Dear Editor,

We are grateful for the referee comments on our manuscript 'Dynamic changes in outlet glaciers in northern Greenland from 1948 to 2015'. We have gone through each of the referee comments and made a number of revisions to the manuscript. These changes have been large, and so there are numerous areas highlighted in the tracked changes document below. In our responses to the reviewer comments we include a description of changes that have been made to the manuscript. Our responses to these referee comments and specific changes in the manuscript are summarised below. We feel that the manuscript has been greatly improved, and once again we thank the editor and both referees for their constructive comments.

Thank you for considering this manuscript for publication.

Emily Hill

Response to Anonymous Referee #1

General comments:

This paper brings together data on glacier terminus position, speed, fjord geometry, and other metrics to examine glacier behavior across northern Greenland over 1948-2015. This is useful data to publish and results are in line with established ideas on glacier dynamics, influence of fjord geometry, and behavior of glaciers with or without floating ice tongues. Several tables' figures are particularly useful for visualizing the results (e.g, Table 2 and Figure 6) and the paper adds new information about several glaciers and is quite thorough in addressing all marine-terminate northern glaciers.

Despite the strengths of the paper, there are fairly substantial areas for improvement:

#1 In an attempt to pull climate and ocean conditions into the analysis, the authors include air temperature data from two weather stations and sea ice concentration from passive microwave (Section 2.4 and results in Section 3.5). The value of including these data seems extremely limited. On the air temperature side, only two weather stations are available, at the southern edges of the study area on the east and west coast. These data are used for a basic determination of changes in air temperature trend. For sea ice, the 25km resolution precludes analysis in narrow fjords or near the ice edge. It is well established that these data do poorly in capturing sea ice concentration at glacier termini in Greenland. Thus both the air and ocean data is severely lacking in detail compared to the other datasets the authors are working with. The authors even note themselves that they are focusing on ice dynamics and not air/ocean forcing (page 7, lines 3-5). I suggest that the authors reconsider the utility of these data and inclusion in the paper. They may instead choose to refer to data already published on Greenland air temperature and sea ice trends. The other analysis in the paper is of more interest and better quality.

We have taken the advice of referee 1 and removed the entire climate forcing section from both the methods and the results. Alongside this, we have shortened the first section of the discussion which referred to climate data. Instead, this section considers the timing of a switch to greater retreat with reference to previously published literature on temperature trends. We also mention some of the climate-forcing controls that have been previously considered important in northern Greenland.

#2 At no point do the authors discuss some of the fundamental differences expected in glaciers with grounded termini versus floating ice tongues. I expected some acknowledgement that the former would have small, more continuous calving events and the latter would experience calving of large tabular icebergs. Since this is exactly what the authors observe, they need to provide some information and context for the behaviour. This can also include a discussion of why smaller dynamic changes might be expected for glaciers with floating ice tongues. Without some of these notes, the results and discussion feel as though they have been pulled out of context from the greater body of glaciological literature.

We have now added a paragraph to the introduction that discusses some of the cyclic behaviour expected of tidewater glaciers, and the key differences in floating and grounded terminus calving behaviour. In the discussion (Section 4.2) we reiterate that we expect the calving and dynamic behaviour of these two categories of glacier to be different, alongside explaining how our results indeed show two dominant calving patterns that are dependent on glacier terminus type.

#3 The paper does suffer some overly complex sentences, wordy phrasing, and occasional poor organization. These items can be taken care of with mindful editing. Joshua Schimel's book Writing Science is an excellent reference for techniques and ideas.

Throughout restructure and rewriting of several large sections of the manuscript we have paid careful attention to sentence and paragraph structure, and hope to have improved on all these factors throughout the paper. In particular these changes are within the results and discussion.

Specific comments by page/line number:

1/12. 'remains unknown' is an overstatement and needs changing

1/12-13 Changed to 'is poorly constrained'

1/23. This sentence is long and the wording at the end is overly complicated. Requires editing

1/25-28. We have improved the wording of the last sentence of the abstract to be shorter and more focused

2/4. Moon et al. 2012 is a paper about ice speed and does not discuss thinning or retreat. This paper is incorrectly referenced in several places in the manuscript (e.g., also 14/32). An appropriate reference for thinning is: Csatho, B. M., A. F. Schenk, C. J. van der Veen, G. Babonis, K. Duncan, S. Rezvanbehbahani, M. R. van den Broeke, S. B. Simonsen, S. Nagarajan, and J. H. Van Angelen (2014), Laser altimetry reveals complex pattern of Greenland Ice Sheet dynamics, *Proceedings of the National Academy of Sciences*, *111*(52), 18478–18483, doi:10.1073/pnas.1411680112.

We apologise for the incorrect reference to this paper and have changed this to be Csatho et al. 2014 instead. This is now on 2/10. In the discussion (14/32) the sentence that incorrectly referenced this paper has now been removed from the manuscript as we shortened this section when condensing the climate material in the paper.

2/19-26. This paragraph would be better ordered: Sentence 2, sentence 1, sentence 3.

3/4-14. We have restructured this paragraph and to avoid overlap removed sentence 2. We now introduce the region in more detail in Section 2.1 (Study region).

4/15-19. Another section that could be simplified/shortened. For example: 'Presence of sea ice and highly fractured termini made terminus picking at Steensby, CH Ostenfeld, and NGIS glaciers more difficult (Refs). Re-digitising all 1999-2015 Landsat terminus positions yielded additional errors of □13% for these glaciers.'

We have simplified as suggested on

6/9-12. We have simplified as suggested

5/3. It's not clear what range you are referring to – include the numbers here instead of 'this'.

7/7. We have amended this to 'incrementing the number of breaks'

5/3-5. This is confusing and I do not clearly understand the process from this description. Please revise.

7/10-13. We have reworded the last couple of sentences at the end of 2.3 to improve the description of the process.

5/11. It is better to refer to 'earlier' and 'later' instead of 'first' and 'second'.

7/19-20. We have amended 'first' and 'second' to 'earlier' and 'later'

5/12. Please specify what you are using to estimate average errors in velocity. This is more clear for other methods descriptions.

7/20. We have added in 'Using dataset error maps' to better describe that we calculated average errors in velocity from the included dataset error maps.

5/29-30. Why use only the difference between 1995/96 and 2015/16 velocity data to calculate change when you have so many years of data between these years. Seems that finding a trend across all years of data would provide a more accurate picture of change.

This is a reasonable point, but our terminus position changes focus on longer-term decadal changes in frontal position change. Thus, we have tried to focus on velocity changes over similarly long time-scales. It is also likely that short-term changes would be more likely to be subject to potentially stochastic variations or variations that lie within the error. Thus, we prefer to focus on longer term velocity trends and we are already conscious that the paper contains a lot of detail and is quite long.

6/9-11. The same comment as above, but for the surface elevation change. Why use just two periods when you have more data in between? As a separate note, please reconsider using 'SEC'. This is not a commonly used acronym and the more you can avoid acronyms the easier it is to read.

See response to previous point. We have also removed the acronym 'SEC' throughout the manuscript.

6/30-31. It is not clear what using 'a flow accumulation threshold of 500 to calculate stream threshold' means. Please clarify.

10/25-28. We have alleviated the confusion in explaining this method, and in doing so have removed the flow accumulation threshold of 500, as this does not affect the drainage catchment delineation.

7/30 and throughout manuscript. Remove ‘clear’. This word is used widely throughout the paper and is superfluous. Recommend removing it in all cases.

11/9 Removed ‘clear’ on this line. We have been through and removed the word ‘clear’ in several places in the paper e.g. on what was 11/19 and on what was 14/5

8/8. Remove ‘1948-1975’ from the first mention, and put these years in the second half of the sentence when you call out that the earliest epoch is 27 years long.

12/5 We have moved 1948-1975 to the second half of the sentence.

9/21-31. This description is poorly organized. I want a sense of what is happening at each glacier. Separate them out and talk about each with greater specificity. Describe how advance/retreat phases were more/less consistent and then changed (or not). How has the character of terminus change varied? I understand the urge to create something of a laundry list of information, and the difficulty into crafting fairly dry information into something that is easy to follow and structured across the paragraph. It is, however, important to work towards this goal. An good example of an organized, engaging description is page 12, lines 27-32.

This section of the results has now been moved from the subheading, and most of the description moved to the floating ice tongue category. While we appreciate the comment on improving the amount of information on individual glaciers, we also feel that the paper is already very detailed in places, and are hesitant to expand on this any further. We are also aware that referee 2 has stated that there is a lot of information provided that makes it difficult to keep track of the important factors. We are obviously happy to add more detail in a further revision if needed.

10/22. ‘Loss of their floating ice tongues’ is incorrect for Petermann – instead just refer to ‘retreat’ or similar.

During the restructure this sentence has now been deleted.

10/27. Something is not ‘synchronous’ with events in the following decade. Reword.

19/17. This has now been changed to ‘were followed by gradual glacier acceleration in the subsequent decade’.

10/30-11/1. It’s not clear if you mean changes in speed after large calving events or only after complete ice tongue removal. Please clarify.

19/25. We have clarified this.

12/2-15. ‘Dramatic’ appears several times in this paragraph – it’s not a particularly useful or quantitative descriptor and I recommend revising/deleting. (‘Clear’ also appears several times in this paragraph).

21/20-30. Removed dramatic and clear throughout this paragraph.

13/19-14/2. Another paragraph in need of reorganization.

This section (3.6) of the manuscript has been re-written to improve organisation and now refers to the two terminus type categories of glacier. It also includes reference to newly included bed topography figures.

14/5 and 8. It is incorrect to refer to a single year (1995) as a change point because you are considering longer epochs. Refer to changes before/during/after those epochs rather than at specific years.

27/31-32. We have now changed this to 'showed a transition from slow low-magnitude advance between 1948 to 1995, to rapid high magnitude retreat between 1996 and 2015'

14/10. Clarify that 'These changes' is not referring to air temperatures.

28/8-9. We have now changed this to 'This switch to terminus retreat in the 1990s is coincident with increased air and ocean temperatures across the Greenland ice-sheet.'

14/15. This paragraph needs an introductory sentence and work on organization and flow.

This section of the discussion has been rewritten/restructured compared to the previous version as climate-oceanic controls have become less of a focus of the paper. The second paragraph of this section now (29/22-33) has a better introductory sentence. It is also better organised, and summarises some of the main climate-ocean controls on outlet glacier behaviour in northern Greenland.

14/26. The second half of this sentence is irrelevant to the discussion.

This section of the discussion has been shortened, and describes climate-ocean forcing factors in far less detail with no real evidence in the results presented in this paper. This sentence has been entirely removed.

15/2-3 (and following paragraph). Acknowledge the role of other ocean processes, like ice front melt, in this sentence/section, followed by the more thorough discussion in the next paragraph. These references (or information within them) may be useful:

Wilson, N. J., and F. Straneo (2015), Water exchange between the continental shelf and the cavity beneath Nioghalvfjerdsbræ (79 North Glacier), *Geophys Res Lett*, *42*(18), 7648–7654, doi:10.1002/2015gl064944.

Choi, Y., M. Morlighem, E. Rignot, J. Mouginot, and M. Wood (2017), Modeling the Response of Nioghalvfjerdsfjorden and Zachariae Isstrøm Glaciers, Greenland, to Ocean Forcing Over the Next Century, *Geophys Res Lett*, *44*(21), 11,071–11,079, doi:10.1002/2017GL075174.

As we have now removed the climate data presented in this paper, we have largely removed the discussion on climate-ocean forcing. This is partly following the comments from referee 2 which suggested that by discussing so many different controls (climate, topography, terminus type), it was difficult to determine the main factors/focus of the paper. One of their comments was also that some of these climate-ocean processes discussed in the previous version of the manuscript were being 'invoked…with little evidence'. In an attempt to refocus the paper, we focus on terminus type, and glacier geometric controls. We include some comments on climate-ocean forcing (Section 4.1) but this is mainly with the direction that climate-ocean forcing may have changed the initial conditions at the terminus, but after that, terminus type and geometry are the main controls on the different behaviour of outlet glaciers in northern Greenland.

16/2. Write these in an order than makes more sense for the actual process, either thinning- retreat-speedup or retreat-speedup-thinning (use this latter one if you want the focus on dynamic thinning due to speedup).

