentence is unclear – you're calculating catchment areas from the flow field right? Could you instead reorient the sentence as, "We calculated each drainage area using catchments constrained by gradients in the DEM"...?

Yes we have calculated catchment areas based on flow direction and flow accumulation raster's derived from the gradients in the GIMP surface DEM. We have adjusted the final sentence of this paragraph as you have suggested.

9/7. Perhaps "Net retreat"?

Changed to 'net retreat'.

9/7. Do these statements pertain to frontal positions (ice tongue fronts and grounded termini), or just grounding lines? Please clarify.

Clarified by changing from 'glacier retreat rates' to 'frontal retreat rates'.

9/14. Is "mean rate of terminus change" more accurate?

Changed as suggested.

9/17. Could you be more direct and just say, "Long-term retreat rates varied across northern Greenland?"

Changed as suggested.

12/2-6. The distinction of terminus type needs to be made earlier to give the reader context to interpret records of terminus front change.

We have addressed this comment largely in our response to the major comment #2. We have restructured this section of the results following the advice given (lines 10/19 to 13/6).

12/12. Already stated previously. Need better topic sentence; why do grounded termini matter? State main result up front and then support with observations.

We have added a topic sentence to highlight the important contribution that calving from grounded outlets make towards ice discharge and sea level rise. We have also added a sentence summarising the main results which is that grounded outlet glaciers had substantially higher retreat rates during the last two decades of the study period (lines 14/4-6).

12/23. Already stated previously. Need better topic sentence; why do floating termini matter? State main result up front and then support with observations.

As above we have followed the suggestion to provide a better topic sentence and main summary of the results. We have now added sentences to the start of this section to this effect (see lines 14/18-20).

17/16. Higher with respect to what? Need to clarify.

Changed to 'had higher thinning rates than grounded termini…'

18/1, Perhaps change to, "different pattern of elevation change compared to the rest of the region: Storstrømmen and L. Bistrup Brae."

Changed as suggested.

19/1. Perhaps it is best to also explicitly separate this section into grounded vs. floating termini?

We have now added subheadings to this section to split it by grounded and floating termini.

19/4. Please clarify what is meant by "split"

To improve the clarity of this sentence we have now changed it to 'Some glaciers rest on inland sloping bed topography, while others have seaward sloping topography'.

19/2 and 22/1. What are the main points of these paragraphs? Please upgrade the topic sentences to better reflect the main point – inland sloping beds are correlated with higher retreat rates at glaciers with grounded termini, but fjord width is not a main determinant. What is a corresponding main point you are trying to get across in describing bed data at glaciers with floating tongues?

We are grateful for the suggestions to improve this section. We have followed the advice for each paragraph, by including a topic sentence followed by more focused key points for the bed topography based on each category of terminus type. In doing so we have also shorten these sections. We also make it clear why we are examining bed topography beneath the grounded portion of glaciers with floating ice tongues.

22/30. Delete acceleration and retreat in southeast Greenland, or support with references and include other regions where this occurred (e.g. SW Greenland, Howat et al., etc.).

As this sentence already contains a lot of information we have just deleted 'acceleration and retreat in south-east Greenland.'

22/31. Please provide more complete and recent references (e.g. Felikson et al., 2017). Also please more explicitly link these changes to climate factors, if that is in fact what you mean to do.

We have included this and other appropriate references (Price et al., 2011 and Nick et al., 2009) for the links between thinning and terminus change in this section.

23/2. Do you show this relationship in the text? If so cite a figure. Also please reword the sentence. "Indeed, surface thinning preceded rapid terminus retreat at many northern Greenland glaciers (Fig. x)." I would be wary of adding sentences referencing old studies in other parts of Greenland and focus more on the region of interest. What is the main point you are trying to make? Is it that climate may be the initial trigger for terminus change? Then make it explicit and cut the fat.

This was actually in reference to examples from other regions of the ice sheet, and we have now removed this sentence. We have made an effort to condense this section and make the key point that 'climate may be the initial trigger for terminus change', hopefully a lot clearer. We state this main point earlier in the paragraph. Sentences referencing old studies in other parts of Greenland have been removed and instead we have made better reference to previous studies in northern Greenland that have linked climatic changes with thinning and retreat. Finally we include the sentence suggested above as support for 'surface thinning being the driver of accelerated retreat since the 1990s'.

23/2. Confusing sentence, please reword. Not initial condition, do you mean forcing?

Changed to forcing

23/9. Delete "the"

Deleted.

23/8. I'm confused, is it climate and ocean forcing at the terminus; or thinning from negative mass balance that causes retreat? I realize they are related (i.e. climate driven), but I think you can be more direct.

In combining and restricting this section of the discussion this sentence has now been removed. Earlier in the section, we have made it clear that we are discussing dynamically induced thinning at the margins of outlet glacier termini, which may have been forced by changes in climate and ocean conditions at the margins.

23/12. This seems like material that could be combined with the previous paragraph. In fact, I would consider making this section a single paragraph that is more direct and punchier. Lots of material is repeated and the topic lacks focus.

We have outlined the changes we have made to this section in response to a previous point (23/2). We have now combined material that was previously in the second paragraph with the first and also made an attempt to shorten and summarise this section. In doing so we hope to have reduced the amount of material that is repeated and improved the focus of this section overall.

23/15. Can also add: Catania G. A., Stearns, L. A., Sutherland, D. A., Fried, M. J., Bartholomaus, T. C., Morlighem, M., et al. (2018). Geometric controls on tidewater glacier retreat in central western Greenland. Journal of Geophysical Research: Earth Surface, 123, 1–14, https://doi.org/10.1029/2017JF004499

Reference added.

23/25. What are the significant differences?

We have deleted this sentence as we did not deem it necessary, and the significant differences in the duration and magnitude of rapid retreat based on terminus type were very similar to the summaries of the 'calving behaviour based on terminus type' given in the previous sentence.

23/26. The last sentence of this paragraph is essentially the same as the first. Consider revising.

We have removed this sentence and revised this section. We now start with the first sentence that states that our analysis showed differences in glacier dynamic response to terminus change based on terminus type before going on to summarise the different calving behaviour based on terminus type.

23/31. What causes the initial near-terminus thinning? Is this supported in the results section? Does retreat lag thinning? If so, reference the appropriate figure. Otherwise, I feel this is unfounded.

We agree with this comment and major comment #3 (see additional response to #3) that it is very difficult and not well supported for us to make statements about near-terminus thinning, and especially the cause of this thinning given the absence of a detailed climate/ocean forcing analysis. Thus, we have shortened this paragraph and merged it with the first paragraph. We now hope to have better focused this section on the dynamic changes that occurred after terminus retreat began, rather than too much focus on the specific initial cause of retreat that we are unable to make from the data we use.

23/33. Ice does not flow inland; perhaps you mean the dynamic response propagates inland, or up-glacier?

Changed to 'and propagates the dynamic response (i.e. acceleration) up-glacier.'

23/33. Change to, "As such, we suggest thinning initiated enhanced retreat…"

Changed as suggested.

24/19. Awkward sentence, consider rewording.

This sentence has been revised in response the next comment.

24/19-20. Where do you show calculation of the force balance, longitudinal stretching and driving stress? Also, you may not have the temporal resolution in the velocity dataset to resolve short-lived dynamic adjustments from individual calving events.

See response to major comment #5. We do not calculate the force balance ourselves and instead infer this to be the case based on annual ice velocities. It is true that by looking at annual ice velocities only we may not be able to resolve short-lived dynamic adjustment. However the point we are trying to make here is that while there may have been some short-lived dynamic adjustments (seasonally), there was not a substantial perturbation in stresses that caused these glaciers to accelerate over longer timescales (annually). To alleviate the confusion to the reader and improve clarity, we have amended these sentences on lines 28/15-20 in the tracked manuscript.

24/27. Delete the comma in this sentence.

Deleted.

28/10. It doesn't really seem that any glaciers are responding linearly to climate forcing. It looks like Ryder has a very nice, episodic advance/retreat cycle.

To clarify this and also address the comment below, we have instead changed this to 'appears to be behaving dissimilarly to the rest of our study glaciers in northern Greenland'.

28/10. It is hard to compare these records to climate forcing without also seeing time series of climate forcing (i.e. air or ocean temperatures).

We agree that it is hard to compare these records to climate forcing, but we feel that re-introducing such records would confuse the main message of the paper (as suggested by previous reviewers for removing it). To reduce the confusion in this example when revising this section we have simply removed the statement 'independently to climate forcing' and instead say that Ryder Glacier appears to be behaving 'dissimilarly to the rest of our study glaciers in northern Greenland'.

29/9. But didn't the results section showed fjord width had little control over retreat rates?

We have removed the word 'widening' to avoid confusion here, and just say 'Continuous retreat into deep fjords…'

Figure 6 and 7. It's hard to read and interpret yellow colored velocity data. I suggest changing to blue or another easily accessible color.

We have changed the colour of the velocity data in both figures to purple. This is hopefully now easier for the reader to interpret, but is less likely to be confused with the green surface elevation change than blue might be.

Figure 9 and 10. The bathymetry colorbars are not needed for each panel. Consider including one at the top or bottom of the figure.

We have removed the colour bars for each panel and left one colour bar for each figure (9 and 10).

Figure 11. Please annotate the ice flow direction and make explicit the location of ice tongues and lateral rifting. It's hard to make out these features without descriptions in the figure.

We have annotated the figure to show the ice flow direction, the location of the ice tongue and the locations of lateral rifting.

Dynamic changes in outlet glaciers in northern Greenland from 1948 to 2015

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Abstract

The Greenland Ice Sheet (GrIS) is losing mass in response to recent climatic and oceanic warming. Since the mid-1990s, tidewater outlet glaciers across the ice sheet have thinned, retreated, and accelerated, but recent changes in northern Greenland have been comparatively understudied. Consequently, the dynamic response (i.e. changes in surface elevation and velocity) of these outlet glaciers to changes at their termini, particularly calving from floating ice tongues, is poorly constrained. Here we use satellite imagery and historical maps to produce an unprecedented 68-year record of terminus change across 18 major outlet glaciers and combine this with previously published surface elevation and velocity datasets. Overall, recent (1995–2015) retreat rates were higher than at any time in the previous 47 years (since 1948). Despite increased retreat rates from the 1990s, there was distinct variability in dynamic glacier behaviour depending on whether the terminus~~ is (or~~ was~~)~~ grounded or floating. Grounded glaciers accelerated and thinned in response to retreat over the last two decades, while most glaciers terminating in ice tongues appeared dynamically insensitive to recent ice tongue retreat and/or total collapse. We also identify glacier geometry (e.g. fjord width, basal topography, and ice tongue confinement) as an important influence on the dynamic ~~re-~~adjustment of glaciers to changes at their termini. Recent grounded-outlet glacier retreat and ice tongue loss across northern Greenland~~,~~ suggests that the region is undergoing rapid change and could soon contribute substantially to sea level rise via the loss of grounded ice.

1 Introduction

Mass loss from the Greenland Ice Sheet (GrIS) has accelerated since the early 2000s, compared to the 1970s and 80s (Kjeldsen et al., 2015; Rignot et al., 2008), and could contribute 0.45–0.82 m of sea level rise by the end of the 21st century (Church et al., 2013). Recent mass loss has been attributed to both a negative surface mass balance and increased ice discharge from marine-terminating glaciers (van den Broeke et al., 2016; Enderlin et al., 2014). The latter contributed ~40% of total mass loss across the GrIS since 1991 (van den Broeke et al., 2016), and increased mass loss was synchronous with widespread glacier acceleration from 1996 to 2010 (Carr et al., 2017b; Joughin et al., 2010; Moon et al., 2012; Rignot and Kanagaratnam, 2006).

Coincident with glacier acceleration, dynamic thinning has occurred at elevations <2000 m on fast flowing marine-terminating outlet glaciers (Abdalati et al., 2001; Krabill et al., 2000), particularly in the south-east and north-west of the GrIS (Csatho et al., 2014; Pritchard et al., 2009). Alongside thinning and acceleration, terminus retreat has been widespread since the 1990s (e.g. Box and Decker, 2011; Carr et al., 2017b; Jensen et al., 2016; Moon and Joughin, 2008), and several studies have identified terminus retreat as a key control on inland ice flow acceleration and dynamic~~ surface~~ thinning (Howat et al., 2005; Joughin et al., 2004, 2010; Nick et al., 2009; Thomas, 2004; Vieli and Nick, 2011).

Ice sheet wide dynamic changes have been linked to 21st century atmospheric/ocean warming, and the loss of sea-ice (e.g. Bevan et al., 2012; Cook et al., 2014; Holland et al., 2008; McFadden et al., 2011; Moon and Joughin, 2008). However, tidewater glaciers can also behave in a cyclic manner, which is not always directly related to climate forcing (Meier and Post, 1987; Pfeffer, 2007), but instead relates to their fjord geometry (Carr et al., 2013; Enderlin et al., 2013; Howat et al., 2007; Powell, 1990). These glacier cycles are characterised by slow~~ long~~ periods of advance (up to centuries) followed by rapid unstable retreat (Meier and Post, 1987; Post, 1975; Post et al., 2011). Once initiated, ~~T~~terminus retreat can initiate dynamic adjustments independent of climate and instead modulated by local outlet glacier geometry and associated resistive stresses. However, differences in the nature of calving ~~nature ~~and basal/lateral resistive stresses acting at tidewater glaciers with either grounded or floating termini can alter their dynamic response to retreat. Continuous small magnitude calving events and the loss of basal and lateral resistance at grounded-termini, can prolong the dynamic readjustment at the terminus. In contrast to continuous calving, large episodic calving events often occur at floating ice tongues, which can decrease buttressing forces on grounded ice, and also increased driving stress and accelerated~~es~~ ice flow (e.g. MacGregor et al., 2012). In the case of floating ice tongues, the response of inland ice to large calving events depends on the amount of lateral resistive stress provided by the tongue prior to calving: the loss of portions of ice tongues that are highly fractured and/or have limited contact with the fjord margins are unlikely to substantially influence inland ice dynamics. ~~Differences in the calving nature and basal/lateral resistive stresses acting at tidewater glaciers with either grounded or floating ice tongues can therefore impact substantially on their dynamic behaviour. Once rapid retreat has begun, tidewater glaciers may behave independently of climate, and are instead controlled by basal and lateral resistance, which differs depending on local topography and whether the glacier terminus is floating or grounded. Calving at glaciers that are grounded at their termini are influenced by both basal and lateral drag, both of which reduce towards their termini. Initial retreat then causes longitudinal stretching, surface crevasse propagation and small magnitude calving events. Calving from floating ice tongues can either happen gradually, calving small icebergs continuously, or via slow rift propagation across the width of the ice tongue, leading to large tabular icebergs that calve episodically. Following these events, reduced lateral drag from the loss of ice contact with the fjord walls can decrease the buttressing forces acting on the grounded portions of the glacier, which increases driving stress, and~~

Most previous work at tidewater glaciers in Greenland has concentrated on the central-west and south-east regions, and ~~most~~ notably at Jakobshavn Isbræ, Helheim, and Kangerdlugssuaq Glaciers (e.g. Howat et al., 2005, 2007; Joughin et al., 2004; Nick et al., 2009). Observations at all three glaciers showed acceleration and surface thinning following terminus retreat. Dynamic changes ~~and,~~ at Jakobshavn, ~~this was in~~ ~~response~~~~are~~have been linked to the gradual collapse of its floating ice tongue (Amundson et al., 2010; Joughin et al., 2008; Krabill et al., 2004). In northern Greenland, several glaciers have thinned (Rignot et al., 1997), accelerated (Joughin et al., 2010), and retreated, losing large sections of their floating ice tongues between 1990 and 2010 (Box and Decker, 2011; Carr et al., 2017b; Jensen et al., 2016; Moon and Joughin, 2008; Murray et al., 2015). Floating ice tongue retreat does not directly contribute to sea level rise. However, with amplified warming and surface melt forecast in northern Greenland (Fettweis et al., 2012; Franco et al., 2011; Mernild et al., 2010), floating ice tongues across the region could soon collapse entirely. ~~After~~ As a consequence, ~~this~~ northern Greenland could become a more substantial contributor dynamic ice discharge and sea level rise. However, ~~far~~ fewer studies have focussed specifically on northern Greenland, with the exception of more detailed work at Petermann and the Northeast Greenland Ice Stream (NEGIS) (e.g. Khan et al., 2015; Nick et al., 2012). ~~Consequently~~As such, ~~there are~~ few long-term records of frontal positions exist ~~longer-term changes in glacier frontal for~~in the region~~. As a result~~, and their potential impact on inland ice flow remains ~~is~~ unclear.

Here we present changes in frontal position, ice velocity and surface elevation over the last 68 years (1948 to 2015) in northern Greenland. We couple a multi-decadal annual terminus position record between 1948 and 2015 with recently published surface elevation and ice velocity datasets. We then use these datasets to evaluate dynamic responses (i.e. acceleration and thinning) to frontal position change and examine disparities in the context of glaciers with floating or grounded termini. ~~We evaluate the dynamic response (i.e. acceleration and thinning) of glaciers in the region to observed changes in terminus position. We evaluate the differences in this response, depending on whether the glacier has a floating ice tongue or a grounded terminus. First, we provide a multi-decadal record of annual terminus positions between 1948 and 2015. We then combine terminus positions with recently published datasets of surface elevation and ice velocity to investigate the dynamic response of these glaciers to frontal position change.~~ Finally, we assess local~~the~~ topographic setting ~~and local glacier controls~~ (i.e. fjord width and depth) as a control on glacier behaviour.

2 Methods

2.1 Study region

We define Northern Greenland as the region of the Greenland Ice Sheet located north of 77°N (Figure 1). This region drains ~40% of the ice sheet by area (Hill et al., 2017; Rignot and Kanagaratnam, 2006) and includes 18 major marine-terminating outlet glaciers, which emanate from 14 major catchments (Figure 1). ~~Early studies in Northern Greenland identified floating ice tongues up to 50 km long (Higgins, 1991; Koch, 1928) and it is now the last area of the GrIS with extant floating ice~~

~~tongues. Studies from the 1950s and 1990s showed thinning and retreat of these large ice tongues (Davies and Krinsley, 1962; Rignot et al., 2001), and recent Greenland-wide studies suggest that terminus changes in northern Greenland are characterised by large iceberg calving events (e.g. Box and Decker, 2011; Moon and Joughin, 2008).~~ Aside from at Petermann Glacier and the NEGIS, little work has focused on the other glaciers in northern Greenland, where the presence of floating ice tongues could alter the dynamic response of inland ice to calving events. Here, we use the ice-ocean mask from the Operation IceBridge BedMachine v3 product (nsidc.org/data/IDBMG4) to categorise glaciers in northern Greenland based on either grounded or floating termini (Howat et al., 2014; Morlighem et al., 2017). We also use the grounding line in this dataset to assess the location of past ice tongues. Currently, five glaciers in northern Greenland terminate in floating ice tongues (Figure 1), which range between 0.5 and 70 km long (Hill et al., 2017). An additional four glaciers have lost their ice tongues entirely over the last two decades (1995 to 2015). Our study region includes a further nine outlet glaciers, which are grounded at their termini. We note that Humboldt glacier is classified as grounded as the majority of the ~100 km long terminus is grounded, despite a small floating ice tongue in the northern section (Carr et al., 2015).

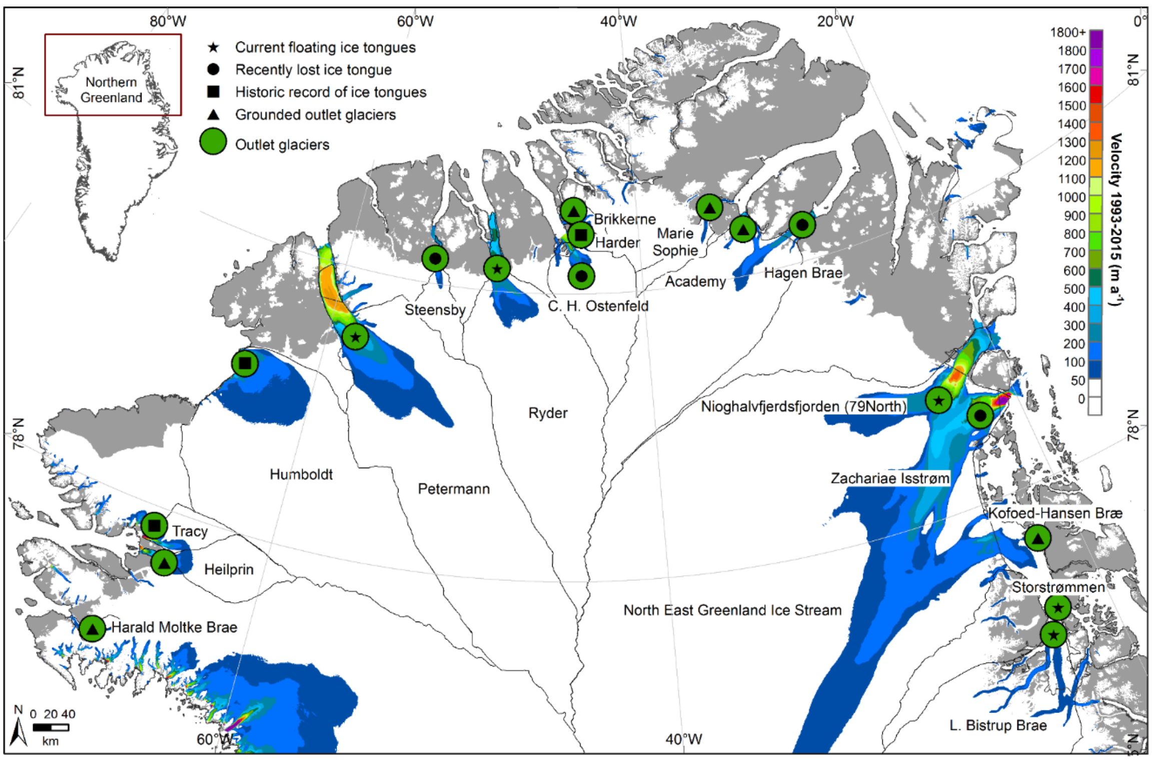


Figure 1: Study region of northern Greenland. Green circles show the location of each of 18 northern Greenland study outlet glaciers. Average glacier velocities (m a^{-1}) are shown between 1993 and 2015 derived from the multi-year mosaic dataset (Joughin et al., 2010). Black outlines show glacier drainage catchments. Symbols represents the state of the glacier terminus. Stars show glaciers which currently have floating ice tongues, circles represent glaciers which lost their ice tongues (during 1995 to 2015), squares denote glaciers which have some previous literature record of a floating ice tongue, and triangles are glaciers which are grounded at their termini and have been throughout the study record.

2.2 Terminus change

2.2.1 Data sources

The terminus positions of 18 study glaciers in northern Greenland (Figure 1) were manually digitised from a combination of satellite imagery and historical topographic navigational charts between 1948 and 2015 (Table S1). From 1975 to 2015 we used Landsat 1–5 MSS (1975–1994), Landsat 7 TM (2000–2013) and Landsat 8 (2013–2015). These scenes were acquired from the United States Geological Survey (USGS) Earth Explorer website (earthexplorer.usgs.gov). To reduce the influence of seasonal changes in terminus position, one scene per year was selected from late summer, and 70% were within one month of the 31st August. Several Landsat MSS images required additional georeferencing and were georeferenced to 2015 Landsat 8 images, as these have the most accurate georeferencing. Early Landsat scenes (1970–1980s) were supplemented with SPOT–1 imagery from the European Space Agency (ESA) (intelligence-airbusds.com). These scenes covered 8 of 18 study glaciers in 1986/87, and were also selected from late August. SPOT–1 scenes were also georeferenced to 2015 Landsat Imagery. Additionally, we used aerial photographs (2 m resolution), which were provided orthorectified by Korsgaard et al. (2016). These covered all study glaciers between Humboldt east to L. Bistrup Bræ in 1978, and Harald Moltke Bræ, Heilprin and Tracy Glaciers in NW Greenland in 1985 (Korsgaard et al., 2016).

To extend the record of glacier terminus positions further back in time, declassified spy images from the Corona satellite were acquired from the USGS Earth Explorer website (Table S1), which covered 5 of 18 glaciers in 1962/63 and Petermann and Ryder Glaciers in 1966. These images were georeferenced to a Landsat 8 scene from 2015, with total RMSE errors of 105 to 360 m. Frontal position changes smaller than this error value were discounted from the assessment. To further assess the historical terminus positions of the glaciers we used navigational map charts from the United States Air Force 1:1,000,000 Operational Navigation Charts from 1968/69 (lib.utexas.edu/maps/onc/). These were made available through the Perry-Castañeda Library, courtesy of the University of Texas Libraries, Austin. Data from 1948 comes from AMS C501 Greenland 1: 250,000 Topographic Series maps distributed by the Polar Geospatial Centre (pgc.umn.edu/data/maps/). All maps were georeferenced to 2015 Landsat 8 imagery using a minimum of 10 ground control points (GCPs), which were tied to recognisable stationary features such as on nunataks and fjord walls. RMSE errors across all glaciers ranged between 150 and 510 m.

2.2.2 Front position mapping

Changes in glacier frontal positions were measured using the commonly adopted box method, which accounts for uneven calving front retreat (e.g. Carr et al., 2013; Howat and Eddy, 2012; Moon and Joughin, 2008). For each glacier, a rectilinear box was drawn parallel to the direction of glacier flow (Figure 2), and extending further inland than the minimum frontal position. Due to Steensby Glacier's sinuous fjord, a curvilinear box was used (see Lea et al., 2014). Glacier frontal positions were digitised in sequential images and the difference between successive terminus polygons give area changes over time within the box. Dividing these areas by the width of the reference box derives width-averaged relative glacier front positions.

Aside from georeferencing errors outlined in the previous section, the main source of error was attributed to manual digitisation (e.g. Carr et al., 2013; Howat and Eddy, 2012; Moon and Joughin, 2008). We quantified this by repeatedly digitising a ~3 km section of rock coastline 20 times for each image type or map source. The resultant total mean errors were: 3.6 m for Landsat 8, 19 m for Landsat 7 ETM, 17 m for Landsat MSS, 20 m for SPOT–1, 16 m for Orthophotographs, 21 m for Corona, and 27 m for historical maps. Overall, the mean total error associated with manual digitising was 19 m, which is below the pixel resolution of all imagery sources except the 15-m panchromatic Landsat band. The presence of sea ice and highly fractured glacier termini made terminus picking at Steensby, C. H. Ostenfeld and glaciers draining the NEGIS more difficult (Bevan et al., 2012; Howat and Eddy, 2012; Murray et al., 2015). Re-digitising all 1999-2015 Landsat terminus positions yielded additional errors of ± 13 % for these glaciers. At these glaciers, similar inaccuracies in identifying the true glacier terminus may have occurred by the authors of the earliest map charts (1948 and 1969), and we therefore consider these to be a broad estimate of the past location of glacier termini rather than exact frontal positions.

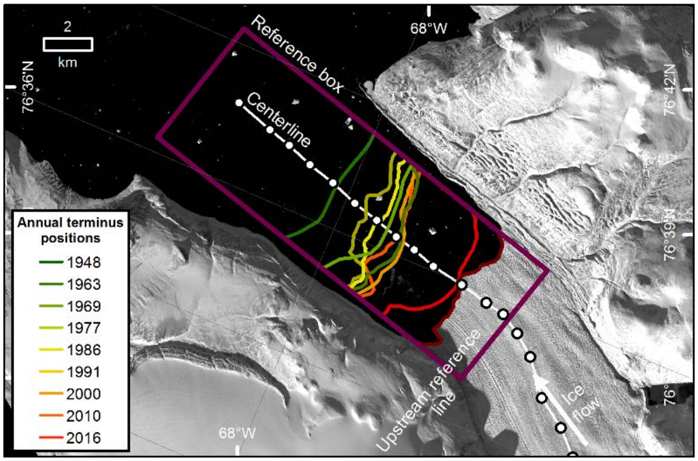


Figure 2: Rectilinear box method used to measure glacier terminus positions. An example at Harald Moltke Bræ, NW Greenland. This includes: reference box (pink), and roughly decadal terminus positions (green to red). The glacier centreline profile is shown in white and the location of 500 m sample points (white circles). Background image is Landsat 8 band 8 from the USGS Earth Explorer.

2.2.3 Changepoint analysis

‘Changepoint’ analysis can be used to objectively identify significant breaks in time series data (Bunce et al., 2018; Carr et al., 2017a). Here we used ~~‘~~changepoint~~’~~ analysis to detect statistically significant breaks in the time-series (1948 to 2015) of terminus position change for each of our 18 study glaciers in northern Greenland. We then compare the timing and duration of these breaks to determine if distinct patterns of terminus change behaviour exist based on terminus type (grounded or floating). ~~We used 'changepoint' analysis to objectively test whether there were significant differences in the timing and duration of terminus position changes in northern Greenland, according to terminus type (grounded or floating). Changepoint analysis is used to identify significant breaks in time-series data, and has previously been used to identify changes in the terminus behaviour of outlet glaciers elsewhere in the Arctic (Bunce et al., 2018; Carr et al., 2017a). We employ a similar technique to detect statistically significant breaks in frontal position data across 18 outlet glaciers in northern Greenland.~~ We employ a similar method introduced in more detail by Carr et al. (2017a). To ~~To~~ do this we use the 'findchangepts' function in MATLAB software which employs the methodology of Killick et al. (2012) and Lavielle (2005). Linear regression was used to detect significant breaks in the frontal position time series: a change point was identified where there was a significant change in the mean and regression coefficients (slope and intercept) of the linear regression equation on either side of a data point. In addition, to allow for the fully automatic estimation of the number of changepoints, we included~~Similar to previous studies, we set the minimum distance between points to 4 (Carr et al., 2017a), to only allow breaks >4 years to occur. This number must be small enough to allow for breaks not to be missed, but also large enough so that breaks do not incorrectly occur between every data point. The results are highly insensitive to incrementing the number of breaks up and down within this range. We also include~~ a minimum threshold penalty value, which we set as the mean terminus position for each glacier. This penalty only allows a changepoint to occur when the time-series deviates significantly from the threshold value. Using these automatically-~~-~~identified changepoints we can determine if statistically different changes in the rate of terminus position change exists for study glaciers in northern Greenland ~~based on~~according to their terminus type. ~~which applies an additional penalty to each prospective changepoint. For this we use the mean terminus position for each glacier. This then allows for an automatic estimation of the number of changepoints, when the timeseries deviates significantly from the penalty value, rather than fixing the maximum number of changepoints ourselves. Changepoints therefore identify statistically significant changes in the rate of terminus position for each of our study glaciers in northern Greenland.~~

2.3 Ice velocity and surface elevation

Previously published datasets of annual ice velocity and surface elevation change were compiled to assess dynamic glacier changes in northern Greenland. Velocity and surface elevation change datasets are generally only available from 1990 onwards. The earliest velocity maps from winters 1991/92 and 1995/96 were acquired from the European Remote Sensing (ERS) satellites (1 and 2), as part of the ESA Greenland Ice Sheet CCI (Climate Change Initiative) project (Nagler et al., 2016). The earlier (1991/92) covers northern Greenland drainage basins from Humboldt and then east to Hagen Bræ, and the later (1995/96) covers all 18 study glaciers. Using dataset error maps we estimated average errors in velocity magnitude across all northern Greenland drainage basins, which were 2.5 m a^{-1} for 1991/92 and 10 m a^{-1} for 1995/96.