We have changed this section slightly to make more reference to the calving styles and discuss the effect on glacier force balance. We have also re-ordered these processes on 30/24 to 'thinning is thought to have initiated enhanced retreat and accelerated terminus velocities'.

16/15-19. It would be useful for the authors to comment on why they think these differences occur among the glaciers they mention. For example, how does scale of event and force balance based on glacier characteristics enter into the discussion. Also, it's not entirely clear whether the authors are consistently referring only to velocity changes on the grounded ice portion of these glaciers.

We are grateful for the suggestion to add in some discussion of how the scale of calving events and differences in the setting of each glacier affect the force balance and thus differences in glacier dynamic behaviour. In this section of the discussion and the following (Sections 4.2 and 4.3) we have made an effort to address this point and make more reference to the calving style of these two terminus types of glacier, and how the differences could impact on the force balance. An example of this is on 31/17 where for floating ice tongue glaciers we say: 'However, in most cases large calving events, appeared not perturb the force balance by neither increasing longitudinal stretching, nor driving stresses on inland grounded ice'. We go into the impact of such calving events and the fjord setting of each glacier in Section 4.3. We also discuss there the different forces (basal vs lateral drag) acting on grounding or floating termini. For example on line 33/12 in reference to floating ice tongues we say 'lateral resistive stresses are the main control on the glacier force balance and driving stresses'. We hope this has now made it clearer throughout the impacts of the scale of calving events and alterations to the force balance at these two types of glacier. In response to the second point, our newly created figures for terminus, velocity and elevation change, we include velocities averaged at the grounded line region of each glacier.

17/4. Another paper just out on this topic: Millan, R., E. Rignot, J. Mouginot, M. Wood, A. A. Bjork, and M. Morlighem (2018), Vulnerability of Southeast Greenland glaciers to warm Atlantic Water from Operation IceBridge and Ocean Melting Greenland data, *Geophys Res Lett*, 1–23, doi:10.1002/2017GL076561.

Included this reference, now on 32/17.

18/4 and 11. What do the authors mean by 'strongly attached to'? How has that been quantified, in this study or others?

33/21-22. We have changed this sentence to now read '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)'. This now makes reference to a new figure we include that shows satellite imagery of the ice tongues of these glaciers before they collapsed.

19/18-19. A few more words are needed on this, and whether or not it is likely these are surge glaciers. Did you look at different data than these other studies? Can you definitely confirm there was no surge in periods where it was previously detected because you have better data or similar?

37/3-7. We have added in an extra couple of sentences to explain the observations made by the studies on these glaciers to suggest surge behaviour. We also add how our long-term record, where we consider terminus changes alongside elevation and velocity changes, provides no substantial evidence for surge-activity at these glaciers. We are wary of adding too much more detail here, as these glaciers are not the main focus of this section, and we instead want the majority of the discussion to be about those which have substantial evidence.

19/20. 'controlled by external forcing' is too vague. Say specifically what mechanisms might be at play and whether there is evidence for it, or what data would be needed.

This sentence has been removed, and we instead just state that while there has been a large advance (similar to some previous observations) we lack detailed data to be able to provide more substantial evidence of it being surge-type.

19/30. Another incorrect reference to Moon et al. 2012. This would be a good place to reference Howat and Eddy 2010 (already listed in the references).

Removed Moon et al. 2012 reference and replaced it with Howat and Eddy 2011.

20/2. A variety of ocean data is available for northern Greenland. It is not, however, being used or analysed in this paper (which is just fine). But please remove this incorrect statement.

This sentence has been removed.

20/24. I understand the urge to end on 'could soon contribute an important component to sea level rise', but this is a vague statement and is not well connected to the paper analysis (which does not discuss sea level). Suggest rewording with a stronger concluding statement that is more specific and tied to the main idea of the paper.

We have removed this sentence and now conclude the paper with a stronger concluding statement that focuses on the main findings of the paper, e.g. region wide increase in retreat rates, differences between terminus types, and the important role of glacier geometry. We also highlight that while ice tongue retreat doesn't appear to matter, once these glaciers become grounded they may discharge greater volumes of grounded ice to the ocean.

27/3. This caption would benefit from more precise language throughout. The use of 'calculated by subtracting 1948 and 2015 positions' is one example.

We have improved and shorted the caption for Table 1.

Table 1. Consider the various order in which glaciers in each category could be listed and choose the one that makes the most sense for the reader or message.

We have now changed the order within each terminus type category to be based on frontal position change rate from highest overall (1948 to 2015) retreat rate through to the highest advance rate. We have used this same ordering for all figures that follow in the manuscript.

Figure 1. The caption includes a lot of information on methods, which seems misplaced.

We are not sure about this comment, there does not appear to be much detail on the methods in this caption. However, in the caption of Figure 2, we do refer to the methods too much, and we have reduced this to just describe the figure.

Figure 2. The legend should have lines rather than boxes.

We have updated the legend to now show lines for terminus positions rather than boxes.

Figure 4. Please reword for improved clarity and brevity.

We have improved the wording of the figure caption for Figure 4.

Figures 7-9. It is very difficult to see the lines/colors in the legend and in the plots. Distinguishing among the surface elevation change lines to understand their progress is only possible in a broad green or blue sense. Understanding the detailed progress is impossible with the current color map.

To improve the presentation of surface elevation and velocity change over time we have replaced figures 7-9 with two figures that are categorised based on terminus type, and show individual glacier frontal position changes and average elevation change along the centreline profile (due to poor resolution at the terminus) and average velocity at the grounding line. We hope this has now significantly improved the ability for the reader to understand the detailed progress of elevation and velocity change alongside terminus changes over time.

Figure 8. Remove the odd floating ice in 8h, which does not appear to be connected to the glacier.

This figure has now been removed and new figures showing bed topography profiles have been created (Figs. 9 and 10). This section of floating ice does not appear on any figure in the manuscript anymore.

Figure 9. Is there no data for showing terminus position in 9c?

This figure has now been removed from the manuscript. On the newly created bed topography Figures (9 and 10) terminus positions are shown for all glaciers.

Figure 10. Instead of ‘inland’ and ‘terminus’ give a number for actual location/distance.

We have also replaced this figure to include one that shows the original profile surface elevation and velocity data (Figure 8). We feel that the colour scale here can provide a clear representation of the overall trend of increased elevation inland, alongside reduced velocity, compared to velocity increase and thinning at the terminus.

Figure 11. It’s quite odd to stack the warmer temperatures below the colder temperatures in these plots. You also mention ‘ocean’ in the caption data, which is not included in the plots.

As we have taken the advice to remove the climate-ocean forcing section of this paper due to poor data quality, this figure is no longer included in the paper.

Technical corrections by line number:

2/5. Delete ‘across the ice sheet’ – unnecessary.

Deleted.

2/30. Delete ‘objectively’ – unnecessary.

Deleted.

7/30. Delete ‘eventual’

Deleted.

10/8. Delete ‘It was also clear that’. I’m not going to note anymore of the instances of ‘clear’, but just repeat that they should all be removed.

Deleted. We have also been through the entire manuscript and deleted all instances of ‘clear’.

11/19. Thickening or thinning?

This has now been changed to ‘Small increased thinning or reduced thickening rates at Academy and Marie-Sophie Glaciers (1999 to 2000: Figure 6f,h)’.

11/21. Delete ‘then’

Deleted.

15/7. ‘concentrations’ instead of ‘conditions’

When removing the climate section of the paper, this sentence has also been removed.

15/9. Remove quotes around calving season.

When removing the climate section of the paper, this sentence has also been removed.

15/11. Remove ','

When removing the climate section of the paper, this sentence has also been removed.

17/19. 'importantly influence' is very awkward – reword

When restructuring this section of the discussion this sentence has been removed.

18/24. Should be 'accompanied by acceleration'

The discussion of Ryder Glacier has been changed (following the advice of referee 2) and so this sentence does not longer exist in the manuscript.

19/17. 'overriding' is poor word choice – please change

Changed to altering

35/5. Replace 'Current' with '2016'

This has been changed in the captions of newly included bed topography figures to 'the most recent recorded terminus position (2015) from this study'.

Figure 12. Delete 'except for the first…position changes

This figure has been deleted

Response to Anonymous Referee #2

General comments:

This manuscript presents a large volume of data for several glaciers in N. Greenland to draw conclusions about their dynamic behaviour over a significantly long time period. The data presented are of some value, but I'm afraid that this manuscript suffers a bit from explaining everything without really explaining anything. What I mean is that there is a dizzying array of information about climate, topography, glacier behavior to keep track of but not one factor comes across as being important to explaining the behavior of all glaciers. It's a challenge for the reader to keep track of all of the information and to make sense of what facts are important throughout the text.

Following the advice of referee 1, we have also entirely removed the climate forcing section, to focus on terminus type and topography. We also feel that by improving the categorisation of glaciers in the region (see next response), we have removed a large amount of the confusion, and highlighted the important factors that we focus on in this paper more clearly.

The other issue I have is with the categorization of glaciers. There are categories 1) grounded terminus; 2) floating ice tongue and 3) potentially surge-type. Two of these reflect the state of the terminus while the last one reflects the inherent dynamics inferred from terminus behavior. Further, several of Category 3 have (or had) floating tongues, making it a challenge to keep up with the author's thoughts at times. Then, there is a second categorization – based on retreat style: 1) steady retreat; 2) rapid retreat; 3) advance. It's just too much to keep track of. In the conclusions, the authors say that "a key conclusion is that the dynamic response of outlet glaciers to perturbations depends on their terminus type". However, with such poorly organized material and categorization it's unclear how this conclusion is supported.

Improving the categorisation of our study glaciers is one of the major aspects we have tried to address in the revision. We agree that there was confusion before, and to alleviate this, we have decided to categorise solely on the terminus type of the glacier in northern Greenland. We still include the results of the changepoint analysis to provide evidence for the differences in the duration/magnitude of terminus changes for these two categories, but do not use it to objectively categorise the glaciers initially. The changes we have made to restructure based on these two categories of glacier based on terminus type are summarised in the following sentences. Firstly, in the introduction we give context to the expected differences in glacier behaviour between glaciers with grounded or floating termini. Then, we have added a new study region section at the beginning of the methods, where, as suggested, we provide an overview of northern Greenland, and identify which glaciers are grounded at their terminus, which had ice tongues over the last two decades (1995 to 2015), and which glaciers in the region still terminate in a floating ice tongue. Then at the beginning of the results Section 3.2 we reiterate these changes, and state that we consider these two categories of terminus type throughout the manuscript. Each section of the results has been restructured and largely re-written accordingly, to be categorised by these two terminus types, and include glaciers with floating ice tongues that were previously in the 'sustained advance/surge-type' category. In the discussion we leave the structure as it was, including the 'Glacier Surging' section, but instead suggest surging at those with the most substantial evidence, and provide an alternative explanation for the behaviour of Ryder Glacier. We hope this now provides a much simpler structure to the results and discussion by comparing these two categories based on terminus type. We think this the manuscript is a lot clearer, and hope this will be the case for the reader too.

In addition, the category of "sustained advance" is completely untrue. These glaciers (shown in 6c) undergo periods of advance AND retreat, in some cases, very rapid retreat, which is a far cry from sustained advance. This type of behavior is typical for glaciers with floating tongues – see MacGregor et al., JGlac 2012 58(209) and other tidewater glaciers – see McNabb et al., JGR-ES 2013 for additional examples of this. I feel as though categorizing these glaciers as "surge type" is a bit "getting off too lightly"– there is likely more to explain here. The authors would benefit from a close read of Steiger et al. (Cryosphere 2017) that suggests pinning points having an impact on glacier terminus positions. Also, the authors should examine the tidewater glacier cycle literature which discusses quite broadly the idea of cyclic glacier changes.

We have largely addressed this point in the previous comment. We also agree that sustained advance is not true at many of these glaciers, and understand the importance of considering these within the tidewater glacier cycle literature. We also agree that there is more to explain here, without jumping to the conclusion of glacier surging. Through our re-categorisation based on terminus type (grounded or floating) alone, we have removed the final category which covered glaciers which had undergone periods of 'sustained advance'. Three of these glaciers have floating ice tongues, and so we discuss these alongside other floating ice tongue glaciers within each section of the results. We have left the discussion section that discusses surging at some of these glaciers, and in the case of Ryder Glacier, we have provided a clearer explanation for its cyclic behaviour based on the evidence provided in the paper.

The authors use BedMachine v2, when BedMachine v3 has been released now for a year. v3 represents significant improvements, particularly in the terminus regions because of the addition of bathymetry data from the OMG project. It would be useful to know how the authors determined if the bed data were good or not. Some glaciers were not sufficiently sampled with radar data for the mass-conserving solution and thus, are not well-constrained in BedMachine. Finally, very little information is provided about how the authors calculated bed slopes at the glacier termini and how bed topography is used in general. The mention of pinning points and the comparison between slopes of the beds of glaciers is described with no data presented.

To our knowledge the latest version of BedMachine v3 was only realised online last September, by which time we had completed the majority of our analyses. We do agree that there are significant improvements in this dataset and so we have spent time going back and incorporating v3. This includes a much more detailed section in the methods, where we consider the errors in the dataset at each glacier in northern Greenland, and describe the method by which we calculated glacier bed slope direction. We have also provided more detail in the supplementary information on the errors and bed slope direction. Additionally, we have created new figures to replace Figures 7-9 in the previous version of the manuscript. This includes figures for each terminus type that show terminus change and elevation/velocity changes averaged along the profile/at the grounding line (see specific comment below), and new figures to show the basal topography of each glacier more clearly. We use individual plots to show the spatial bed topography of each glacier, and below the bed elevation along each glacier centreline. This also includes the location of the current terminus as included on the previous versions of bed topography figures. We hope to have now made a much clearer assessment of the bed topography beneath these glaciers, and a clearer explanation for our method of bed slope calculation.

In the discussion, the authors invoke processes such as increased ablation rates, water drainage to the ice bed, and the removal of sea ice to explain the timing of glacier retreat. However, these correlations are presented as anecdotes, with very little in the way of evidence suggesting cause/effect. They discuss topography as well stating that bed topography is a “key control on the behaviour of glaciers in northern Greenland” but provide very little in the way of evidence for the reader to understand how this conclusion came to be. Bed topography is inherently three-dimensional and so presenting the topography in the small-scale images in the figures is not sufficient evidence for the reader.

In response to the first sentence, we have followed the suggestion of referee 1 and removed the climate data from the manuscript. This includes removing the section of the discussion that covered such processes of ablation, and water drainage. The main focus of this paper is not to explain these processes in any detail, and we agree that we do not have the evidence in the data we present to support these suggestions. Instead we have shortened the first section of the discussion (4.1) which covered the timing of glacier retreat, to now refer to previously published literature, which has highlighted several processes that may be important in forcing glacier retreat in northern Greenland. We adjust the focus from suggesting which processes may have controlled the timing of retreat, to the idea that climate-ocean forcing may have been the initial driver of rapid retreat, after which glacier geometry becomes a more important control on glacier retreat.

In response to the comment on bed topography, we have restructured Section 4.3 of the discussion which covered topographical controls on glacier behaviour. We hope that by including more detailed figures of the bed topography at each study glacier, we have made the evidence clearer for how the glacier geometry can be a control on glacier behaviour. As well as this, we have re-written this section (4.3), to focus more heavily on how the force balance may have been altered by the glacier geometry, and also included a figure (11), which gives examples of the confinement of three ice tongues in satellite imagery, to support our argument on the differences between lateral resistive stresses at these ice tongues.

Some additional edits are made in-line with the text in the attached pdf, but towards the middle I stopped correcting small things.

It would be nice to have a paragraph here (at the beginning of the methods) describing the region and which of the glaciers have ice shelves etc.

As mentioned above, we appreciate the advice to add a paragraph that introduces the region. We have done this, by giving an overview to the region we define as northern Greenland, and included a description of which glaciers have floating ice tongues. We have also included symbols on Figure 1, to show which glaciers currently have floating ice tongues, which have recently lost them (1995 to 2015), those which have some historical evidence in the literature for floating ice tongues, and those which are grounded at their terminus throughout the study period.

3/9 Am I correct then in assuming that just one image per year was used in analysis?

Yes and we have updated this in the manuscript.

6/21 this reads as if the authors performed this work, but I am assuming that they merely used the existing bed map derived by Morlighem. Also, there were significant updates in BedMachinev3 that should be incorporated.

We have updated this to read less like we did the work ourselves. As stated in more detail above, we have now incorporated the newest version (v3) of the BedMachine dataset

6/28 refer in here to Table 2, where these data are presented

We have added in reference to Table 3 (formerly table 2 as we have added an additional table showing mean decadal terminus changes for each terminus type).

7/4 RACMO and MAR data provide basic climate data for all of Greenland. Instead, I would just eliminate this sentence.

This entire climate section has been removed, and along with it, this sentence.

9/22 except for Ryder, which you show advancing as early as 1950.

We have removed this sentence to avoid confusion.

10/2 which ones are floating?

We have removed this subheading entirely during the restructure of the categories, so the subheadings are now split by grounded-terminus outlet glaciers and floating-terminus outlet glaciers

13/2 This has resulted in a noted increase in glacier runoff published by Brice Noel in 2016 (I think).

This climate section of the results has now been removed entirely.

17/11 I doubt that retreat rates would be related to the slope of the over-deepened bed, but instead to the balance of forces at the glacier terminus.

When restructuring this section of the discussion we have removed this sentence, and focus more generally on the impact of deep basal troughs on the stability of the terminus.

Figure 6: I'm confused by this categorization into a), b), c) because Fig. 9 shows that several of the "potential surge-type glaciers" also have floating ice shelves

We have changed the categorisation throughout the paper, and therefore have adjusted this figure to just show periods of minimal and rapid terminus change. The glaciers have then been ordered based on terminus type, either floating or grounded terminus, and by overall frontal position change rates (Table 1), within each category.

Figure 7,8,9: it would make more sense (to me) to see the terminus-averaged velocity plotted with time to compare to the time-series of the terminus position.

We agree and have made substantial changes to these figures to show this data. Figures 7-9 have been replaced by two figures (Figure 6 and 7) which show terminus changes with time alongside grounding line averaged velocities, and elevation changes averaged along the entire glacier profile (due to poorer resolution). We believe this new figures provide better representation of the results where we discuss changes in velocity and surface elevation change through time. These new figures improve the visualisation over the previous figures which were difficult to see specific changes in elevation/velocity through time.

Figure 12: Since you refer to NEGIS in the manuscript when referencing this figure, it might be good to add glacier names to it.

As we have removed the entire climate section from the manuscript this figure has now been removed.

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, ~~marine-terminating~~tidewater outlet glaciers across the ~~GrIS~~ice sheet have thinned, retreated, and accelerated~~ and thinned~~, 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, ~~remains unknown.~~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~~, but change-point analysis reveals three categories of frontal position change: (i) minimal change followed by steady and continuous~~ (since 1948). Despite increased retreat~~, (ii) minimal change followed by a switch to a period of short-lived rapid retreat, (iii) glaciers that underwent cycles of advance and retreat. Furthermore, these categories appear to be linked to~~ rates from the 1990s, there was distinct variability in dynamic glacier behaviour depending on whether the terminus ~~type, with those in category (i) having~~is (or was) grounded ~~termini and those in category (ii) characterised by~~or floating~~ ice tongues. We interpret~~. Grounded glaciers accelerated and thinned in response to retreat over the last two decades, while most glaciers ~~in category (iii) as surge-type. Glacier~~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~~ and~~, basal topography~~) is also~~, and ice tongue confinement) as an important influence on the dynamic re-adjustment of glaciers to changes at their termini. ~~Taken together, the loss of several ice tongues and the recent acceleration in the~~ Recent grounded-outlet glacier retreat ~~of numerous marine-terminating glaciers suggests~~ and ice tongue loss across northern Greenland, suggests that the region is undergoing rapid change and could soon ~~impact on some large catchments that have capacity to~~ contribute ~~an important component~~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 21^{st} 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 outlet~~(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 ~~of~~ <2000 m ~~elevation has occurred~~ on fast flowing marine-terminating outlet glaciers (Abdalati et al., 2001; Krabill et al., 2000), particularly in the south-east and north-west ~~regions of the ice sheet (Moon et al., 2012; Pritchard et al., 2009).~~ of the GrIS (Csatho et al., 2014; Pritchard et al., 2009). Alongside thinning and acceleration, terminus retreat has been widespread since the 1990s ~~across the ice sheet~~ (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 21^{st} 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 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 accelerates ice flow (e.g. MacGregor et al., 2012). However, 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.

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 and, at Jakobshavn, this was in response to the gradual collapse of its floating ice tongue (Amundson et al., 2010; Joughin et al., 2008b; 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). 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, there are few records of longer-term changes in glacier frontal for the region and their potential impact on inland ice flow 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 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 the topographic setting and local glacier controls (i.e. fjord width and depth) 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).

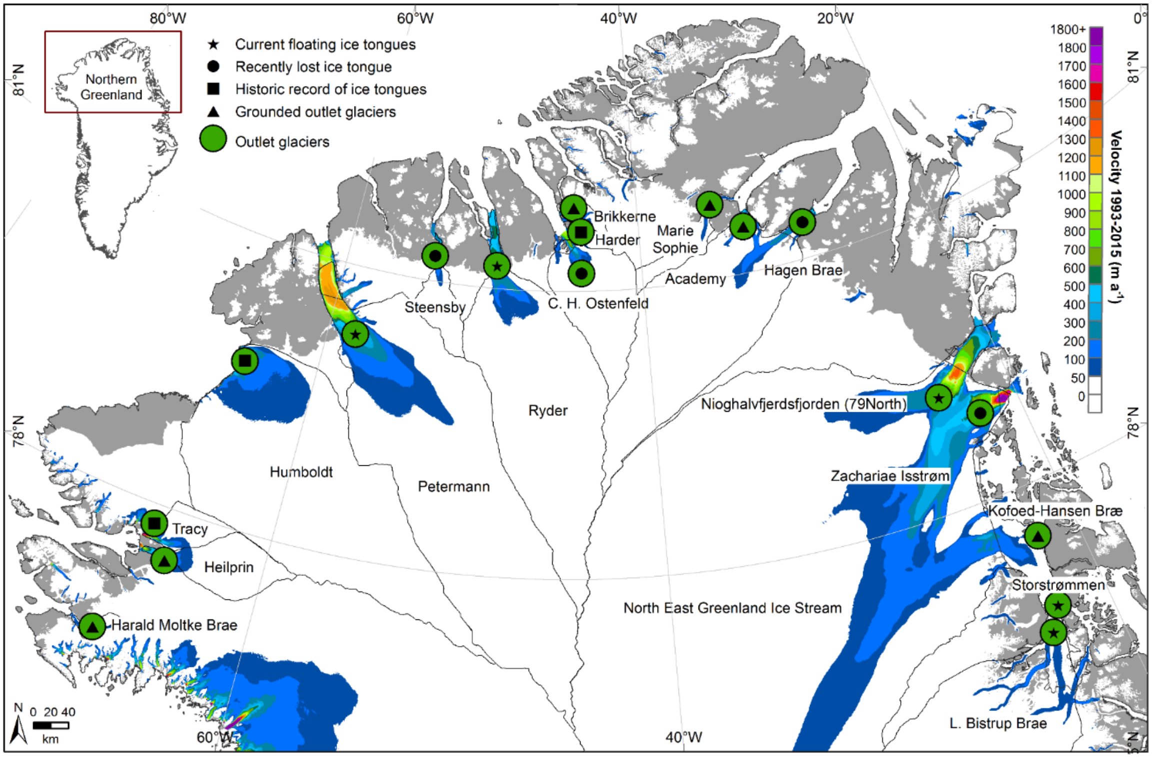


Figure 1: Study region of northern Greenland. Green circles show the location of each of 18 northern Greenland study outlet glaciers. Average glacier velocities (m a^{-1}) are shown between 1993 and 2015 derived from the multi-year mosaic dataset (Joughin et al., 2010). Black outlines show glacier drainage 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.~~1~~2.1 Data sources

~~Terminus~~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, ~~scenes were~~one scene per year was selected from late summer~~ each year~~, 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~~ imagery~~, 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).~~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 ~~associated with frontal positions is~~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 ~~primarily~~ associated with manual digitising was 19 m, which is below the pixel resolution of all imagery sources except the 15-m panchromatic Landsat band. ~~Similar to other studies (e.g. Bevan et al., 2012; Howat and Eddy, 2012; Murray et al., 2015), an additional source of error occurs in selecting the correct terminus position at several glaciers, due to the presence of year round sea ice and the fractured nature of the glacier terminus. This was particularly the case at Steensby and C. H. Ostenfeld and glaciers draining the Northeast Greenland Ice Stream (Figure 1). These glaciers were the only ones affected by these uncertainties, and so we re-digitised all Landsat terminus positions from 1999 to 2015 to estimate the error in mapping the terminus position. Additional errors were calculated to be ± 13 % for Steensby, C. H. Ostenfeld, Nioghalvfjerdsfjorden, and Zachariae Isstrøm.~~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.