Subsequent velocity datasets were primarily acquired from the NASA MEaSUREs program (Joughin et al., 2010). These velocity maps were derived from 500 m resolution Interferometric Synthetic Aperture Radar (InSAR) pairs from the RADARSAT satellite in winter 2000/01, and then annually from winter 2005/06 to 2009/10 (Joughin et al., 2010). Using the dataset error values (Joughin et al., 2010), we estimate mean velocity errors across all years and study drainage catchments to be 6.3 m a^{-1}. For 7 study glaciers, additional annual velocity data, derived from ERS1, ERS2 and Envisat satellites, were available annually between 1991/92 to 1997/98 and between 2003/04 to 2009/10 from the ESA Greenland CCI project (Nagler et al., 2016). Winter velocities from these data were calculated from October to April.

For the winters of 2010/11, 2011/12 and 2012/13, glacier velocity maps were also acquired from InSAR (TerraSAR-X image pairs) for 11 of 18 study glaciers (Joughin et al., 2010). Despite higher spatial resolution (100 m), these maps are limited to the grounding line and extend 27–56 km inland. Mean error for these data is 23 m a^{-1} across all years (Joughin et al., 2010). Winter velocities for 2013/14 were derived from intensity tracking of RADARSAT-2 satellite data, and from offset tracking of Sentinel-1 radar data for 2014/15 and 2015/16, as part of the ESA CCI project (Nagler et al., 2016). The published mean error of these data from a central section of northern Greenland is 7.3 m a^{-1} (Nagler et al., 2015). Using the earliest full regional velocity map (1995/96) and the most recent record (2015/16), the rate of annual velocity change was calculated over this 20-year period.

We use surface elevation change data from ERS-1, ERS-2, Envisat, and Cryosat-2 radar altimetry for 1992 to 2015, which were made available by the ESA's Greenland Ice Sheet CCI project (Khvorostovsky, 2012; Simonsen and Sørensen, 2017; Sørensen et al., 2015). Data from 1992 to 2011 were acquired from the ERS-1, ERS-2 and Envisat satellites, using a combination of cross-over and repeat track analysis, which have then been merged to create a continuous dataset across satellites (Khvorostovsky, 2012). These data are provided in 5-year running means from 1992–1996 to 2007–2011 and at a resolution of 5 km. For the most recent elevation change (2011 to 2015), we used Crysosat-2 satellite elevation change which are provided in 2-year means (Simonsen and Sørensen, 2017). These data were generated using the Least Mean Squares method, where grid cells were subtracted from the Greenland Ice Mapping Project (GIMP) DEM (Howat et al., 2014) and corrected for backscatter and leading edge width (Simonsen and Sørensen, 2017). Calculations were made at a 1 km grid resolution and resampled to 5 km to conform with 1992–2011 datasets (Simonsen and Sørensen, 2017). Using error estimates (Simonsen and Sørensen, 2017), we calculated mean errors across all years and across all northern Greenland drainage basins to be ±0.14 m a^{-1}. Elevation changes from 1992–1996 were compared to elevation changes for 2014–2015 to assess how changes in surface elevation have evolved during the study period.

Velocity and surface elevation time series were extracted along each glacier centreline, which were drawn following

Lea et al. (2014). To draw these centrelines we first calculated euclidean distance ~~was calculated~~ between parallel fjord walls that were digitised in 2015 Landsat 8 imagery. The maximum distance line (i.e. centreline) was then traced from the furthest terminus extent back to ~~the ice divide~~the inland end of the glacier fjord. Annual average velocities were calculated within 5 km inland of the grounding line of each glacier, and elevation change rates were averaged across the entire centreline profile due to poorer/coarser data resolution (Figure 2).

2.4 Fjord width and basal topography

To assess the control of fjord geometry on outlet glacier behaviour we calculate fjord width and depth. Fjord width was measured perpendicular to glacier centrelines following Carr et al. (2014). Points were extracted at 500 m intervals along each fjord wall and joined by lines that crossed the fjord. The length of these lines is the width between the fjord walls, and changes along each fjord were fitted with a linear regression model to determine if the fjord widens or narrows with distance inland. To determine the fjord bathymetry of each study glacier in northern Greenland, regional basal topography was taken from the Operation IceBridge BedMachine v3 dataset which is derived from ice thickness and mass conservation (Morlighem et al., 2017). Basal topography was sampled at 500 m points along glacier centrelines. Using the error map from BedMachine v3 (Figure S1), we calculated errors along the grounded and non-grounded portions of each glacier centreline profile (Table S2). Mean grounded bed topography errors at 14 of 18 study glaciers range between 25 and 87 metres. These glaciers are well constrained by the mass conservation method, which works best for fast flowing areas near the glacier terminus (Morlighem et al., 2014, 2017). The remaining four glaciers (Storstrømmen, L. Bistrup Bræ, Kofoed-Hansen Bræ, and Brikkerne Glacier) have higher errors (from 112 to 215 m), owing to poor data coverage and kriging interpolation (Morlighem et al., 2017). Mean errors in bathymetry data are greater at all glaciers, averaging 156 metres and ranging from 15 to 283 m. To assess bed slope direction, we fit each glacier profile from the grounding line to 20 km inland with a linear regression model. These sections of each bed profile and model fit are presented in Figure S2, while entire bed profiles, and landward/seaward direction are presented in the results. Errors in basal topography do not significantly affect our assessment of bed slope direction, and we only use topography along the grounded portion of the glacier where errors are lowest. We treat basal profiles in the far east of the study region with caution due to their higher errors. Finally, to estimate drainage catchment areas and the percentage of each catchment below present sea level for each study glacier, surface drainage catchments (Table 3) were delineated using the GIMP surface DEM (Howat et al., 2014) and topographic analysis functions within TopoToolbox in MATLAB (Schwanghart and Kuhn, 2010). ~~The surface DEM was used to calculate flow direction, which was then used to affiliate raster cells with each surface drainage catchment.~~ We calculated each drainage area using catchments constrained by gradients in the surface DEM.

3. Results

3.1 Changes in glacier frontal position (1948–2015)

Across northern Greenland, 13 of the 18 study glaciers underwent net~~overall~~ retreat between 1948 and 2015, while the remaining five advanced (Figure 3). However, l~~L~~ong-term ~~glacier~~ frontal retreat rates (1948–2015) varied between glaciers across northern Greenland (Table 1), and ranged ~~between~~ from -15 m a^{-1} at Marie-Sophie Glacier, to twenty times greater at Petermann Glacier (-311 m a^{-1}).~~At Petermann Glacier, the high retreat rate resulted from two large calving events in 2010 and 2012, which together removed 27 km of its floating ice tongue (Falkner *et al*>, 2011; Johannessen, Babiker and Miles, 2013). Zachariae Isstrøm, which partially drains the NEGIS, had a similarly high retreat rate of -282 m a^{-1}, which resulted in the loss of its 21-km floating ice tongue between 2002 and 2012 (Table 1).There was variability in the long-term overall retreat rates across northern Greenland. A further five glaciers had retreat rates that exceeded -100 m a^{-1} (Table 1), and the remaining 6 glaciers that underwent retreat did so at rates of -15 to -58 m a^{-1}. Between 1948 and 2015, Ryder, Storstrømmen and L. Bistrup Bræ Glaciers advanced at a similar mean rate (~40 m a^{-1}), while Brikkerne Glacier advanced at 82 m a^{-1} (Table 1). Steensby Glacier underwent minimal change during the study period (1 m a^{-1}: 1948–2015), but with a high rate of retreat from 1978 to 2015 (-366 m a^{-1}).~~ At outlet glaciers in northern Greenland, we expect terminus changes and dynamic response to be different dependent on terminus type (i.e. floating or grounded). Nine outlet glaciers were grounded at their terminus throughout the study period, while at the end of the study period another nine still had ice tongues or lost them during the last two decades (1996 to 2015: Figure 1, Table 1). Our statistical changepoint analysis compared the duration and magnitude of frontal position changes at all study glaciers: this confirms that, in general, there are two different types of frontal position behaviour and dynamic response to calving based on terminus type (grounded or floating).

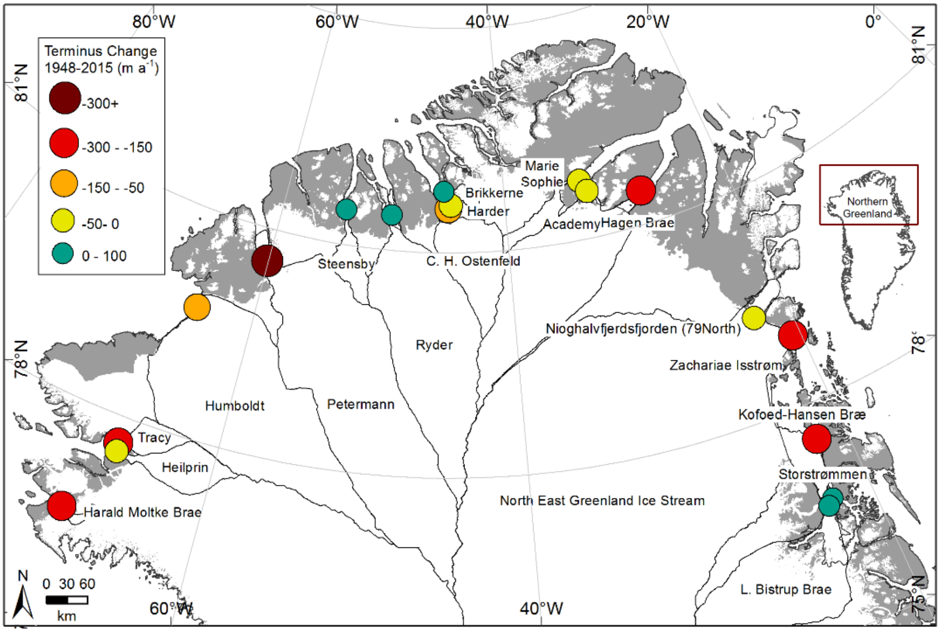


Figure 3: Overall mean rate of terminus change (m a^{-1}) at 18 outlet glaciers in northern Greenland from 1948 to 2015. Green circles represent glaciers which have undergone overall advance during the record, while yellow to red circles represent increasing retreat rates from 0 to larger than -300 m a^{-1}

Table 1: Summary data for 18 northern Greenland outlet glaciers, ordered according to terminus type and by frontal position rate (from high retreat to high advance). Annual rates of terminus change are given for the entire record (1948 to 2015). Average velocity change along each glacier centreline from winter 1995/96 to 2015/2016. Average surface elevation change rates along each glacier centreline were differenced from the earliest record (1992-1996) and the most recent (2014/15).

	Northern Greenland Outlet Glaciers	**Terminus Change (1948–2015) (m a^{-1})**	**Velocity Change (1995/96– 2015/16) (m a^{-1})**	**Difference in surface elevation change rates (1992-1996 and 2014-2015) (m a^{-1})**
Category 1: Grounded terminus	Tracy	-173	36.8	-0.11
	Kofoed-Hansen Bræ	-169	-0.06	0.12
	Harald Moltke Bræ	-156	22.6	
	Humboldt	-111	0.32	-0.51
	Heilprin	-45	7.16	-0.15
	Academy	-31	-4.87	-0.97
	Harder	-25	0.58	-0.89
	Marie-Sophie	-15	1.03	-0.43
	Brikkerne	82	-2.56	
Category 2: Floating ice tongue	Petermann	-311	3.78	-1.34
	Zachariae Isstrøm	-282	20.3	-2.98
	Hagen Bræ	-162	6.45	-0.83
	C. H. Ostenfeld	-58	2.96	-1.26
	Nioghalvfjerdsfjorden	-28	1.62	-1.99
	Steensby	2	2.59	-0.33
	L. Bistrup Bræ	39	-3.89	0.57
	Storstrømmen	41	-1.11	-0.18
	Ryder	43	-0.08	0.47

~~While many glaciers retreated substantially, there were large differences in the timing and magnitude of retreat between glaciers (Table 1, Figure 3).~~In addition to the long-term record of frontal position change (1948–2015), we further~~To~~ assess the variability of retreat rates across northern Greenland, by~~we~~ presenting mean retreat rates across five decadal time periods (1976–1985, 1986–1995, 1996–2005, 2006–2015) in Figure 4 (a-e), except for the earliest epoch (1948–1975) which spans 27 years due to image availability. We also present mean decadal frontal position change based on terminus type in Table 2. During the first epoch (1948 to 1975) small advances and retreats took place across the region (< 500 m a^{-1} magnitude). This was followed by a decade (1976–85) dominated by glacier advance, in particular at glaciers with floating ice tongues (Table 2), ~~and several glaciers with~~ which had high retreat rates for the entire study period (e.g. Hagen Bræ, Zachariae Isstrøm, Petermann: Table 1)~~ underwent advance during this period~~. In the subsequent epoch (1986 to 1995), a mixture of advance and retreat occurred and the range of frontal position changes was great, from -780 m a^{-1} retreat at C. H. Ostenfeld to 750 m a^{-1} advance at Storstrømmen (Figure 4c). During the last two decades of the study period (1996 to 2015), retreat rates were substantially higher than in the previous three epochs. However, variability in the magnitude of frontal position change over this period appears to be particularly related to terminus type (grounded or floating).~~,~~ Decadal mean retreat rates at glaciers with ice tongues (-745 to -835 m a^{-1}) were substantially higher than at grounded-outlet glaciers (-99 to 165 m a^{-1}: Table 2). ~~peaking at Petermann Glacier (-2200 m a^{-1}; Figure 4e, f). In particular, high magnitude retreat during this period at Hagen Bræ, Zachariae Isstrøm, and Petermann far outweighed earlier advances.~~ Based on the differences in terminus behaviour observed over the long-term and decadal time series based on terminus type (grounded or floating), we now treat these as separate categories for the remainder of the results, during which we describe short-term trends derived from our changepoint analysis (Figure 5).

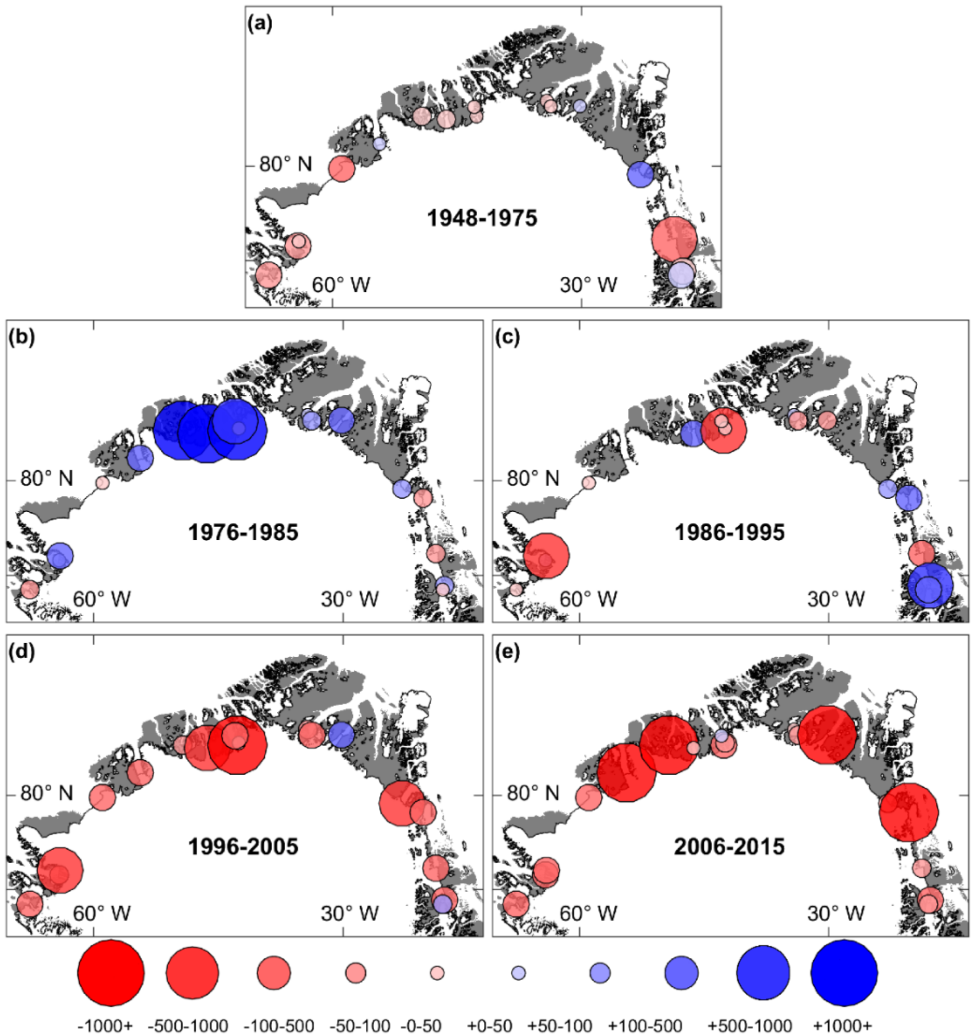


Figure 4: Mean decadal rates of terminus change across northern Greenland. These are shown for five epochs between 1948 and 2015. Increasing red circles represent glacier retreat rates between 0 and exceeding -1000 m a^{-1}. Increasing blue circles represent advance rates between 0 and exceeding 1000 m a^{-1}.

Table 2: Mean decadal frontal position change for all study outlet glaciers in northern Greenland, and split based on our two glacier categories of terminus type: grounded-terminus or terminating in a floating ice tongue

Mean terminus change (m a^{-1})	**1948-1975**	**1976-1985**	**1986-1995**	**1996-2005**	**2006-2015**
All (n =18)	-63.65	503.36	-7.83	-454.99	-467.06
Grounded-terminus (n =9)	-167.35	93.87	-112.07	-164.50	-99.23
Floating-terminus (n =9)	40.05	912.84	126.19	-745.49	-834.88

3.1~~2~~.1 Grounded-terminus outlet glaciers

Calving~~-~~-induced retreat of grounded marine-terminating outlet glaciers, ~~importantly~~ contributes to dynamic ice discharge and directly to sea level rise. At grounded outlet glaciers in northern Greenland (nine of our study glaciers: Figure 5), retreat rates increased substantially during the last two decades (1996 to 2015) of the study period.~~Nine of the major outlet glaciers considered in this study are grounded at their termini (Figure 5). For these glaciers, there was~~ At the beginning of our record, grounded outlet glaciers went through an initial period of minimal frontal position change averaging -26 m a^{-1} and ranging from 24 m a^{-1} advance at Kofoed-Hansen Bræ to -105 m a^{-1} retreat at Tracy Glacier (Figure 5). Frontal position change then switched to a period of higher magnitude retreat at eight glaciers (excluding Brikkerne), which lasted for an average of 26 years. During this period, frontal position change averaged -150 m a^{-1}, and net retreats ranged from -0.6 to 8 km. The greatest total terminus changes took place at Tracy Glacier (8 km retreat: 1981–2015), Harald Moltke Bræ (5 km retreat: 1988–2015), and Kofoed-Hansen Bræ (4.6 km: 1973–2015: Figure 6a-c). The timing of this switch from minimal change to steady retreat was not uniform, but most glaciers began steadily retreating from the 1990s to 2000s and continued at the same rate thereafter (Figure 5). The exception to this pattern of behaviour is Brikkerne glacier, which instead advanced by 9 km between 1968 and 1978 before returning to minimal terminus change (Figure 6i).

3.1~~2~~.2 Glaciers with floating ice tongues

The retreat of floating glacier termini can reduce the resistive stresses at the terminus~~,~~ and increase the dynamic glacier response to calving. Rapid retreat in the form of large episodic calving events removed substantial floating ice sections (11.6–26 km net retreat: Figure 7) from several northern Greenland outlet glaciers (Zachariae Isstrøm, Petermann and Steensby, C. H. Ostenfeld, and Hagen Bræ) between 1995 and 2015. However, frontal position changes at some glaciers with floating ice tongues were instead cyclic. At the beginning of the study period, six of ~~our~~the nine study glaciers with floating ice tongues ~~Nine glaciers terminated in floating ice tongues during the study period. Six of these glaciers~~ showed minimal terminus change/advance ~~at the beginning of the record~~ (93 m a^{-1}), followed by short-lived rapid retreat, lasting less than 6 years on average (Figure 5). During the phases of rapid retreat, rates ranged between -700 m a^{-1} at Nioghalvfjerdsfjorden to -8997 m a^{-1} at Petermann Glacier (Figure 5), and were on average 40 times greater (-4536 m a^{-1}) than during the steady retreat phases at glaciers grounded at their terminus (-150 m a^{-1}). During this period, large calving events ~~This~~ led to complete ice tongue loss at Zachariae Isstrøm by 2011/12, and at C. H. Ostenfeld, Steensby and Hagen Bræ by 2016 (Figure 7). Rapid retreat was often followed by another period of relative minimal terminus change (-437 m a^{-1}) compared to order of magnitude earlier retreat (e.g. Petermann Glacier and Hagen Bræ: Figure 5). ~~For five glaciers (Zachariae Isstrøm, Petermann and Steensby, C. H. Ostenfeld, and Hagen Bræ), rapid retreat removed substantial floating ice sections (11.6–26 km net retreat: Figure 7), through large episodic calving events. This led to complete ice tongue loss at Zachariae Isstrøm by 2011/12, and at C. H. Ostenfeld, Steensby and Hagen Bræ by 2016 (Figure 7).~~ Similar to glaciers with grounded-termini, the timing of the switch to ~~-~~rapid retreat was not synchronous, but mainly occurred after 1990 (Figure 5). At most glaciers, the duration of rapid retreat was short-lived (< 5 years) in comparison to the duration of steady retreat (> 13 years) at grounded-glaciers.

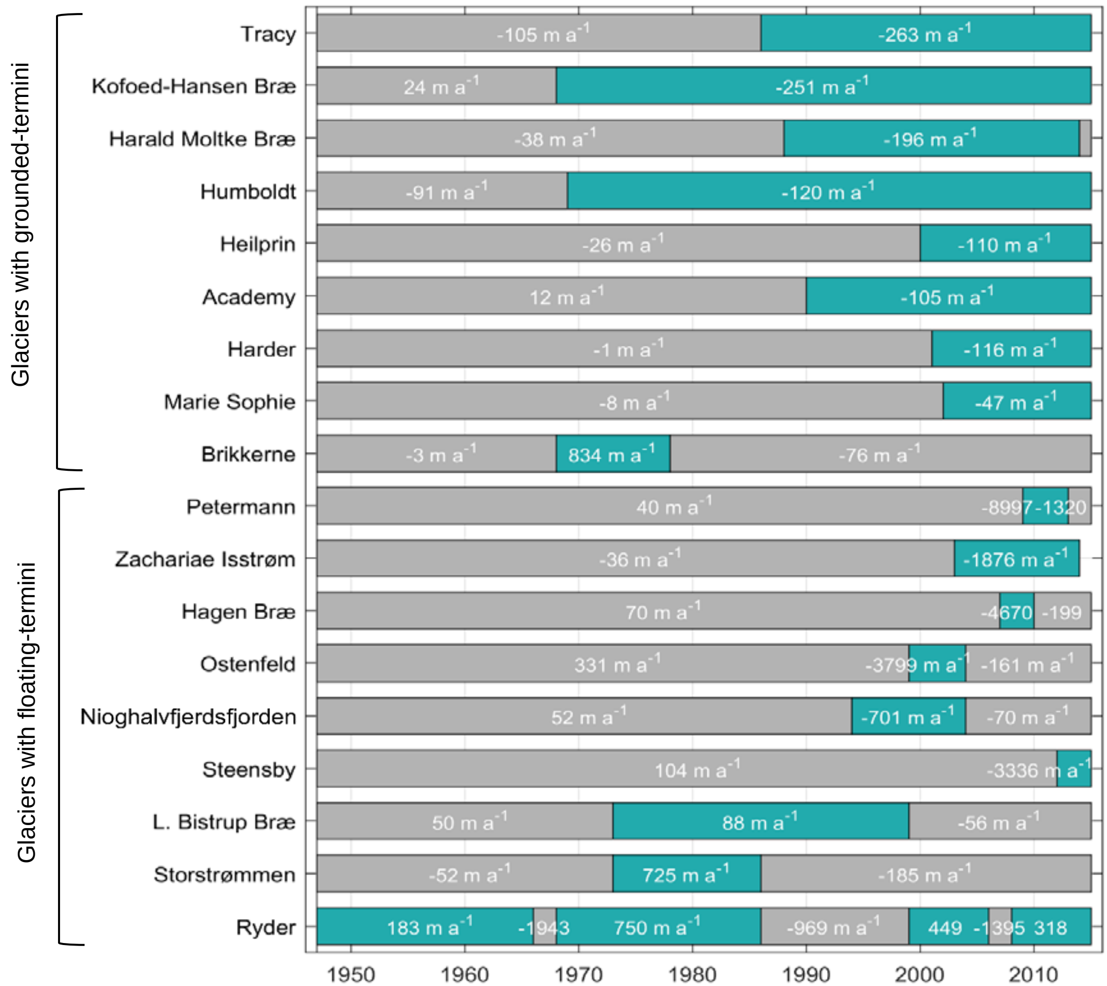


Figure 5: Retreat rates during identified changepoint time periods for each pre-defined category of glacier based on either grounded or floating termini. Glaciers are then ordered based on their overall (1948-2015: Table 1) frontal position change rates within each of these categories. Grey bars show their periods of minimal/variable terminus change (in some cases advance) and turquoise bars show the period of higher magnitude frontal position change.

Several glaciers with floating ice tongues (Storstrømmen, L. Bistrup Bræ, and Ryder) have instead shown cyclic periods of advance and retreat between 1948 and 2015 (Figure 7g-i). Periods of terminus advance at these glaciers averaged ~420 m a^{-1} and lasted for an average of 18 years (Figure 5). Adjacent glaciers Storstrømmen and L. Bistrup Bræ advanced during a similar period (from 1973 to 1990), and for ~13–17 years. After this, both glaciers underwent relatively limited terminus change from 2000 onwards (Figure 5). Despite synchronous advance, their advance rates differed by almost an order of magnitude (89 m a^{-1} at L. Bistrup Bræ, and 725 m a^{-1} at Storstrømmen, Figure 5). At Ryder Glacier, there were four main cycles of glacier advance and retreat during the record. These took place between 1948–1996, 1968–1986, 1999–2006, and 2008–2015 and advance rates ranged from 183 to 750 m a^{-1} (Figure 5). Periods of advance (7–48 years) were separated by shorter periods (2–13 years) of higher magnitude retreat (ranging from -960 to -1950 m a^{-1}) (Figures 5).

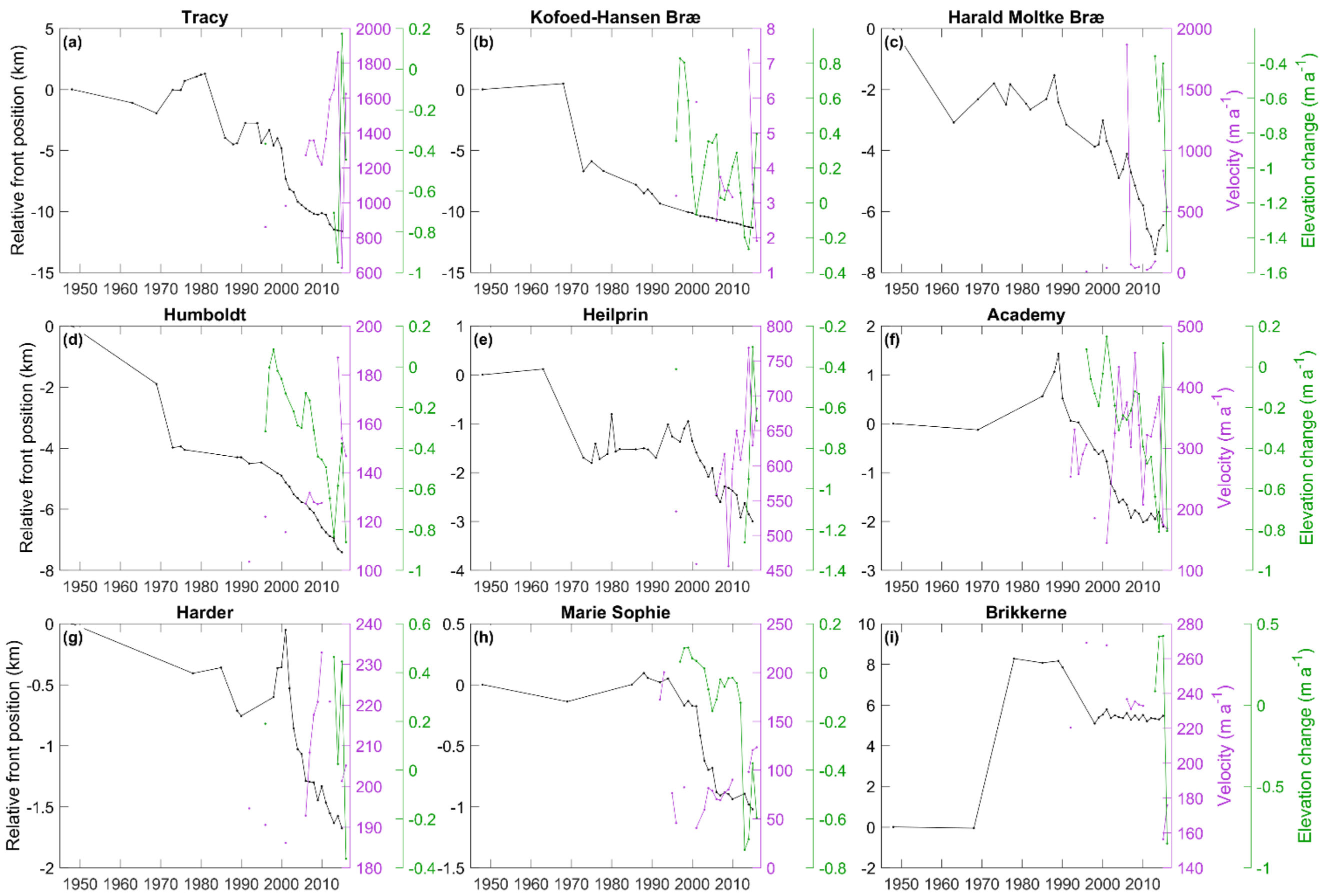


Figure 6: Front position, velocity and elevation change at nine outlet glaciers grounded at their terminus in northern Greenland. Left axes show relative front position (black line) between 1948 and 2015 relative to their initial position in 1948. Grounding line velocities (orange) on right axes one between 1996 and 2015. Surface elevation changes averaged across the glacier centreline profile (green) for 1996 to 2015.