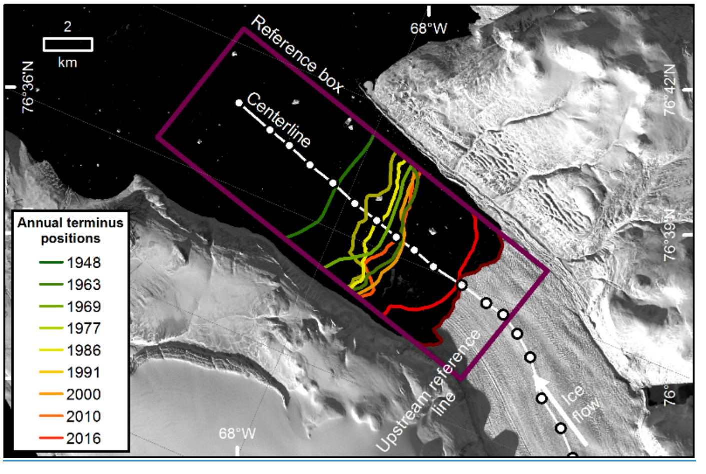


Figure 2: Rectilinear box method used to measure glacier terminus positions. An example at Harald Moltke Bræ, NW Greenland. This includes: reference box (pink), and roughly decadal terminus positions (green to red). The glacier centreline profile is shown in white and the location of 500 m sample points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

2.~~1~~2.3 Changepoint analysis

We used 'changepoint' analysis to objectively test whether ~~different categories~~there were significant differences in the timing and duration of terminus ~~change behaviour exist~~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. 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. 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 ~~using~~which applies an additional penalty to each prospective changepoint. For this we use the mean terminus position~~, which only allows~~ for ~~a changepoint when total error decreases by the minimum threshold.~~each glacier. This ~~penalty value~~ then allows for an automatic estimation of the number of ~~change points along each time series of frontal~~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 ~~data~~for each of our study glaciers in northern Greenland.

2.~~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 ~~first~~earlier (1991/92) covers northern Greenland drainage basins from Humboldt and then east to Hagen Bræ, and the ~~second~~later (1995/96) covers all 18 study glaciers. ~~We~~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), ~~To assess velocity errors, we use the published error estimates to calculate mean velocity errors across all years and spanning all drainage catchments in northern Greenland. Mean velocity errors were 6.3 m a^{-1}.~~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 derived from InSAR (TerraSAR-X image pairs) for 11 of 18 study glaciers (Joughin et al., 2011). 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.~~ 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 ~~(SEC)~~ data from ERS-1, ERS-2, Envisat, and Cryosat-2 radar altimetry for 1992 to 2015, ~~and~~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 ~~derived~~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 ~~SEC~~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}. ~~To compare~~Elevation changes ~~in SEC~~ from 1992 ~~to 2015, 5-year running means (m a^{-1}) from 1992 to~~ –1996 were ~~differenced with the most recent estimates of SEC~~compared to elevation changes for ~~the two-year period~~ 2014–2015~~.~~ to assess how changes in surface elevation have evolved during the study period.

~~Profile data from all velocity~~Velocity and surface elevation time series were extracted along each glacier centreline, which were drawn following ~~the method of~~ Lea et al. (2014). The Euclidean distance was calculated between parallel fjord walls that were digitised in 2015 Landsat 8 imagery. The maximum distance line was then traced from the furthest terminus extent back to the ice divide. Annual ~~profiles of velocity and SEC~~average velocities were ~~sampled at 500 m along~~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.~~3~~4 Fjord width~~, ice surface~~ 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 ~~the method of~~ 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 bathymetry of each study glacier in northern Greenland, regional ice surface topography was acquired from the GIMP DEM, with a resolution of 150 m (Howat et al., 2014). Ice thickness and bed topography data were taken from the Operation Ice Bridge BedMachine v2 dataset, which uses radar ice thicknesses data, and the mass conservation method, to derive ice thicknesses (Morlighem et al., 2014). Bed topography was then derived from subtracting ice thickness from the GIMP surface DEM (Morlighem et al., 2014). Surface, ice thickness and bed topography were also extracted at 500 m intervals along glacier centrelines. Bed profiles were then fit with a linear regression model to establish retrograde or seaward sloping beds. To estimate drainage catchment areas and the percentage of each catchment below present sea level for each study glacier, surface drainage catchments were delineated using the GIMP surface DEM and topographic analysis functions within TopoToolbox in MATLAB (Schwanghart and Kuhn, 2010). First, all sinks in the DEM were filled and the resultant DEM was used calculate flow direction and flow accumulation. Secondly, we used a flow accumulation threshold of 500 to calculate stream order. Flow direction and stream order gridded outputs were then used to delineate surface drainage catchments.~~

~~2.4 Climatic and oceanic data~~

~~To provide some ocean-climate context to the observations of each outlet glacier, we acquired data on air temperatures and sea ice concentrations. It is beyond the scope of this paper to undertake a detailed assessment of the precise drivers of recent retreat at each glacier and we instead focus on dynamic glacier change in response to terminus perturbations. This is in part due to the limited availability of detailed region wide climate-ocean data for northern Greenland. Annual surface air temperatures were taken from the only two long-term automatic weather stations in the region: Pituffik (PK) (76°32'N, 68°45'W) in northwest Greenland, and Danmarkshavn (DK) (76°46'N, 18°40'W), in northeast Greenland (Figure 1). These datasets are provided by the Danish Meteorological Institute (DMI) as part of the historical climate data collection (Vinther et al., 2006), and were chosen due to their long and continuous record from 1948–49 to 2015. Mean air temperatures were subjected to changepoint analysis to highlight potentially significant breaks in annual air temperature time series data during the study period. Daily air temperatures from these stations which cover 1974 to 2006 (PK) and 1958 to 2013 (DK) were also used to calculate the number of positive degree days (PDDs), and mean summer (June, July August) temperatures.~~

~~Sea ice concentrations (SIC) from the Nimbus-7 SMMR, and Special Sensor Microwave/Imager (SSM/IS) sensors from the Defence Meteorological Satellite Program (DMSP), were acquired from the National Snow and Ice Data Centre (NSIDC:~~

~~Cavalieri et al., 1996). These data provide the longest continuous record (1979–2015) of sea ice conditions across northern Greenland, although at the expense of a relatively coarse resolution (25 km), which may compromise the accuracy of SICs near the glacier terminus. Thus, these can only be used to assess region wide changes in sea ice conditions. Annual SICs were taken from September each year, which is considered the annual minimum of sea ice extent. These September estimates were split into decadal anomalies from the 1979 to 2015 mean. Due to the absence of accurate and systematic regional datasets of both sea surface and subsurface temperatures, we do not assess the regional impacts of ocean temperatures on dynamic outlet glacier change in northern Greenland.~~

. 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.

3. Results

3.1 Changes in glacier frontal position (1948–2015)

Across northern Greenland, 13 of the 18 study glaciers underwent overall retreat between 1948 and 2015, while the remaining five advanced (Figure 3). Long-term glacier retreat rates (1948–2015) ranged between -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 et al., 2013). Zachariae Isstrøm, which partially drains the NEGIS, had a similarly high retreat rate of -282 m a^{-1}, which resulted in the ~~eventual~~ loss of its 21-km floating ice tongue between 2002 and 2012 (Table 1).

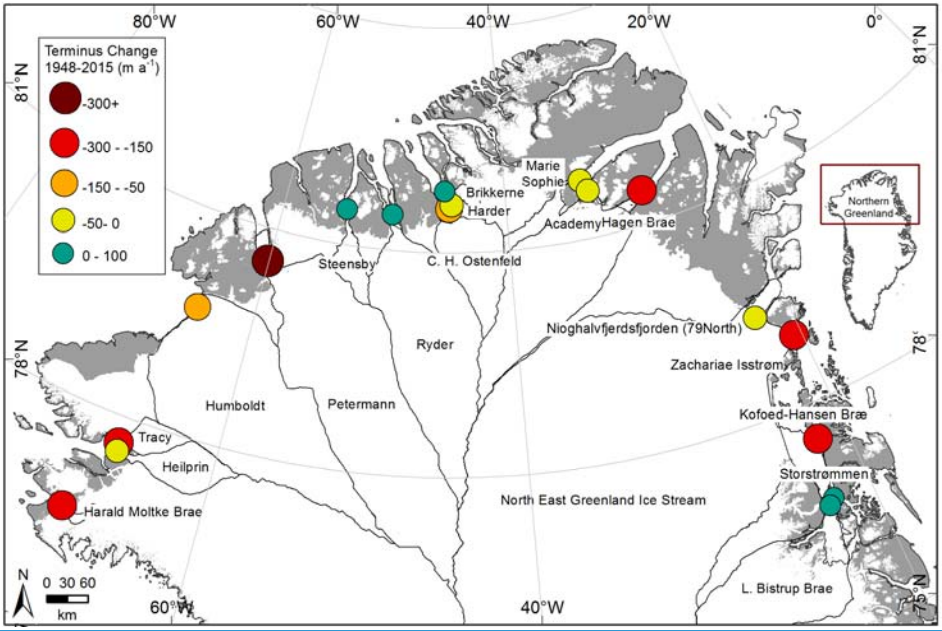


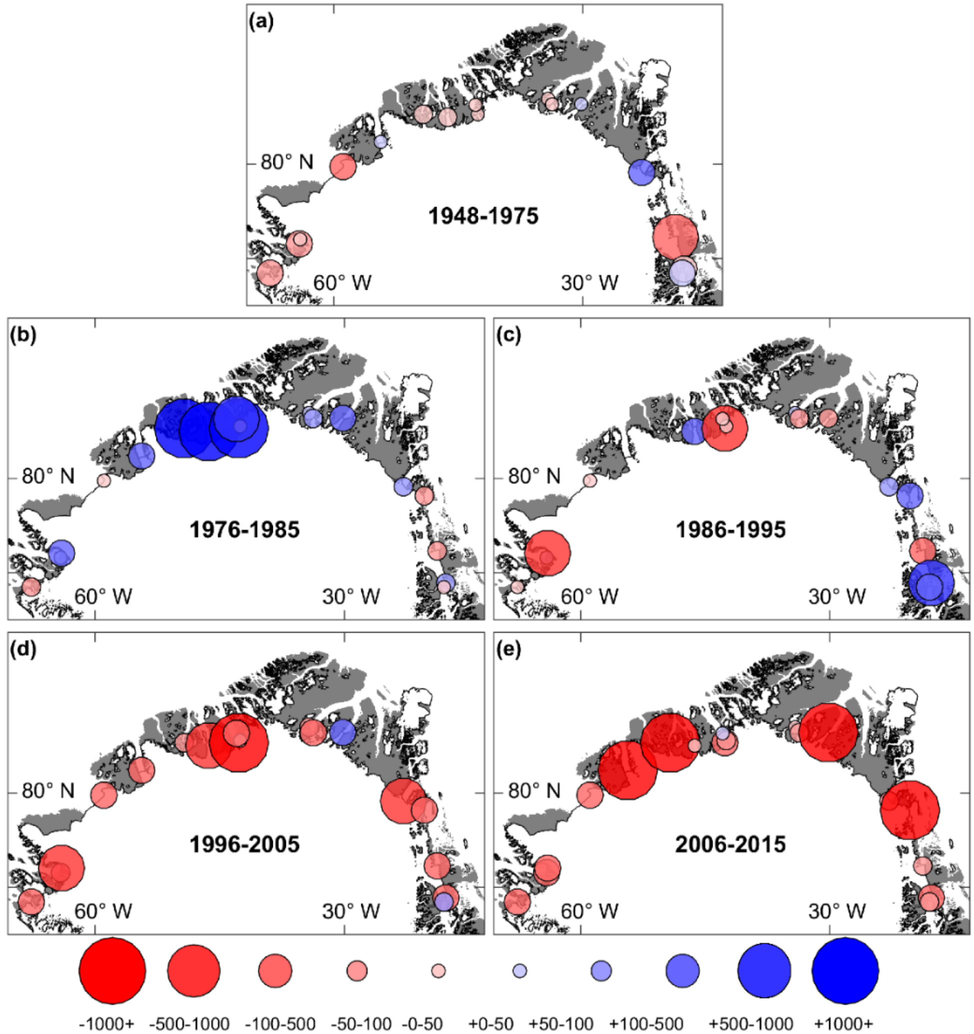
Figure 3: Overall rate of terminus change (m a^{-1}) at 18 outlet glaciers in northern Greenland from 1948 to 2015. Green circles represent glaciers which have undergone overall advance during the record, while yellow to red circles represent increasing retreat rates from 0 to larger than -300 m a^{-1}

There was ~~clear~~ 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}).