3.2~~3~~ Ice velocity change

3.2~~3~~.1 Grounded-terminus outlet glaciers

Overall, most grounded outlet glaciers in northern Greenland~~Six of the nine outlet glaciers with grounded termini~~ accelerated along their centreline profiles (ranging from 0.32 to 37 m a^{-1}) from 1996 to 2016 (Table 1). Acceleration at these glaciers was also greatest (averaging ~~On average, these glaciers accelerated by~~ 27%), ~~following the onset of~~during periods of steady retreat ~~at each glacier~~ (Figure 5). This was particularly the case in northwest Greenland at ~~For example, Tracy and~~ Heilprin, Tracy, and Harald Moltke Brae. ~~accelerated substantially during their steady retreat periods (Table 1).~~ At Heilprin Glacier this resulted in a 49% increase (from 458 to 681 m a^{-1}) in grounding line velocity from 2001 to 2016 (Figure 6e), during which the glacier retreated at -110 m a^{-1} (Figure 5). Substantially greater acceleration (89%) took place at Tracy Glacier from 1996 to 2016 (Figure 6a), which was associated with higher magnitude retreat rates (-263 m a^{-1}: Figure 5). Harald Moltke Bræ also accelerated between 1990 and 2016 (22 m a^{-1}: Table 1), and retreated at -196 m a^{-1} (Figure 5). However, it underwent two very large velocity increases (> 1000 m a^{-1}) between 2001 and 2006 and again during winter 2013/14, both of which coincided with short-lived glacier advance (0.5–0.8 km: Figure 6c). Slower flowing grounded outlet glaciers in the region ~~Humboldt, Harder, and Marie-Sophie Glaciers flowed more slowly than other grounded-terminus glaciers~~ (< 400 m a^{-1}: Humboldt, Harder, and Marie-Sophie Glaciers) also ~~, but still showed large~~ accelerated by~~ions~~ ~~(~~27–108%~~)~~ ~~at their termini~~ during steady retreat (Figure 6). Alternatively, ~~Harald Moltke Bræ also accelerated between 1990 and 2016 (22 m a^{-1}: Table 1), and retreated at -196 m a^{-1} (Figure 5). However, it underwent two very large velocity increases (> 1000 m a^{-1}) between 2001 and 2006 and again during winter 2013/14, both of which coincided with short-lived glacier advance (0.5–0.8 km: Figure 6c).~~ s~~S~~ome grounded-terminus outlet glaciers did not show substantial acceleration following retreat: Kofoed-Hansen Bræ and Academy Glacier had sustained periods of steady retreat, but showed no net trend in velocity and high variability (Figure 6b,f), which did not coincide with periods of increased retreat rates (Figure 5). Brikkerne Glacier decelerated from 1996 to 2016, while the terminus position changed little (Figure 6i).

3.2~~3~~.2 Glaciers with floating ice tongues

Despite major retreat episodes and ice tongue disintegration, most glaciers in northern Greenland that terminate in floating ice tongues (except Zachariae Isstrøm) ~~of the glaciers with floating ice tongues~~ showed minimal net velocity change between 1996 and 2016~~, despite major retreat episodes and tongue disintegration on certain glaciers~~ (Table 1). In contrast to grounded-outlet glaciers, the velocity response to retreat was also more variable between individual glaciers. However, we identify ~~Within this period there was more variability, and~~ two main patterns in velocity change f~~which f~~ollowing~~ed~~ periods of rapid retreat: 1) short-lived, minimal glacier acceleration, followed by some deceleration, 2) continuous acceleration following initial terminus retreat. The first pattern of velocity change encompasses seven of nine glaciers with floating ice tongues, the clearest examples of which are at ~~Four outlet glaciers with floating ice tongues (~~C. H. Ostenfeld, Hagen Bræ, Petermann Glacier and Steensby Glacier. In all cases, rapid ice tongue retreat was followed by~~) showed~~ short-lived (< 3 year) low magnitude (<8% acceleration, but ~25% at Steensby) grounding-line acceleration~~ following rapid ice tongue retreat~~. After retreat ceased, ~~At the former three, there was <8% increase in speed, while Steensby Glacier accelerated by ~25%. At all four glaciers, after retreat and acceleration, ~~ice flow decelerated, ranging from 2% at Petermann to 28% at Hagen Bræ. In addition, prior to rapid retreat some glaciers advanced. In the year preceding rapid retreat (2005 to 2006), Hagen Brae showed higher magnitude acceleration (~52%) alongside some glacier advance. This was also the case at Ryder Glacier, which showed cyclic behaviour, of grounding line acceleration (~8%: 4.7–5.5 m a^{-1}) during both 7-year periods of terminus advance, followed by ~~more dramatic ~~deceleration (11%) during ~~periods of ~~high magnitude retreat (~2 years) in-between periods of advance. Storstrømmen and L. Bistrup Bræ also show evidence of some acceleration immediately following retreat, later followed by deceleration (Figure 7h.i) from 2010 to 2016. However, in contrast to most glaciers which flow fastest at their terminus, velocities at both glaciers are fastest inland, and decrease with distance towards the terminus (Figure 8). Grounding line terminus velocities accelerated by 350% and 150% at Storstrømmen and L. Bistrup Bræ throughout the record (1996 to 2016: Figure 7); and velocities ~20–40 km inland decelerated by 10–15 m a^{-1} (> 54%).

The second pattern of velocity change~~,~~ occurred at both glaciers draining the NEGIS ~~Despite minimal velocity change over the entire study period (Table 1) at most glaciers with floating ice tongues, during this period,~~where ice tongue retreat ~~at both glaciers draining the NEGIS, were~~was followed by gradual glacier acceleration in the subsequent decade (2006 to 2016: 43% at Zachariae Isstrøm and 10% at Nioghalvfjerdsfjorden). This prolonged glacier acceleration following retreat, is more similar to patterns observed on grounded termini, rather than the other floating tongues. Further, the removal of the entire ice tongue at Zachariae Isstrøm in 2011/12 was followed by glacier acceleration (125 m a^{-2}: 2012 to 2016, Figure 7g), whereas other glaciers (e.g. C. H. Ostenfeld and Hagen Bræ) underwent a similar collapse, but changes in velocities were limited. Despite this behaviour in the northeast of the study region, the majority of glaciers in northern Greenland showed negligible acceleration in response to retreat and/or collapse of their floating ice tongues.

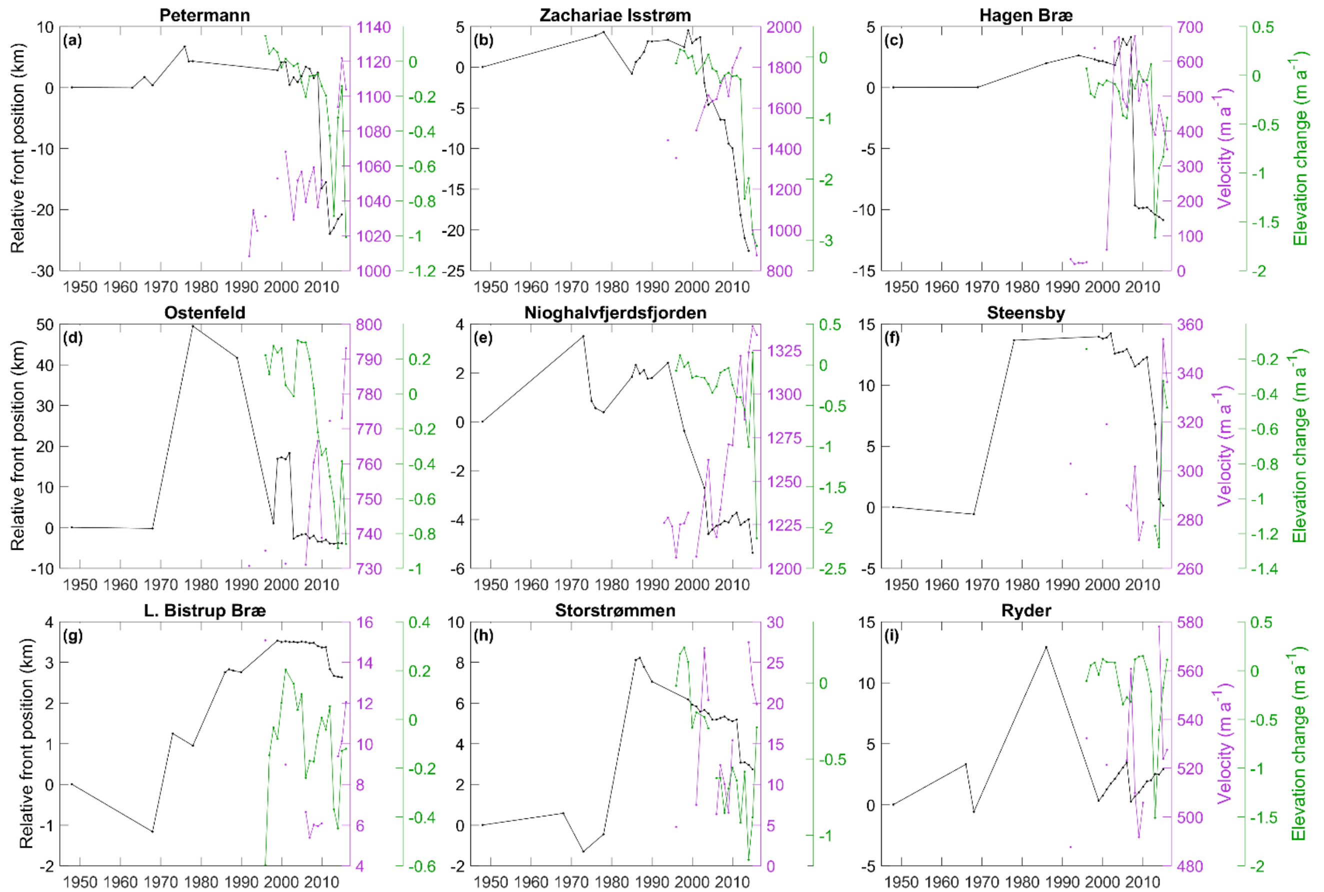


Figure 7: Front position, velocity and elevation change at nine outlet glaciers which terminate in floating ice tongues in northern Greenland. Left axes show relative front position (black line) between 1948 and 2015 relative to their initial position in 1948. Grounding line velocities (orange) on right axes one between 1996 and 2015. Surface elevation changes averaged across the glacier centreline profile (green) for 1996 to 2015.

3.34 Surface elevation change

3.34.1 Grounded-terminus outlet glaciers

Alongside continuous retreat and acceleration at ~~Thinning rates on all~~ outlet glaciers with grounded-termini ~~(except Kofoed-Hansen Bræ~~, thinning rates ~~)~~ increased between 1992–1996 and 2014–2015 (Table 1). In most cases, ~~Short-term~~ surface lowering was synchronous with the start of their steady retreat (Figure 6). ~~and~~ E~~e~~xamples of this were at Marie-Sophie and Academy Glaciers, where~~.~~ s~~S~~mall increased thinning or reduced thickening rates ~~at Academy and Marie-Sophie Glaciers~~ (1999 to 2000: Figure 6f,h), were followed by high retreat rates in the following years at both Marie-Sophie (-130 m a^{-1}: 2001 to 2004) and Academy Glacier (-205 m a^{-1}: 2001 to 2003). Periods of greater retreat (2001 to 2003/04) were followed by dramatically increased thinning rates at both glaciers to -0.3 m a^{-1} (Academy) and -0.16 m a^{-1} (Marie-Sophie: Figure 6f,h).

Thinning rates similarly increased strongly from -0.19 m a^{-1} to -0.78 m a^{-1} at Humboldt Glacier from 1996–2005 to 2005–2012, which coincided with increased retreat rates (-98 to -160 m a^{-1}: Figure 6d). Limited data prevent us from commenting in depth on elevation changes at glaciers in NW Greenland. However, the few years of data available at Harald Moltke Bræ show increased thinning between 2012 and 2015, coincident with retreat (Figure 6c). Within this record lies an anomalous year of reduced thinning rates (2013 to 2014), which were coincident with an order of magnitude increase in velocity (~1000 m a^{-1}) and 0.8 km terminus advance.

3.3~~4~~.2 Glaciers with floating ice tongues

~~Several~~ In general, glaciers with floating ice tongues ~~experienced even~~had higher thinning rates than grounded termini from 1992–1996 to 2014–2015 (Table 1), and were characterised by short-lived increases in thinning rates following ice tongue retreat. In several cases ~~This occurred at~~(e.g. Petermann, Hagen Bræ, and Zachariae Isstrøm), ~~which all showed a~~ slight thickening occurred before ice tongue retreat/collapse, followed by a switch to thinning immediately before large calving events (Figure 7). For example, ~~rates of elevation change at~~ Petermann Glacier switched from negligible thickening in 2008 (0.03 m a^{-1}) to thinning (-0.22 m a^{-1}) in 2009, before the removal of 27 km of floating ice in the following three years (2010 to 2013: Figure 7a). At Zachariae Isstrøm a switch to thinning was synchronous with the onset of rapid retreat in 2003 (Figure 7b), although thinning rates were greater once the entire ice tongue was lost ~~between~~ (2011 to ~~and~~ 2012). During or immediately after floating ice tongue retreat, t~~T~~hinning rates ~~during and immediately after floating ice tongue retreat~~ increased from minimal change (< -0.2 m a^{-1} thinning) to -0.8 m a^{-1} at Petermann Glacier (2010 to 2013), -1.7 m a^{-1} at Hagen Bræ (2007/11 to 2012/13), and -2 m a^{-1} at Zachariae Isstrøm (2011/12 to 2012/13: Figure 7). ~~At these three glaciers,~~This increased thinning was also coincident with acceleration during the years following ice tongue removal (Figure 7). Other glaciers showed more gradual and smaller increases in thinning rates (Figure 7). For example, at C. H. Ostenfeld the removal of 21 km of floating ice between 2002 and 2003 was followed by a steady and low magnitude increased thinning rates at a rate of -0.15 m a^{-1} from 2006 to 2014 (Figure 7d). In this case, velocity increases alongside increased thinning rates were also gradual, but minimal in comparison to other glaciers. Ryder Glacier also showed increased thinning rates prior to retreat (2005–2006) but was followed by a rapid switch to thickening as ice flow accelerated, and the calving front advanced (Figure 7i).

Two glaciers with floating ice tongues in northeast Greenland showed a different pattern of elevation change to the rest of the region:~~.~~ Storstrømmen and L. Bistrup Bræ thinned at the glacier terminus and thickened inland from 1996 to 2015 (Figure 8). Periods of glacier advance (~1970s–80s) at both Storstrømmen and L. Bistrup Bræ preceded the earliest record of elevation change and, following this, their terminus positions underwent minimal change (Figure 5). Between 1996 and 2015, inland elevation change was minimal (Figure 8), whereas greater thinning took place at the terminus. Large retreat events of 2.1 km at Storstrømmen and 0.7 km at L. Bistrup Bræ between 2011 and 2013 coincided with increased terminus thinning rates of -0.8 m a^{-1} at Storstrømmen (2011 to 2012) and -1.76 m a^{-1} at L. Bistrup Bræ (2011 to 2013: Figure 8). These spatial patterns of elevation change were synchronous with velocity variations: deceleration and thickening occurred inland, while acceleration, thinning, and retreat were synchronous at the terminus (Figure 8).

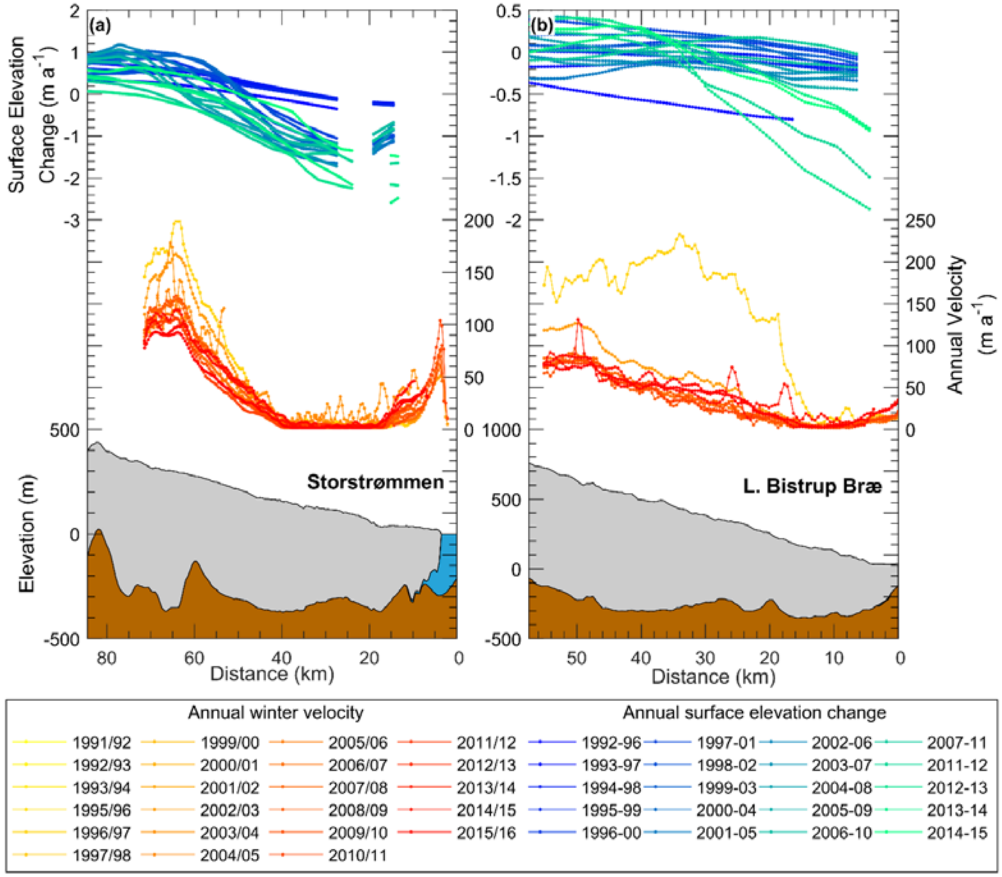


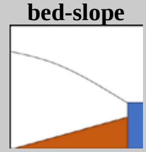
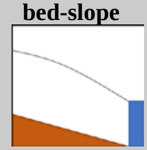
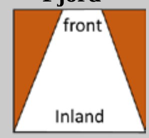
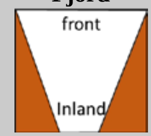
Figure 8: Annual surface elevation change, annual velocity and surface/bed topography for two outlet glaciers in northeast Greenland: Storstrømmen (a) and L. Bistrup Bræ (b). Blue to green coloured lines represent annual surface elevation through time (1992–96 to 2014–15) and yellow through to red lines represent annual winter velocity from 1991/92 to 2015/16.

3.4~~6~~ Topographic factors

3.4.1 Grounded-terminus outlet glaciers

Distinct variability in glacier geometry exists between individual outlet glaciers in northern Greenland. At many ~~grounded~~ outlet glaciers with grounded termini (Harald Moltke Brae, Heilprin, Tracy and Humboldt), deep inland sloping beds are correlated with higher retreat rates (averaging -121 m a^{-1}), and greater increases in velocity (Table 1). These glaciers rest between -33 and -370 m below sea level (Figure 9) and appear to have been retreating down steep bed-slopes (Figure S2) away from topographic ridges at the end of their fjords (Figure 9). However, variability in fjord width (widening/narrowing) does not appear to be a main determinant of higher retreat rates (Table 3). Additionally, some grounded outlets (Harder, Academy, and Marie-Sophie) have shallower seaward sloping topography which correlated with lower magnitude retreat rates (-24 m a^{-1}: Table 1).

Table 3: Glacier-specific factors at 18 northern Greenland study glaciers. This includes: the size and percentage of each surface drainage basin below sea level, the direction of the bed slope 20 km inland of the grounding line (inland or seaward), and whether the fjord widens or narrows with distance inland. Red and blue shading for bed-slope and fjord width represent expected instability, and stability respectively for each parameter.

	Northern Greenland Outlet Glaciers	**Drainage Basin Size (km^2)**	**% of drainage basin below sea level**	**Inland bed-slope** 	**Seaward bed-slope** 	**Widening Fjord** 	**Narrowing Fjord** 
Category 1: Grounded terminus	Tracy	3,176	3.6	X			X
	Kofoed-Hansen Bræ	[b]	[b]	X		X	
	Harald Moltke Bræ	666	17	X			X
	Humboldt	51,815	27	X		*Does not terminate in fjord*	
	Heilprin	6,593	2.9	X		X	
	Academy	[a]	[a]		X	X	
	Harder	792	0.2		X		X
	Marie-Sophie	2,567	6.8		X	X	
	Brikkerne	929	2.3		X		X
Category 2: Floating ice tongue	Petermann	60,093	67	X		X	
	Zachariae Isstrøm	257,542[b]	54	X		X	
	Hagen Bræ	30,250[a]	20		X	X	
	C. H. Ostenfeld	11,013	1.5	X			X
	Nioghalvfjerdsfjorden	[b]	[b]	X			X
	Steensby	3,356	4.2	X			X
	L. Bistrup Bræ	26,660	4.4	X		X	
	Storstrømmen	[b]	[b]	X		X	
	Ryder	36,384	40		X	X	

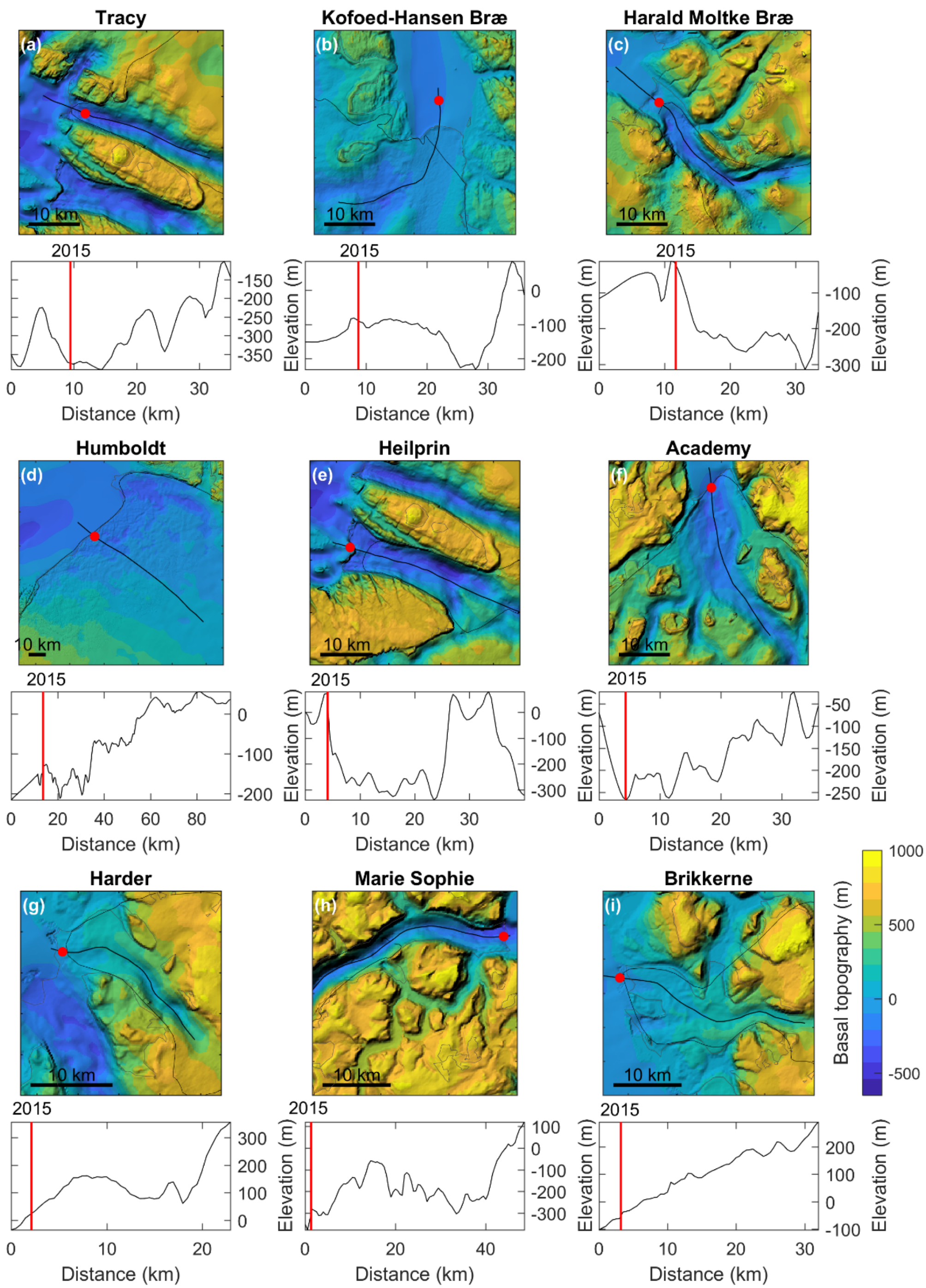


Figure 9: Basal topography from Operation IceBridge BedMachine v3 (Morlighem et al., 2017) beneath nine study glaciers with grounded termini in northern Greenland. Red points represent the position of the terminus/grounding line at each glacier from our most recent record of their terminus position (2015). Black lines are glacier centreline profiles. Profile plots show basal elevations along each glacier centreline profile and solid red lines nearest to zero show the terminus location.

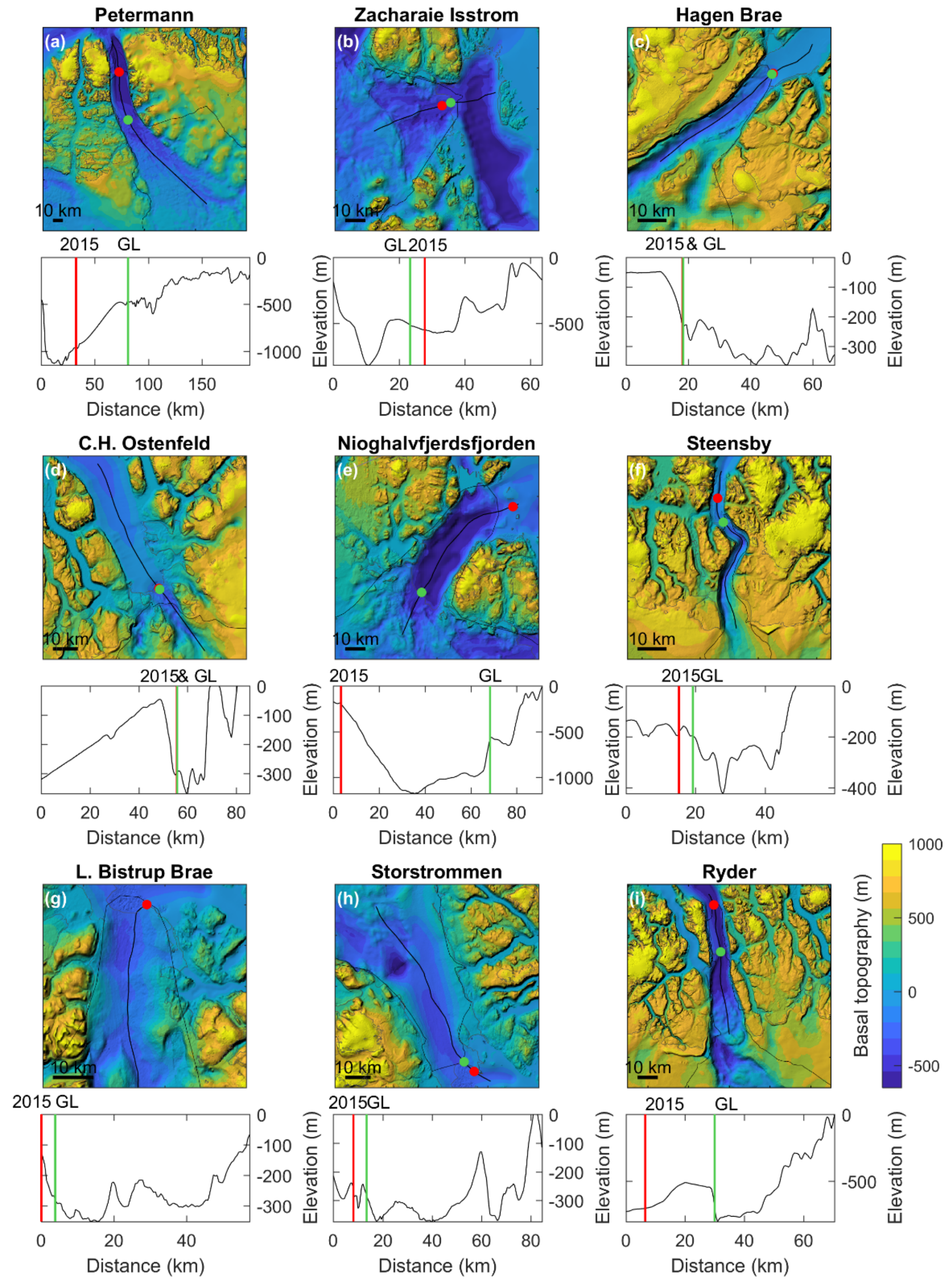


Figure 10: Basal topography from Operation IceBridge BedMachine v3 (Morlighem et al., 2017) beneath nine study glaciers which terminate in floating ice tongues in northern Greenland. Red points represent the most recent recorded terminus position (2015) from this study. Green points represent the location of the grounding line along the centreline profile from the GIMP DEM mask (Howat et al., 2014). Profile plots show basal elevations along each glacier centreline profile, where closest to zero red lines show the terminus locations, and further inland green lines shown the grounding line.