~~**While substantial**~~**Table 1:** Summary data for 18 northern Greenland outlet glaciers, ordered according to terminus type and by frontal position rate (from high retreat ~~has taken place at~~ 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 ~~in the region~~retreated substantially, there ~~are~~were large differences in the timing and magnitude of retreat between glaciers~~, and throughout the study period~~ (Table 1, ~~Fig.~~Figure 3). To assess the variability of retreat rates across northern Greenland, we present mean retreat rates across five decadal time periods (~~1948–1975,~~ 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. 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 ~~(with some minor retreat at certain~~, and several glaciers~~) between 1976 and 1985. Several glaciers with overall~~ with high retreat rates for the entire study period (e.g. Hagen Bræ, Zachariae Isstrøm, Petermann) underwent advance during this period. In the subsequent epoch (1986 to 1995), a mixture of advance and retreat occurred~~. Rates~~ and the range of frontal position ~~change were greater than during previous intervals, ranging~~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, peaking at Petermann Glacier (-2200 m a^{-1}; Figure 4e, f). ~~Retreat~~In particular, high magnitude retreat during this period at Hagen Bræ, Zachariae Isstrøm, and Petermann far outweighed earlier advances.



~~3.2 Categories~~

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}.

3.2~~.1 Category 1: Minimal~~ Frontal position change~~, followed by steady~~ according to terminus type

Despite an increase in retreat rates from 1996 across the study region, the magnitude of frontal position change during the last two decades (1996 to 2015) varied considerably between glaciers and according to terminus type (i.e. grounded versus floating). 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). During this period, 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). We expect terminus changes and dynamic response to be different dependent on terminus type, and for this reason, throughout our analysis we treat these as separate categories. Additionally, we use statistical changepoint analysis to compare 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 5), which we now describe throughout our results.

~~Eight of 18 study~~

Table 2: Mean decadal frontal position change for all study outlet glaciers in northern Greenland~~ fall into the first category of terminus behaviour, and we note that all of these~~, 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

3.2.1 Grounded-terminus outlet glaciers

Nine of the major outlet glaciers considered in this study are grounded at their ~~terminus and lack floating ice tongues~~termini (Figure ~~7~~5). For these glaciers, there was ~~a transition~~an initial period of minimal frontal position change averaging -26 m a^{-1} and ranging from ~~minimal frontal position retreat/~~24 m a^{-1} advance ~~(e.g. Academy~~at Kofoed-Hansen Bræ to -105 m a^{-1} retreat at Tracy Glacier~~, Fig. 7o),~~. Frontal position change then switched to a period of ~~steady~~higher magnitude retreat at eight glaciers (excluding Brikkerne), which lasted for an average of 26 years~~ (Figure 6b).~~. During ~~the initial~~this period~~ of minimal change~~, frontal position change averaged -~~67 m a^{-1} across these eight glaciers, which increased to -~~150 m a^{-1}~~ during the period of steady retreat (Figure 6b). Net retreat during this latter period~~, and net retreats ranged from -0.6 to 8 km~~, and the~~. 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 ~~the majority of~~most glaciers began steadily retreating from the 1990s to 2000s and continued at the same rate thereafter (Figure ~~6b~~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).

~~3.2.2 Category 2: Minimal change, followed by rapid, short-lived retreat~~

~~The second category of glacier frontal position change encompasses six~~3.2.2 Glaciers with floating ice tongues

Nine glaciers ~~which currently, or recently,~~ terminated in ~~long~~ floating ice tongues~~. These~~ during the study period. Six of these glaciers ~~also~~ 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 ~~6a~~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 ~~6a~~5), and were on average 40 times greater (-4536 m a-

^{1}) than during the steady retreat phases at ~~Category~~ glaciers grounded at their terminus (-150 m a^{-1} ~~glaciers.~~). 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 ~~6a~~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 ~~8~~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 ~~8~~7). Similar to ~~Category 1~~ glaciers with grounded-termini, the timing of the switch to rapid retreat ~~is~~was not synchronous, but mainly ~~occurs~~occurred after 1990 (Figure ~~6a~~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 ~~Category 1~~ grounded-glaciers.

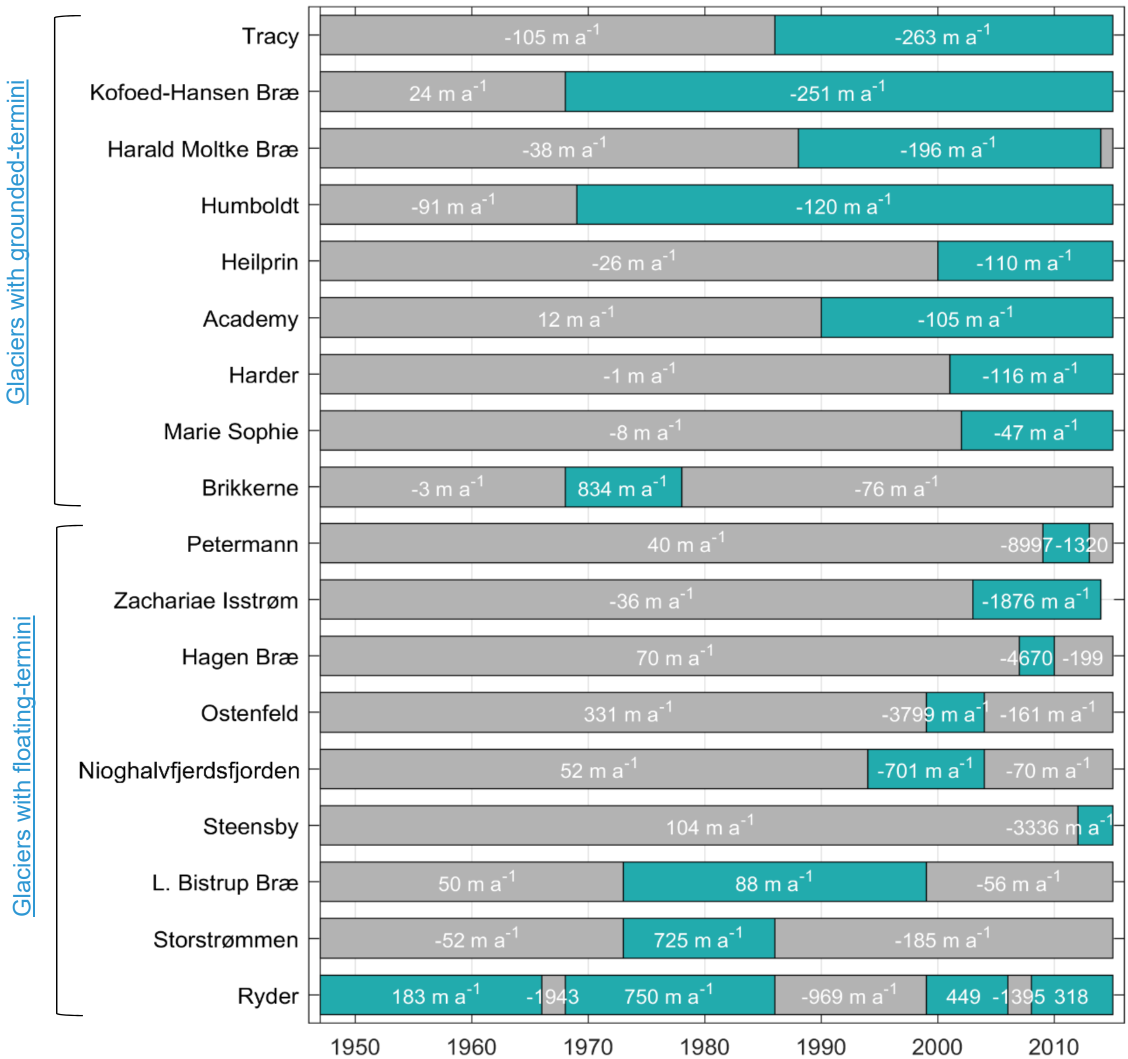


Figure 5: Retreat rates during identified changepoint time periods for each pre-defined category of glacier based on either grounded or floating termini. Glaciers are then ordered based on their overall (1948-2015: Table 1) frontal position change rates within each of these categories. Grey bars show 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 shown cyclic periods of ~~sustained glacier~~ advance ~~at some (or several) point(s)~~and retreat between 1948 and 2015 ~~(> ~90 m a^{-1}: Table 1).~~(Figure 7g-i). Periods of terminus advance at these glaciers averaged ~420 m a^{-1} and lasted for an average ~~duration~~ of 18 years (Figure ~~6c). All four~~5). Adjacent glaciers ~~began advancing in the 1970s (Figure 6c). Some adjacent glaciers (e.g.~~ Storstrømmen and L. Bistrup Bræ~~) continued to advance for~~ advanced during a similar period ~~(~13–17 years (~~from 1973 to 1990), ~~before undergoing~~and for ~13–17 years. After this, both glaciers underwent relatively limited terminus change from 2000 onwards (Figure ~~6c~~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, ~~Fig. 6e~~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 ~~6e~~5). Periods of advance (7–48 years) were separated by ~~generally~~ shorter periods (2–13 years) of higher magnitude retreat (ranging from -960 to -1950 m a^{-1}) (Figures ~~6c). Brikkerne Glacier showed 9 km advance between 1968 and 1978, but between 2000 and 2010 it showed very little change in front position (Figure 9a).~~5).