3.4.2 Glaciers with floating ice tongues

Basal topography beneath floating ice tongues does not impact on their dynamic response to retreat. Instead, we examine bed topography inland of the grounding line, which may have implications for grounding line retreat and associated instability once ice tongues collapse. ~~In contrast to grounded-terminus glaciers, those which terminate in floating ice tongues have~~ D~~d~~eeper bed topography (-73 to -1000 m below sea level: Figure 10) exists at floating ice tongues, and most (seven of nine) also have inland sloping ~~bed~~ topography within 20 km of their grounding lines (Table 3). Unlike grounded outlet glaciers there is no obvious link to higher retreat rates or fjord widths between these glaciers. However, the current grounding line position along glacier bed profiles appear to be correlated with differences in the dynamic response of glaciers to either large calving events or entire ice tongue collapse. ~~At the remaining two glaciers (Hagen Bræ and Ryder) their bed topography slopes seaward (Table 3). While bed profiles at Petermann, C. H. Ostenfeld, and Steensby have retrograde bed slopes close to the grounding line (Figure S2), further inland they show steeper seaward sloping topography (Figure 10). Additionally, current~~ G~~g~~rounding line positions at Petermann, C. H. Ostenfeld and Hagen Bræ, rest on relatively flat topography (Figure 10a,c,d), rather than retrograde slopes. In all cases, either large calving events at Petermann Glacier or entire ice tongue collapse at C. H. Ostenfeld and Hagen Brae, coincided with limited glacier acceleration. In contrast, the grounding lines of g~~Like most other floating ice tongue glaciers, Ryder Glacier also has a deep basal trough (~800 m below sea level) 20 km inland of the grounding line, but further inland (~50 km from the terminus) it has a steep seaward sloping bed, and a large topographic ridge immediately seaward of the current grounding line position (Figure 10c). G~~laciers draining the NEGIS (Nioghalvfjerdsfjorden and Zachariae Isstrøm), ~~have even~~rest on steeper inland sloping beds (Figure 10), ~~profiles immediately inland of their grounding line positions than most other glaciers with floating ice tongues (Figure 10). Both Nioghalvfjerdsfjorden and Zachariae Isstrøm experienced~~ which correlates with their gradual ice tongue retreat and prolonged glacier acceleration~~, dissimilar to the dynamic behaviour of most other glaciers with floating ice tongues~~. Since losing its ice tongue in 2011/12, Zachariae Isstrøm retreated down its steep basal trough, past the recorded (nominal date of 2007 in BedMachine dataset) grounding line position (Figure 10b). A possible exception to this pattern of grounding line instability on retrograde slopes is Ryder Glacier. It too ~~Further south-east in the study region, Storstrømmen and L. Bistrup Bræ also have deep basal troughs, particularly close to their current grounding lines, but high errors in this region mean we do not consider their bed topography further.~~ ~~Like most other floating ice tongue glaciers, Ryder Glacier also~~ has a deep basal trough (~800 m below sea level) 20 km inland of the grounding line, but further inland (~50 km from the terminus) it has a steep seaward sloping bed, and a large topographic ridge immediately seaward of the current grounding line position (Figure 10c).

4. Discussion

4.1 Timing of glacier change between 1948 and 2016

Decadal terminus changes at all 18 study glaciers (Figure 4), showed a transition from slow low magnitude advance and retreat (averaging +72 m a^{-1}) between 1948 and 1995 to rapid high magnitude retreat (averaging -445 m a^{-1}) between 1996 and 2015. The latter period included the onset of steady retreat at most grounded outlet glaciers in northern Greenland, and the occurrence of large, rapid retreat events at floating ice tongue glaciers (Figure 5). While this switch from minimal terminus change/advance to more rapid retreat is perhaps similar to the cyclic behaviour of tidewater glaciers (Meier and Post, 1987; Pfeffer, 2007), it is unlikely that this pattern of widespread retreat is driven by internal factors alone (e.g. Nick et al., 2007). Instead, climate~~-~~-induced dynamic thinning at outlet glacier margins (Khan et al., 2014; Pritchard et al., 2009), ~~due to negative mass balance (van den Broeke et al., 2016; Khan et al., 2015; Pritchard et al., 2009),~~ may have been the initial ~~condition~~ forcing for increased glacier retreat rates in northern Greenland. T~~Importantly, t~~he switch to terminus retreat the 1990s was coincident with: increased air and ocean temperatures across the GrIS (e.g. Box et al., 2009; Hanna et al., 2008; Luckman et al., 2006), ice marginal thinning (< 2000 m elevation) since the 1990s (Abdalati et al., 2001; van den Broeke et al., 2016; Krabill et al., 2000), and with Arctic-wide increased retreat rates (Carr et al., 2017b; Moon and Joughin, 2008; Jensen et al., 2016). Previous studies in northern Greenland have suggested that climate-ocean forcing at glacier termini i.e. increased air temperatures, reduced sea ice concentration, and ocean warming induced basal melt, triggered dynamic thinning, retreat, and mass loss from outlet glacier margins (Khan et al., 2014; Reeh et al., 2001; Rignot et al., 2001; Rignot and Steffen, 2008). ~~Previous studies in northern Greenland have identified a number of potential triggers for glacier retreat in the region: 1) the loss of sea ice buttressing, particularly in the NEGIS (Khan et al., 2014; Reeh et al., 2001) and 2) increased basal melt rates beneath floating ice tongues due to ocean warming (Reeh et al., 2001; Rignot et al., 2001; Rignot and Steffen, 2008; Wilson et al., 2017)~~.~~, acceleration and retreat in south-east Greenland. Thinning rates also increased in the GrIS ablation area (< 2000 m elevation) since the 1990s (Abdalati et al., 2001; van den Broeke et al., 2016; Krabill et al., 2000). At several glaciers, e.g. Jakobshavn (Thomas et al., 2011), and Helheim and Kangerdlugssuaq in the south-east (Howat et al., 2008; Luckman et al., 2006), increasing temperatures after the 1990s increased thinning in the ablation zone, which reduced basal/lateral drag and instigated a period of rapid terminus retreat.~~ Here, we do not assess in detail the climate-ocean forcing mechanisms that may have influenced recent terminus change behaviour in northern Greenland, partly due to lack of data and partly ~~as the main~~because the focus of this paper is on glacier dynamics and their interaction with topography. However, we ~~do~~ note that surface thinning preceded rapid terminus retreat at many northern Greenland glaciers (Figures 6 and 7). Therefore, we suggest that dynamic thinning could have been the initial forcing that accelerated glacier retreat in northern Greenland since the 1990s (cf. Felikson et al., 2017; Nick et al., 2009; Price et al., 2011). ~~es 6 and 7. Similar to previous studies (refs) we suggest there is a link between thinning and retreat in northern Greenland~~However, in line with tidewater glacier cyclic behaviour, it is likely that after an initial change in dynamics at the terminus triggered by climate forcing, fjord width and depth become more important controls (see Section

4.3) on the duration and magnitude of retreat at individual glaciers (Benn et al., 2007; Catania et al., 2018; MacGregor et al., 2012).

~~Climatic and oceanic changes may have been the initial trigger of retreat in northern Greenland, with subsequent retreat being sustained by the fjord topography (i.e. basal topography and fjord width: Section 4.3). However, in line with tidewater glacier cyclic behaviour, it is likely that after an initial change in dynamics at the terminus triggered by climate forcing, fjord width and depth become more important controls on the duration and magnitude of retreat at individual glaciers (Benn et al., 2007; MacGregor et al., 2012). Here, we do not assess in detail the climate-ocean forcing mechanisms that may have influenced recent terminus change behaviour in northern Greenland, partly due to lack of data and partly as the main focus of this paper is on glacier dynamics and their interaction with topography. Instead we focus on the patterns of terminus change, dynamic glacier behaviour, and geometric controls. We highlight ascertaining the climate-ocean drivers on recent outlet glacier behaviour as an important area of future work in northern Greenland.~~

4.2 Dynamic glacier response to terminus change

Our analysis of ~~terminus~~ termini behaviour shows that the dynamic glacier response (acceleration and thinning) to a frontal position change is highly dependent on whether the terminus is grounded or the glacier terminates in a floating ice tongue (Benn et al., 2007). Informed by our changepoint analysis, ~~Across northern Greenland~~ we observe two dominant calving behaviours in northern Greenland based on these terminus types: 1) low magnitude continuous calving events/terminus retreat at grounded outlet glaciers, 2) large episodic tabular calving events at glaciers with floating ice tongues. ~~Our changepoint analysis also revealed significant differences in the duration and magnitude of rapid retreat based on terminus type. Different calving styles at these two categories of glacier correspond to variances in their dynamic glacier response (acceleration and thinning) to terminus chang~~Independent of these styles (continuous vs episodic), calving at both categories of terminus type is influenced by the velocity structure of the glacier, and ice velocity itself is sensitive to changes in terminus position and alterations to the force balance, i.e. decreased basal/lateral resistance and increased driving stress (Benn et al., 2007). In the previous section, we hypothesised that i~~I~~ncreased thinning at the glacier terminus (~1990s), may have initiated enhanced retreat and accelerated terminus velocities in the following two decades (1996 to 2015), similar to other regions of the ice sheet (e.g. Luckman et al., 2006; McFadden et al., 2011; Moon and Joughin, 2008). Such thinning could ~~-~~cause~~s~~ downstream increases in velocity, which stretches the ice, promotes crevasse propagation induced calving, and propagates the dynamic response (i.e. acceleration) up-glacier~~accelerates flow inland~~. However, the coarse resolution of our elevation change datasets limits our ability to deduce the initial cause of accelerated retreat, so instead we focus on the trends in dynamic glacier changes (acceleration and thinning), after the onset of retreat.~~As such, thinning is thought to have initiated enhanced retreat and accelerated terminus velocities, similar to other regions of the ice sheet (e.g. Luckman et al., 2006; McFadden et al., 2011; Moon and Joughin, 2008). Indeed, across northern Greenland our results suggest that terminus thinning (~1990s) could have been the initial criterion for instigating enhanced calving and terminus retreat in the following two decades (1996 to 2015).~~

Following an assumed initial change in terminus conditions (~1990s), outlet glaciers in northern Greenland that are grounded at their terminus, underwent prolonged periods of steady terminus retreat (on average -150 m a^{-1}), that usually lasted for two to three decades (Figure 5). Like grounded-outlet glaciers elsewhere, e.g. Helheim and Kangerdlugssuaq (Howat et al., 2005, 2007, 2008) and in west Greenland (McFadden et al., 2011), periods of steady and continuous retreat at grounded-terminus outlet glaciers in northern Greenland were accompanied by increased annual ice velocities (27-110%), and dynamic thinning (Figure 6). From this dynamic response we suggest that continuous calving and retreat, and the associated reduction in resistive stresses at the terminus, substantially altered the force balance by increasing longitudinal stretching and driving stress. This prolonged stress perturbation at the terminus of most grounded outlet glaciers in northern Greenland, allowed acceleration and thinning to propagate inland and continue for a longer period as most glaciers may have not reached a stable geometry (McFadden et al., 2011; Nick et al., 2009: Section 4.3).

In contrast, terminus changes at most glaciers with floating ice tongues were characterised by short-lived (<6 years), significantly higher magnitude retreat events that averaged -4536 m a^{-1} (after ~1990s). These high magnitude retreat events were often due to the calving large tabular icebergs, initiated by rift propagation (e.g. MacGregor et al., 2012). However, these large calving events were followed by minimal/and or short-lived increases in annual velocity, and short-term increases in ice surface thinning rates (Figure 7). From these velocity records we infer that in most cases large calving events, appeared not to substantially perturb the glacier force balance by neither increasing longitudinal stretching, nor driving stresses on ~~inland~~ grounded ice, which would lead to annual acceleration (Figure 7). ~~Instead, terminus retreat was followed by minimal/and or short-lived increases in annual velocity, and short-term increases in ice surface thinning rates (Figure 7).~~ This was particularly the case at Petermann, Hagen Bræ and C. H. Ostenfeld, in response to ice tongue collapse or large calving events. This contrasts with the behaviour of ice-tongue terminating glaciers elsewhere in Greenland (e.g. Joughin et al., 2004, 2008) and glaciers draining into Antarctic ice shelves (e.g. Scambos et al., 2004), which instead showed prolonged acceleration and dynamic thinning following the loss of substantial floating ice. At some glaciers short-lived acceleration was followed by reduced retreat, and deceleration (e.g. Hagen Bræ), which represents a rapid re-adjustment at the terminus, and that calving at floating ice tongue glaciers in northern Greenland~~,~~ appear to limit the dynamic glacier response to large calving events. This could be due to limited lateral resistance provided by floating ice tongues (Section 4.3).

However, Zachariae Isstrøm was a notable exception to this pattern. At Zachariae Isstrøm, sustained annual calving was accompanied by a longer period of glacier acceleration and thinning (Figure 7b). This is comparable to the behaviour of grounded outlet glaciers in northern Greenland, and ice-tongue terminating glaciers elsewhere (e.g. Jakobshavn Isbræ: Joughin et al., 2004, 2008). In this case, continuous retreat is likely to have gradually reduced resistive forces (i.e. backstress) acting on inland grounded ice, causing higher magnitude and prolonged flow acceleration. Apart from Zachariae Isstrøm, our data show outlet glaciers in northern Greenland have been largely insensitive to either entire ice tongue loss (C. H. Ostenfeld, Steensby and Hagen Bræ), or large iceberg calving events (Petermann, Nioghalvfjerdsfjorden). Thus, despite some similarities (e.g. Zachariae Isstrøm to grounded-behaviour), region wide glacier behaviour in northern Greenland appears dependent on whether the terminus is grounded or floating, due to their calving nature and dynamic response to perturbations of their termini. This highlights the need to consider terminus type when assessing the long-term response of outlet glaciers to changes at their terminus.

4.3 Influence of glacier geometry

While climate-ocean forcing may have triggered a change in glacier dynamics at the terminus of outlet glaciers in northern Greenland (e.g. Khan et al., 2014; Reeh et al., 2001), glacier geometry (e.g. width and depth of fjords) may have determined the duration and extent of the resultant retreat. Indeed, variations in basal topography and fjord width have been previously identified as an important control on the dynamic response of glaciers in many regions of the GrIS (e.g. Carr et al., 2013, 2017b; Howat and Eddy, 2011; McFadden et al., 2011; Millan et al., 2018; Thomas et al., 2009). Collectively these factors could explain differences between grounded-terminus and floating ice-tongue glaciers (McFadden et al., 2011), as well as individual glacier variability.

Calving from grounded outlet margins is controlled by both basal and lateral drag, and both reduce as a glacier retreats into a deeper and wider fjord (Benn et al., 2007). At grounded outlet glaciers in northern Greenland, prolonged acceleration and thinning following retreat suggests that these glaciers were still adjusting to terminus change by the end of the study period in 2015. This is likely due to deep basal topography (> 200 m below sea level), and retrograde bed slopes (~20 km of their grounding zones) beneath most grounded-terminus glaciers (Figure 9). We suggest grounded-terminus retreat into deeper water contributed to: (i) buoyancy driven feedbacks, as the ice thinned to flotation (van der Veen, 1996), (ii) the penetration of basal crevasses through the full ice thickness (van der Veen, 1998, 2007), and (iii) subsequent enhanced rates of calving and continued retreat (e.g. Joughin et al., 2008). Our results showed grounded-outlet glaciers which retreated into deeper fjords, had higher retreat rates (e.g. Tracy, Harald Moltke Bræ, and Heilprin), than those with shallower basal troughs (e.g. Academy and Marie-Sophie). The former three glaciers also appear to be retreating downslope from topographic highs at the edge of their fjords (Figure 9a,c,e).

Unlike grounded-termini, floating ice tongues predominantly provide resistive stresses through their contact with the lateral fjord margins. Consequently, lateral resistive stresses are the main control on the glacier force balance and driving stresses, and hence the impact of terminus retreat on inland ice dynamics. Our data have shown variability in glacier response to ice tongues loss (Figure 7), and we suggest that this could be due to differences in the lateral resistive the floating ice tongue provides when it is in place. Once the ice tongue has entirely collapsed, the terminus becomes grounded, at which point basal drag becomes an important control, and basal topography at and immediately inland of the grounding line becomes more significant.

At most glaciers with floating ice tongues in northern Greenland, the minimal dynamic response to ice tongue retreat and/or collapse (Figure 7), may be due to limited lateral resistance provided by their floating ice tongues. In particular, C. H. Ostenfeld and Hagen Bræ, have heavy rifting along their shear margins, appear relatively un-confined by their fjord walls, and weakly attached to the grounded terminus (Figure 11b,c). Indeed, both glaciers showed no significant increase in flow speeds following large calving events. This suggests that, in both cases, the buttressing provide by the tongues was minimal, and large ice tongue retreats caused a limited change in the inland force balance. Alternatively, Steensby Glacier showed some acceleration (~25%) following ice tongue retreat, which could be due to both a greater loss of lateral resistive stresses from a well-confined ice tongue, and retreat past a narrower sinuous section of the fjord (Figure 11a).

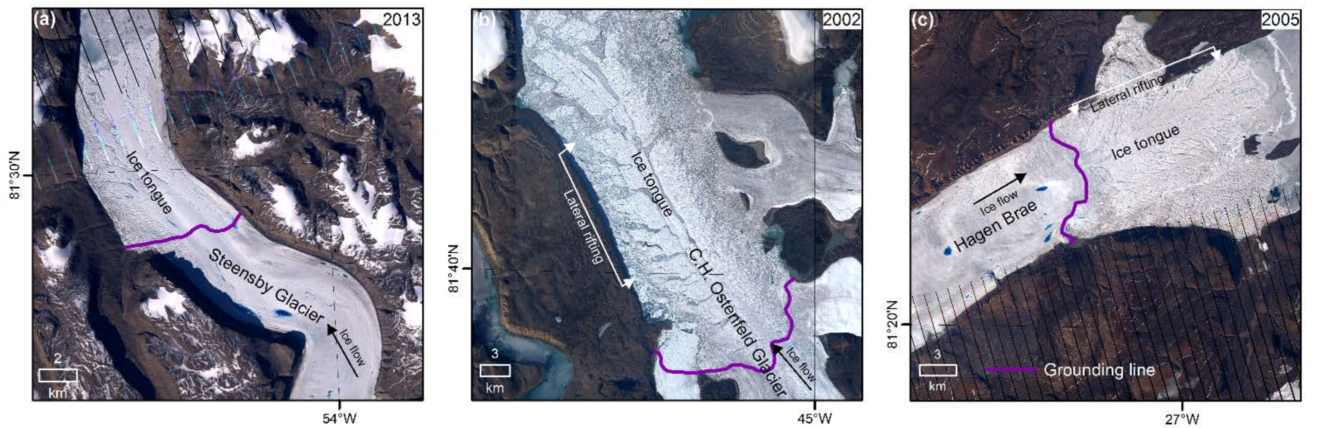


Figure 11: Landsat imagery of three glaciers which terminate in floating ice tongues in northern Greenland before their ice tongue collapse. (a) Steensby Glacier in 2013, (b) C. H. Ostenfeld Glacier in 2002, (c) Hagen Bræ in 2005. Purple lines denote the location of the grounding line.

As well as the lack of resistive stress provided by their ice tongues, the limited response of Hagen Bræ and C. H. Ostenfeld to terminus retreat (Figure 7) may result from their basal topography: following retreat, both grounding lines retreated into shallow water (Figure 10). This may have supressed retreat rates, as it reduces grounding line thickness and therefore discharge. In turn, this would reduce the impact on inland ice velocities and surface thinning rates (Vieli and Nick, 2011). The flat sections of basal topography beneath the grounding lines of Petermann Glacier and Nioghalvfjerdsfjorden may also control their future response to ice tongue collapse, as their grounding lines would need to retreat ~20 km inland to sit on a retrograde slope (Figure 8b, g). In contrast, ice tongue collapse at Zachariae Isstrøm, was followed by continued acceleration, retreat, and more dramatic thinning (Figure 7b). Here, the deep retrograde bed-slope that extends ~20 km inland of the grounding line, is likely responsible for continued retreat (Khan et al., 2014; Mouginot et al., 2015). Retreat into deeper water, gradually reduced buttressing forces, and caused continuous glacier acceleration and surface thinning following ice tongue collapse, similar to Jakobshavn Isbræ (Vieli and Nick, 2011).

4.4 Glacier surging

Surge-type behaviour has been previously documented at several outlet glaciers in northern Greenland (e.g. Hill et al., 2017; Rignot et al., 2001; Weidick et al., 1994), but detailed evidence for surging is rare. Here we briefly discuss how the surge-nature of several glaciers in northern Greenland may have altered their dynamic behaviour independent of their terminus type.

Our results provide ~~substantial~~ further evidence for the presence of three surge-type glaciers in northern Greenland (Storstrømmen, L. Bistrup Bræ, and Harald Moltke Bræ). This is based on the following characteristics: 1) substantial periods of glacier advance (> 90 m a^{-1}) followed by retreat during the study period, 2) accelerated ice flow coincident with periods of advance, and 3) surface thickening inland and thinning at the terminus position indicative of a quiescent surge-phase. ~~We also provide a long-term record for Ryder Glacier, which suggests its previously recorded surge-behaviour (Joughin et al., 1996, 1999), may instead by related to cyclic tidewater glacier behaviour and basal topographic controls.~~ Both ~~Two glaciers in northeast Greenland show strong evidence of being surge-type:~~ Storstrømmen and L. Bistrup Bræ have floating ice tongues which ~~. Interestingly both glaciers~~ began ~~to~~ advancing ~~e at a similar time, despite separate drainage catchments~~in the 1970s (Reeh et al., 1999), and ~~advance~~ continued until 1985 at Storstrømmen, and 1998 at L. Bistrup Bræ (Figure 5). ~~Unfortunately,~~While velocity and surface elevation change datasets do not cover this period, ~~. However,~~ dynamic changes ~~at both glaciers between~~later on (1992 to~~and~~ 2016: Figure 8) were indicative of ~~periods of~~ quiescence (Abdalati et al., 2001; Csatho et al., 2014; Thomas et al., 2009). ~~.~~In this respect, these glaciers have behaved differently to the majority of glaciers in the region with floating ice tongues i.e. thickening and deceleration inland, and thinning and acceleration at the terminus ~~Both glaciers show inland thickening, which coincides with slower glacier flow, and a terminus region of greater thinning, coincident with acceleration and retreat~~ (Figure 8). ~~Terminus and dynamic glacier changes recorded in this study at Storstrømmen and L. Bistrup Bræ (Figure 7g,h) provide firmer evidence to support previous work that identified a surge event at 1970s (Reeh et al., 1999), and highlighted evidence of quiescence since (Abdalati et al., 2001; Csatho et al., 2014; Thomas et al., 2009).~~ In northwest Greenland, Harald Moltke Bræ has been previously considered surge-type. Here we record an additional surge event from 2013 to 2014, based on high magnitude acceleration (~1000 m a^{-1}) and glacier advance (0.8 km: Figure 6c). This glacier fits the conventional definition of surging, i.e. a short active phase, which included an order of magnitude increase in velocity. However, it has a short surge-cycle (< 10 years) compared to most other glaciers in the Arctic, and underwent overall retreat from the late 1980s to 2015 (Figure 5). This suggests that despite short-lived surge events, recent climate-ocean forcing may be altering its cyclical behaviour.

~~Several other glaciers in northern Greenland have also been identified as potentially surge type (Academy and Hagen Bræ: Rignot and Kanagaratnam, 2006; Thomas et al., 2009). These observations were based on limited elevation records which suggested thickening at the terminus of Hagen Brae (Thomas et al., 2009), and some speed up recorded at Academy Glacier in 2005 (Rignot and Kanagaratnam, 2006). However, our detailed, long term (1948 to 2015) analysis of terminus positions, acceleration and thinning, show no substantial evidence (i.e. cycles of advance/retreat or order of magnitude increases in velocity) to suggest these glaciers are surge-type. Another previously documented surge-glacier is Brikkerne, due to its fast movement and advance seen in early aerial photographs (Higgins, 1991; Higgins and Weidick, 1990). Indeed, terminus changes recorded here confirm a period of advance between 1969 and 1978, followed by a period of apparent terminus stability (Figure 6i). However, due to the lack of detailed elevation and surface velocity observations during this period of advance, we are unable to provide more substantial evidence to classify it as surge-type.~~

Finally, we ~~consider~~draw attention to Ryder Glacier ~~is an exception to most outlet glaciers in the region and~~as it appears to be behaving dissimilarly to the rest of our study glaciers in northern Greenland. ~~non-linearly to climate forcing (Figure 7i)~~It too ~~. Ryder~~ has also been referred to as surge-type in the past (Joughin et al., 1996, 1999; Rignot et al., 2001), and ~~, largely due to a 'mini-surge' event in 1996 (Joughin et al., 1996). Indeed, it~~ has shown some surge-like behaviour during our study period (1948–2015): several cycles of advance (~7-years) and retreat (2-years), ~~during the study period (1948–2015),~~ and some acceleration during advance. Additionally, previous studies also identified near-terminus thinning (2–4 m a^{-1}: 1997 to 1999) and, at ~50 km inland, a similar magnitude of thickening (Abdalati et al., 2001), which is indicative of the quiescent phase of surge-type glaciers (e.g. Kamb et al., 1985; Meier and Post, 1969; Sharp, 1988). However, the behaviour of Ryder Glacier appears to be more characteristic of a tidewater glacier cycle, which ~~Despite this, the short surge-cycle (9 years), minimal glacier acceleration (~8%) during advance, and a cyclic pattern of slow advance followed by rapid retreat, is more characteristic of cyclic tidewater glacier behaviour. We instead suggest that Ryder Glacier cyclic behaviour~~ may be controlled by basal topography. In contrast to the role of basal topography at most other outlet glaciers in northern Greenland (i.e. unstable retreat down inland sloping beds), a large basal ridge (Figure 10i) or terminal moraine/moraine shoal at Ryder Glacier may have promoted periods of glacier advance (Alley, 1991; Nick et al., 2007; Powell, 1990). Nevertheless, further investigation on the cyclic nature and precise controls on Ryder Glaciers' dynamic behaviour is needed.

~~The glacier rests in a deep basal trough (~1000 m below sea level), that slopes seaward, and has a large basal ridge in front of the glacier grounding line (Figure 10i). We suggest this could be a terminal moraine, or moraine shoal, which may have promoted periods of glacier advance (Alley, 1991; Powell, 1990). Similar to Columbia Glacier (Alley, 1991; Nick et al., 2007), the deep basal depression just inland of the grounding line (Figure 10i), and steep seaward bed slope further inland, could have allowed relative terminus stability. As the same time, this could have promoted the build-up of a large moraine seaward of the grounding line, and the decrease in water depth then promoted glacier advance (Alley, 1991; Nick et al., 2007). Shoal advance may have allowed slow terminus advance through this deep basal trough (~7 years), and minimal retreat away from this~~

~~moraine caused rapid retreat (~2 years) back into the trough. We therefore suggest that instead of surging, Ryder Glacier is controlled by internally driven tidewater glacier cycles, and re-advance may be promoted by the presence of a moraine shoal.~~

5. Conclusions

Outlet glaciers in northern Greenland drain ~40% of the ice sheet by area but remain understudied compared to other regions of the ice sheet. We have analysed the dynamics of 18 major marine-terminating outlet glaciers in northern Greenland between 1948 and 2015. Overall, long-term glacier retreat rates ranged from -15 to -311 m a^{-1} over the entire study period. Between 1948 and 1995 glaciers exhibited generally low magnitude advance and retreat, with an average frontal position change of +72 m a^{-1} (advance) across the 18 study glaciers. Following this, there was a regional transition to more rapid and widespread retreat, when average frontal position change was -445 m a^{-1} (1995 to 2015). This was coincident with accelerated retreat in other regions of the ice sheet (e.g. Carr et al., 2013; Howat et al., 2008; Howat and Eddy, 2011). From 1996 to 2015, most glaciers also experienced accelerated ice flow and increased dynamic thinning.

While increased retreat rates from the mid-1990s were near-ubiquitous, we observe distinct differences in glacier behaviour depending on whether the terminus is grounded or floating. Three factors play a role in the dynamic behaviour of these two types of glacier; i) different methods of calving (i.e. ~~,~~ continuous small magnitude calving vs large episodic calving); ii) differences in resistive stresses at the terminus~~,~~; iii) glacier geometry. Continuous retreat into deep~~, widening~~ fjords at grounded-terminus glaciers led to a greater reduction in basal/lateral resistive stresses, and caused high magnitude acceleration and dynamic thinning. In contrast, large episodic calving events, from unconfined ice tongues that provided little lateral resistance meant that most glaciers with floating ice tongues appear dynamically insensitive to the retreat of their terminus. We note there are exceptions; continuous ice tongue retreat at Zachariae Isstrøm caused prolonged acceleration and thinning, and several glaciers with ice tongues went through cycles of advance and retreat during the study record (e.g. Ryder Glacier). At Zachariae Isstrøm this can be explained by the method of glacier calving (continuous rather than episodic), and a deep wide fjord that promoted unstable retreat. Glacier advance can be explained by surging, or topographic controls which allow cyclic advance and retreat. We provide further evidence for surging at three glaciers (Harald Moltke Bræ, Storstrømmen and L. Bistrup Bræ) in northern Greenland, and an explanation for the cyclic behaviour of Ryder Glacier, which is likely related to topographic controls (e.g. moraine shoal), that allowed the re-advance of the terminus. While we have shown that northern Greenland has begun to undergo rapid dynamic change over the last two decades (1996 to 2015), we highlight variability between individual glaciers and the importance of considering terminus type and glacier geometry (basal topography, fjord width and ice tongue confinement) when considering future glacier response to climate change across this region of the ice sheet. Currently, ice tongue retreat does not appear to substantially affect inland ice dynamics.~~ , h~~However, once these glaciers become grounded, they may accelerate, thin, and increase the volume of grounded ice discharge into the ocean.

Data availability

Shapefiles of frontal positions for all 18 outlet glaciers in this study between 1948 and 2015 are freely available on request to the corresponding author. All other data sources, including: satellite imagery, historical maps, surface elevation change, annual velocity, climate and ocean, and topographic data, are already available online. The sources of each of these datasets are given in the text and the supplementary information.

Author contribution

The initial project was designed by all authors, and E. A. Hill led the data analysis and interpretation, with comments throughout from all authors. E. A. Hill led the manuscript writing, and all authors contributed towards the editing of the manuscript and figures.

Competing interests

The authors declare that they have no conflict of interest.

Acknowledgements

This work was supported by a Doctoral Studentship award to E. A. Hill at Newcastle University, UK, from the IAPETUS Natural Environment Research Council Doctoral Training Partnership (grant number: NE/L002590/1). We thank the ESA for granting access to SPOT–1 data (project ID: 32435). We are also grateful for Corona imagery which was digitised on request to the US Geological Survey. We acknowledge several free datasets used in this work. Historical map charts were made available from the Polar Geospatial Centre and the Perry-Castañeda Library at the University of Texas, Austin. We are grateful for Cryosat and ESA surface elevation change data, and Sentinel annual Greenland wide velocity maps made freely available as part of the ESA Greenland Climate Change Initiative. MEaSUREs velocity maps (Joughin et al., 2010), IceBridge BedMachine v3~~2~~ (Morlighem et al., 2017~~4~~), ~~and sea ice concentrations (Cavalieri et al., 1996) are~~is available from the National Snow and Ice Data Centre (NSIDC). Landsat imagery were acquired from the US Geological Survey.~~ Surface air temperature data were acquired from the Danish Meteorological Institute (Vinther et al., 2006).~~ We are extremely grateful to the Editor of this manuscript - Andreas Vieli - and to three anonymous reviews whose comments led to improvements in both the content and clarity.

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