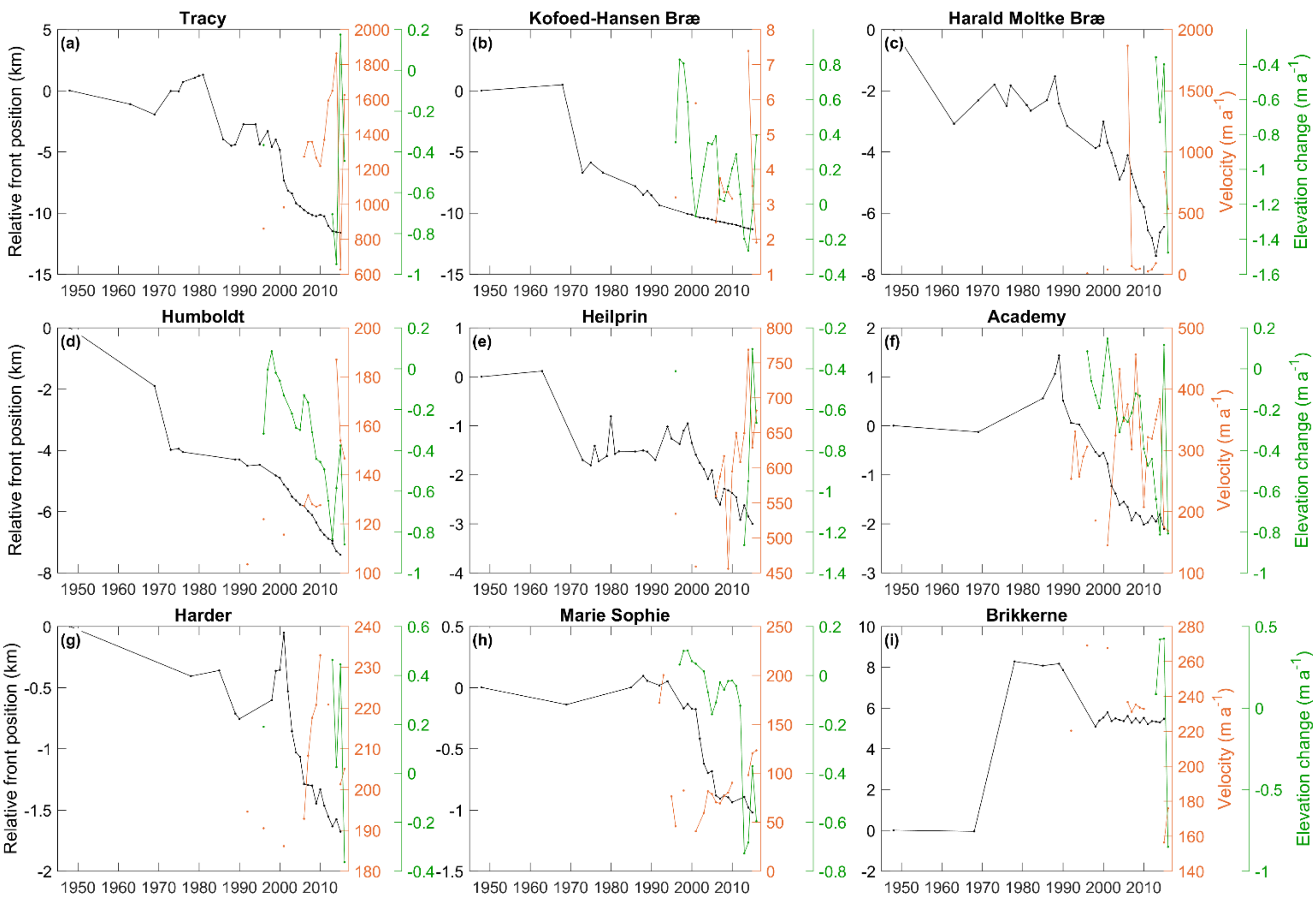


Figure 6: Front position, velocity and elevation change at nine outlet glaciers grounded at their terminus in northern Greenland. Left axes show relative front position (black line) between 1948 and 2015 relative to their initial position in 1948. Grounding line velocities (orange) on right axes one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

3.3 Ice velocity change

~~3.3.1 Category 1: Minimal change, followed by steady retreat~~3.3.1 Grounded-terminus outlet glaciers

Six of the nine outlet glaciers with grounded termini~~ (6 of 8)~~ accelerated along their centreline profiles (ranging from 0.32 to 37 m a^{-1}) from 1996 to 2016 (Table 1). ~~Terminus acceleration equated to >~~On average, these glaciers accelerated by 27%, following the onset of steady retreat ~~from the 1990s.~~at each glacier (Figure 5). For example, Tracy and Heilprin accelerated substantially during their steady retreat periods (Table 1). At Heilprin Glacier this resulted in a ~~45~~49% increase (~~607~~from 458 to ~~878~~681 m a^{-1}) in grounding line velocity from 2001 to 2016 (Figure ~~7a~~6e), during which the glacier retreated at -110 m a^{-1} (Figure ~~6~~5). Substantially greater acceleration (89%) took place at Tracy Glacier from 1996 to 2016 (~~156%),~~Figure 6a), which was associated with higher magnitude retreat rates (-263 m a^{-1}: Figure ~~6). It was also clear that from 1996 to 2016, velocity increases propagated inland (~20 km) at both glaciers (Figure 7~~5). Humboldt, Harder, and Marie-Sophie Glaciers flowed more slowly than other grounded-terminus glaciers (< 400 m a^{-1}), but still showed large accelerations (27–108%) at their termini during steady retreat (Figure 6). Harald Moltke Bræ also accelerated between 1990 and 2016 (22 m a^{-1}: Table 1), and retreated at -196 m a^{-1} (Figure ~~6b~~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). Some grounded-terminus outlet glaciers did not show substantial acceleration following retreat: ~~Academy Glacier and~~ Kofoed-Hansen Bræ and Academy Glacier had sustained periods of steady retreat, but showed ~~distinct~~no net trend in velocity and high variability ~~in velocity change throughout~~ (Figure ~~7c,d~~6b,f), which ~~cannot be linked to the timing~~did not coincide with periods of increased retreat rates (Figure ~~6).~~ 5). Brikkerne Glacier decelerated from 1996 to 2016, while the terminus position changed little (Figure 6i).

3.3.2 ~~Category 2: Minimal~~ Glaciers with floating ice tongues

All but one (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). Within this period there was more variability, and two main patterns in velocity change which followed periods of rapid: 1) short-lived, minimal glacier acceleration, followed by ~~rapid, short-lived retrea~~ some deceleration, 2) continuous acceleration following initial terminus retreat. Four outlet glaciers with floating ice tongues (C. H. Ostenfeld, Hagen Bræ, Petermann Glacier and Steensby Glacier) showed short-lived (< 3 year) low magnitude grounding-line acceleration following rapid ice tongue retreat. 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 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 ~~Category 1~~most glaciers ~~grounded~~which flow fastest at their terminus, ~~most glaciers in Category 2 with floating ice tongues (5 of 6) showed minimal increases in velocity between 1996 and 2016 (Table 1). Following periods of rapid retreat, there were two dominant patterns in velocity change: 1) several glaciers showed minimal (< 5%) increases in velocity, 2) other glaciers had short-lived acceleration that did not propagate inland. For example, Petermann and C. H. Ostenfeld only accelerated by <4% at their grounding line following the 26 and 19 km loss of their floating ice tongues, respectively (Figure 8b,i).~~ 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%).

Despite ~~showing~~ minimal ~~acceleration, increased ice flow continued at these glaciers for several years after ice tongue loss (Figure 8b,i). Conversely ice tongues retreats of 14 and 12 km at Hagen Bræ and Steensby Glacier, were followed by greater but short-lived, grounding line acceleration (< 13%) in the following winters (Figure 8a,c). Once both glaciers returned to periods of minimal terminus~~ velocity change~~, they subsequently decelerated (Figure 8). However, minimal/and or short-lived acceleration was not ubiquitous. Instead, ice tongue retreats for ~10 years~~ over the entire study period (Table 1) at most glaciers with floating ice tongues, during this period, ice tongue retreat at both glaciers draining the NEGIS~~ (Figure 6)~~, were ~~synchronous with~~followed by gradual glacier acceleration in the ~~following~~subsequent decade (2006 to 2016: 43% at Zachariae Isstrøm and 10% at Nioghalvfjerdsfjorden). This prolonged~~, high magnitude~~ glacier acceleration following retreat, is more ~~characteristic of Category 1 glaciers with~~similar to patterns observed on grounded termini~~. Another key difference is that entire ice tongue~~ , rather than the other floating tongues. Further, the removal ~~at some glaciers (e.g.~~ of the entire ice tongue at Zachariae Isstrøm in 2011/12~~)~~ was ~~succeeded~~followed by glacier acceleration (125 m a^{-1}~~2~~: 2012 to 2016, Figure ~~8h), compared to minimal acceleration following ice tongue removal at others (e.g.~~ 7g), whereas other glaciers (e.g. C. H. Ostenfeld and Hagen Bræ~~). Overall, most glaciers with floating ice tongues~~) 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 ~~which did not propagate inland.~~in response to retreat and/or collapse of their floating ice tongues.

~~3.3.3 Category 3: Sustained periods of glacier advance~~

~~Four glaciers underwent sustained periods of glacier advance and showed overall deceleration from 1996 to 2016 (Table 1). In contrast to Category 1 and 2 glaciers, periods of advance coincided with acceleration (Figure 9). This behaviour was most distinct at Ryder Glacier, which accelerated by ~8% (4.7–5.5 m a^{-1}) during both 7-year periods of glacier advance (Figure 9h). Between these periods of advance (~2 years), large retreat events took place (e.g. 2006–2008: Figure 6c), which coincided with some deceleration (-27 m a^{-1}). While velocity data are absent for the periods of early advance at Storstrømmen and L. Bistrup in the 1970s, we note similar velocity behaviour during the more recent record (Figure 9). In contrast to most other outlet glaciers in northern Greenland, velocities at Storstrømmen and L. Bistrup Bræ are fastest inland, and decrease towards~~

~~the terminus (Figure 9b,c). However, throughout the record (1996 to 2016), grounding line terminus velocities accelerated by 350% and 150% at Storstrømmen and L. Bistrup Bræ (Figure 9); and velocities ~20–40 km inland decelerated by 10–15 m a^{-1} (> 54%). A similar pattern of terminus acceleration and inland deceleration took place at Kofoed-Hansen Bræ, which drains the northern branch of Storstrømmen (Figure 7l).~~

~~3.4 Surface elevation change~~

~~3.4.1 Category 1: Minimal change, followed by steady retreat~~

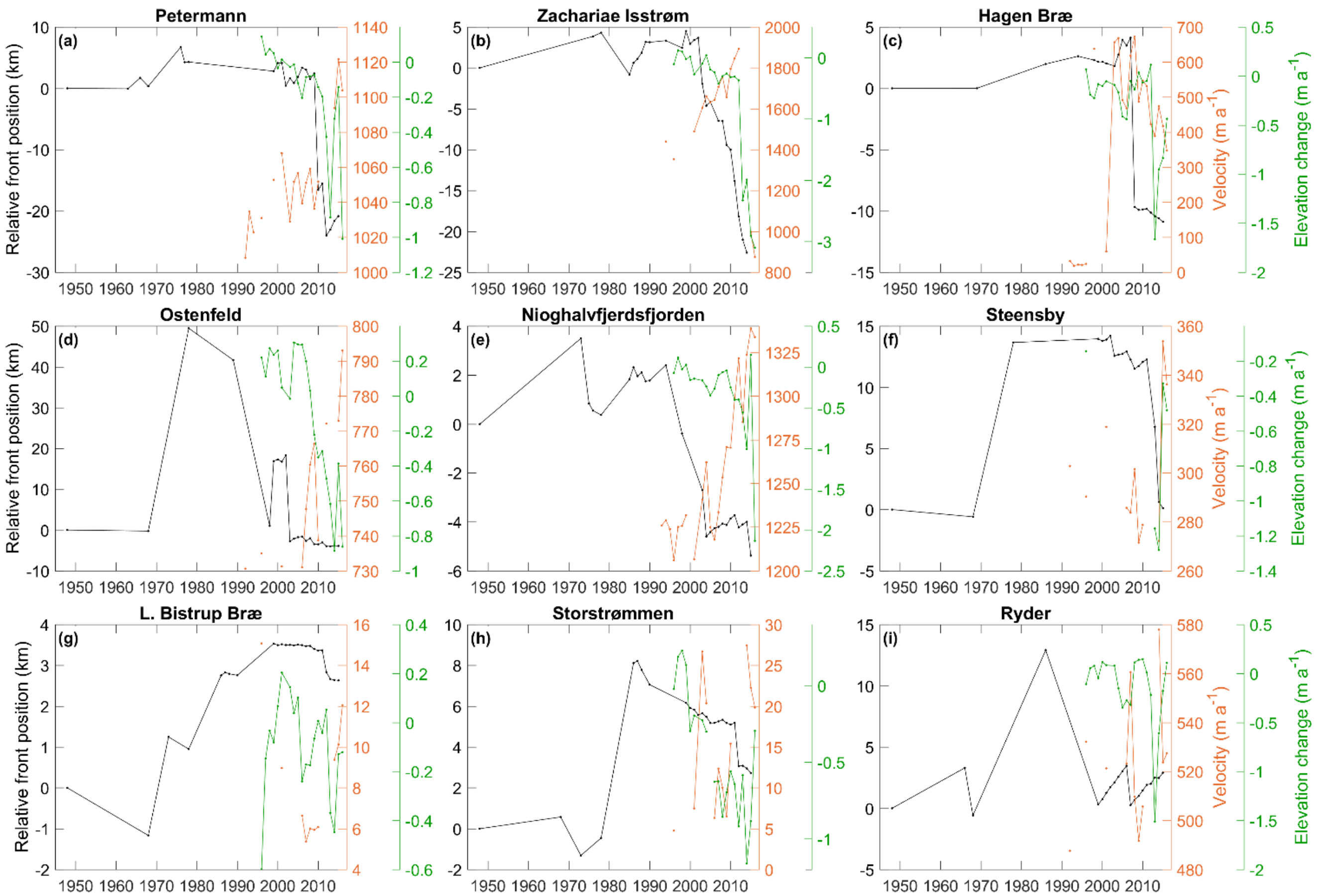


Figure 7: Front position, velocity and elevation change at nine outlet glaciers which terminate in floating ice tongues in northern Greenland. Left axes show relative front position (black line) between 1948 and 2015 relative to their initial position in 1948. Grounding line velocities (orange) on right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

3.4 Surface elevation change

3.4.1 Grounded-terminus outlet glaciers

Thinning rates on all ~~Category 1~~ outlet glaciers with grounded-termini (except Kofoed-Hansen Bræ) increased between ~~the period~~ 1992–1996 and 2014–2015 (Table 1). Short-term ~~(1–2 years)~~ surface lowering was synchronous with the start of their steady retreat and ~~clear~~ examples of this were at Marie-Sophie and Academy Glaciers. ~~A reduction in~~ Small increased thinning or reduced thickening rates ~~(~0.06 m a^{-1}:~~ at Academy and Marie-Sophie Glaciers (1999 to 2000~~), was~~: 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 ~~then~~ followed by dramatically increased thinning rates at both glaciers to -0.3 m a^{-1} (Academy) and -0.16 m a^{-1} (Marie-Sophie~~) and -0.3 m a^{-1} (Academy~~: Figure ~~7i,k~~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 ~~SEC~~ 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 ~~7e, g~~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. ~~A single exception to increased thinning rates at grounded-terminus glaciers was Kofoed-Hansen Bræ, where thinning extends only ~20 km inland of the terminus, before it switches to thickening further inland (Figure 7l).~~

3.4.2 ~~Category 2: Minimal change, followed by rapid, short-lived retreat~~

~~In comparison to grounded-terminus glaciers in Category 1, those~~Glaciers with floating ice tongues~~ in Category 2~~

Several glaciers with floating ice tongues experienced even higher thinning rates from 1992–1996 to 2014–2015 (Table 1), and were characterised by short-lived ~~dramatic~~ increases in thinning rates following ice tongue retreat. This ~~was clear~~occurred at Petermann, Hagen Bræ, and Zachariae Isstrøm, which all showed a slight thickening before ice tongue retreat/collapse, followed by a ~~clear~~ 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 ~~clear~~ switch to thinning was ~~also~~ synchronous with the onset of rapid retreat in 2003 (Figure ~~8h, k~~7b), although thinning rates ~~increased more dramatically~~were greater once the entire ice tongue was lost between 2011 and 2012. Thinning 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 ~~2011/12~~2012/13), and -~~4.3~~2 m a^{-1} at Zachariae Isstrøm (2011/12 to 2012~~). In all cases, dramatic increases in~~/13: Figure 7). At these three glaciers, increased thinning ~~rates were~~was also coincident with acceleration during the years following ice tongue removal (Figure ~~8~~7). Other glaciers showed more gradual and ~~less dramatic~~smaller increases in thinning rates (Figure ~~8~~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.~~04~~15 m a^{-1} from ~~2003~~2006 to ~~2011~~2014 (Figure ~~8i~~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).

~~3.4.3 Category 3: Sustained periods of glacier advance~~

~~Surface elevation data coverage was more limited at these glaciers in northern Greenland, so we focus on those with the most complete record (Storstrømmen and L. Bistrup Bræ).~~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 ~~9b, c). This was also partly seen at Kofoed-Hansen Bræ (Figure 7l).~~8). Periods of glacier advance (~1970s–80s) at both Storstrømmen and L. Bistrup Bræ preceded the earliest record of ~~SEC~~ elevation change and, following this, their terminus positions underwent minimal change (Figure ~~6~~5). Between 1996 and 2015, inland elevation change was minimal (Figure ~~10~~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 ~~10). The~~8). These spatial ~~pattern~~patterns of elevation ~~changes~~change were synchronous with velocity variations: deceleration and thickening occurred inland, while acceleration, thinning, and retreat were synchronous at the terminus (Figure ~~9). Despite poor SEC data at Ryder Glacier (Figure 9d), it is possible to comment on elevation changes during periods of recent advance (1999 to 2015). Surface elevation change 34 km inland of the grounding line switched from thickening during 1996 to 2002 (0.04 m a^{-1}) to substantial thinning from 2003 to 2006 (-2.7 m a^{-1}). Increased thinning rates coincided with an ~8% increase in ice velocities which preceded a large 3.2 km calving event in 2006 (Figure 9h). Following this retreat event, elevation change inland switched back to thickening of 0.1 m a^{-1} by 2007, which was coincident with deceleration of -27 m a^{-1} from 2006 to 2008.~~8).

~~3.5 Climate-ocean forcing~~

~~Annual air temperatures from Pituffik (NW Greenland) and Danmarkshavn (NE Greenland) range between -7.9 and -13.6°C from 1948 to 2015, and showed a significant increasing trend (p-value < 0.01) from the early 1990s onwards (Figure 11). At both stations, changepoint analysis revealed a significant change in mean annual air temperatures around 2000 (Figure 11). Annual air temperatures were 1.4°C warmer from 2000 to 2015 than mean temperatures of -11.1°C (Pituffik) and -12.1°C (Danmarkshavn) from 1948 to 1999. While annual air temperatures show this clear break, summer temperatures (JJA) remain relatively constant at both stations (Figure 11). Before the change-point in 2000, average annual positive degree days (PDDs) at Danmarkshavn were 254 (1958 to 1999) and 364 at Pituffik (1974 to 1999). After 2000, mean PDDs then increased to 352 at Danmarkshavn from 2000 to 2015 and increased even more dramatically to 667 at Pituffik from 2000 to the end of the PDD record (2006: Figure 11). Thus, a clear difference between NE and NW Greenland exists, where air temperatures and PDDs are greater in the northwest (Pituffik: Figure 11).~~

~~Coincident with increased air temperatures from 1990s, decadal sea ice concentrations were anomalously low across northern Greenland from 1986 to 1995 relative to the overall mean from 1979 to 2015 (Figure 12b). At the NEGIS, in particular, SICs remained up to 20% lower than the 1979 to 2015 mean throughout the following decade (1996 to 2005: Figure 12c). In the final decade (2006 to 2015), this was followed by a switch to greater SICs in the northeast region, and a reduction in sea ice concentrations in the NW in comparison to the 1979 to 2015 mean (Figure 12).~~

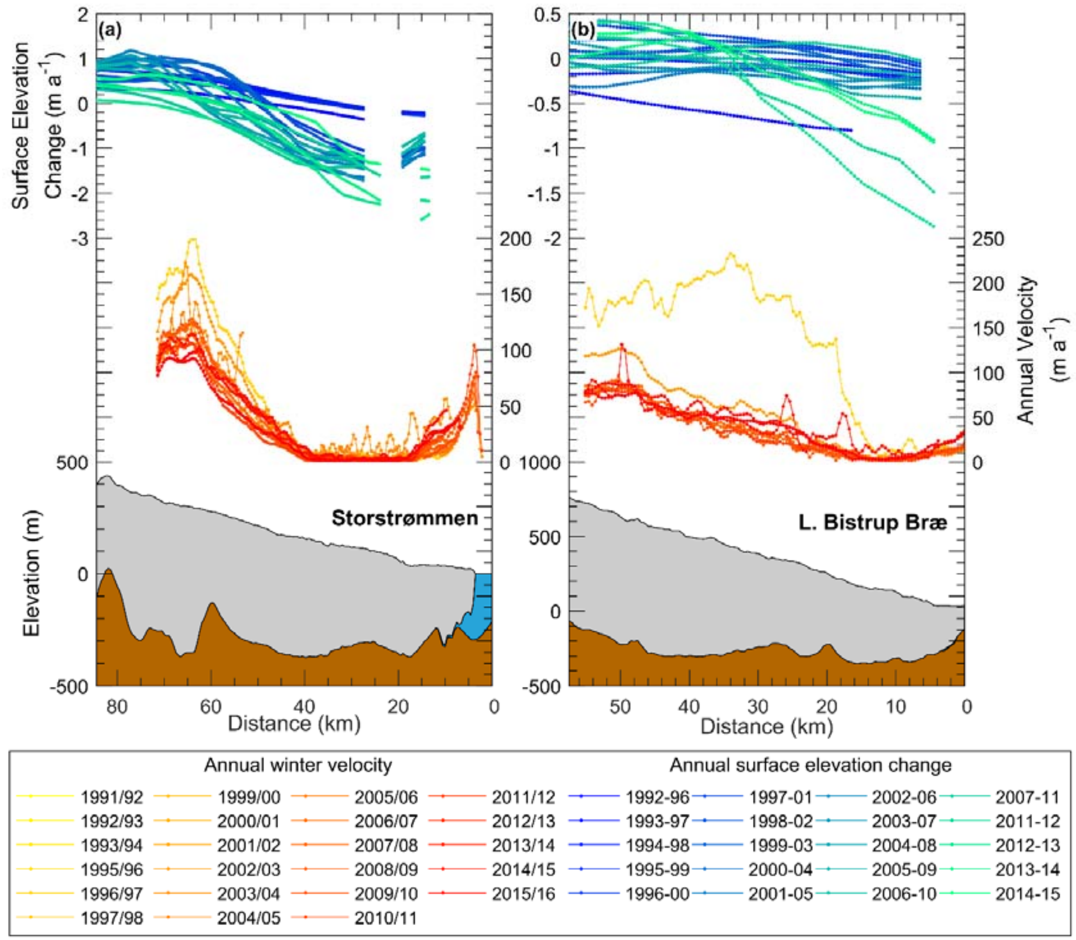
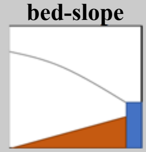
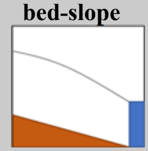
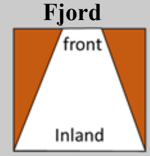
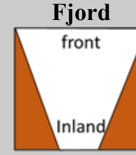


Figure 8: Annual surface elevation change, annual velocity and surface/bed topography for two outlet glaciers in northeast Greenland: Storstrømmen (a) and L. Bistrup Bræ (b). Blue to green coloured lines represent annual surface elevation through time (1992–96 to 2014–15) and yellow through to red lines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

3.6 Topographic factors

Distinct variability in glacier geometry exists between individual outlet glaciers in northern Greenland. Glaciers ~~with~~that are grounded at their termini~~ in Category 1~~, tend to be characterised by deep beds, that in all but two cases (Harder and Brikkerne) rest below sea level (-33 to -370 m below sea level~~). Several of these catchments~~: Figure 9). There is a split between glaciers which rest on ~~reverse bed slopes (e.g. Heilprin, Tracy and~~ inland sloping bed topography and seaward sloping topography (Table 3, Figure 9). Harald Moltke Bræ~~: Table 2), but several others have relatively flat~~, Tracy, Heilprin and Humboldt Glaciers have the steepest inland sloping bed profiles ~~(e.g.~~ 20 km inland of their grounding line (Figure S2), and currently appear to have retreated downslope away from topographic ridges (Figure 9). In contrast, Harder, Brikkerne, Academy and Marie~~–~~-Sophie~~, Humboldt, Academy: Figure 7i-j). Catchments that have the largest areas resting below sea level are Harald Moltke Bræ (17%) and Humboldt (27%:~~ Glaciers all slope seaward (Table ~~2).~~3), and have retreated into shallower water (Figure 9). Deeper, inland sloping bed topography is associated with higher mean retreat rates (-121 m a^{-1}) and greater velocity increases (Table 1). Retreat rates at glaciers with seaward sloping beds average -24 m a^{-1} (Table 1), excluding Brikkerne which advanced. Grounded-terminus glaciers in ~~Category 1~~northern Greenland are ~~also~~ mainly confined within long narrow fjords (5–16 km wide), ~~which widen inland~~ but there is no apparent correspondence between widening/narrowing fjords (Table ~~2). Most Category 2~~3), and higher retreat rates (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 (km²)**	**% 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	

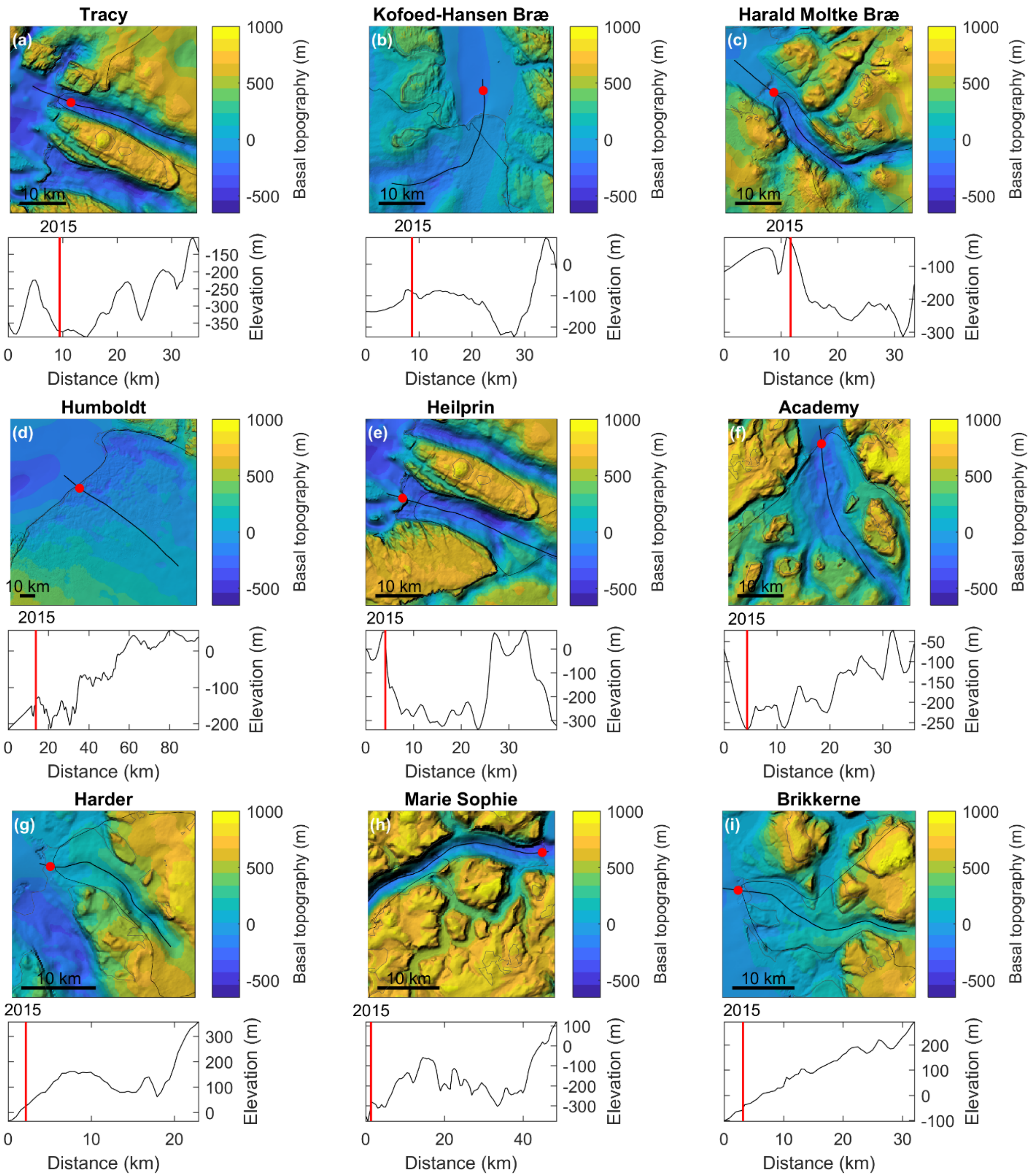


Figure 9: Basal topography from Operation IceBridge BedMachine v3 (Morlighem et al., 2017) beneath nine study glaciers with grounded termini in northern Greenland. Red points represent the position of the terminus/grounding line at each glacier from our most recent record of their terminus position (2015). 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.

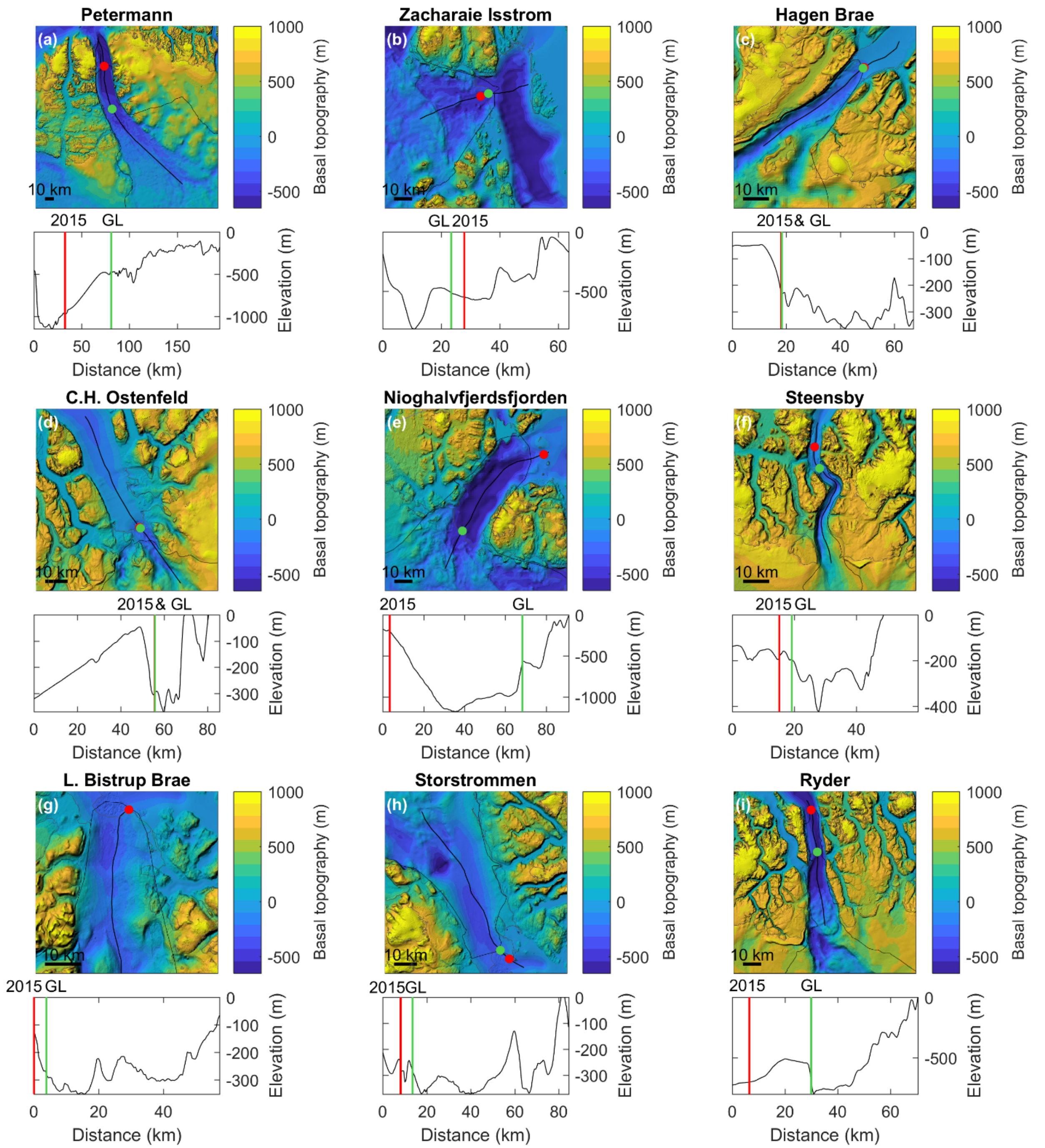


Figure 10: Basal topography from Operation IceBridge BedMachine v3 (Morlighem et al., 2017) beneath nine study glaciers which terminate in floating ice tongues in northern Greenland. Red points represent the most recent recorded terminus position (2015) from this study. Green points represent the location 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.

In contrast to grounded-terminus glaciers, those which terminate in floating ice tongues have deeper bed topography (-73 to -~~480 m below sea level) and all lie on~~ 1000 m below sea level: Figure 10) and greater proportions of their glacier catchments below sea level (Table 3). Fjords widths are also on average (19 km) wider than grounded-terminus glaciers (9 km) and the majority widen with distance inland (Table 3). Basal topographic profiles beneath seven of nine glaciers with floating tongues show inland sloping bed topography within 20 km of the grounding line (Table 3). 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 ~~(Table 2). Several catchments~~ close to the grounding line (Figure S2), further inland they show steeper seaward sloping topography (Figure 10). Additionally, current grounding line positions at Petermann, C. H. Ostenfeld and Hagen Bræ, rest on relatively flat topography (Figure 10a,c,d), rather than retrograde slopes. Like most other floating ice tongue glaciers, Ryder Glacier also ~~have~~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 ~~proportions that rest below sea level, particularly~~topographic ridge immediately seaward of the current grounding line position (Figure 10c). Glaciers draining the NEGIS (~~54%) and Petermann Glacier (67%). While all Category 2 glaciers have overall inland sloping beds, their current grounding line positions vary between resting on steep sloping sections (e.g. Zachariae Isstrøm and Steensby), to relatively flat topography (e.g. Hagen Bræ and C. H. Ostenfeld: Figure 8). Fjord widths are, on average (21 km), wider than Category 1 glaciers, although some terminate in long narrow fjords (Petermann, Steensby, C. H. Ostenfeld), while others are less confined by fjord walls (~~Nioghalvfjerdsfjorden and Zachariae Isstrøm~~). Glaciers which~~), have ~~shown periods of sustained advance (Category 3)~~even steeper inland sloping bed profiles immediately inland of their grounding line positions than most other glaciers with floating ice tongues (Figure 10). Both Nioghalvfjerdsfjorden and Zachariae Isstrøm experienced 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). Further south-east in the study region, Storstrømmen and L. Bistrup Bræ also ~~rest below sea level, reaching a maximum of ~1000 m near the grounding line at Ryder Glacier (Figure 9d). All four glaciers show basal depressions, which reach depths ~26% lower than the rest of their basal profiles (Figure 9). Fjord widths vary greatly for these glaciers, but on average are narrower than Category 2, but wider than Category 1 (17 km).~~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.

4. Discussion

4.1 Timing of glacier change ~~and climateDecadal retreat rates~~ between 1948 and 2015

Decadal terminus changes at all 18 study glaciers (Figure 4~~) show~~), showed a ~~clear~~ transition ~~to overall retreat in 1995: average front position change switched~~ from slow low magnitude advance and retreat (averaging +72 m a^{-1} ~~(advance:~~) between 1948 ~~to 1995) to~~and 1995 to rapid high magnitude retreat (averaging -445 m a^{-1} ~~(retreat:~~) between 1996 ~~to~~and 2015~~). This includes~~.

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 6). Increased decadal rates of terminus change across northern Greenland from 1995 coincided with increased air temperatures from the 1990s–2000s onwards (Figure 11). After the year 2000, mean air temperatures were 1.4°C warmer compared to the 1948–1999 average, in both the northwest and northeast regions of the GrIS (Figure 11). These changes coincide~~ 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). Importantly, the 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) and with Arctic-wide increased retreat rates ~~(Carr et al., 2017b), acceleration and retreat in south-east Greenland (Howat et al., 2008; Seale et al., 2011), and, to some extent, recent changes in north-west Greenland (e.g. Carr et al., 2013; Moon et al., 2012).~~

~~Increased thinning rates have taken place in the ablation areas (< 2000 m elevation) around the GrIS~~(Carr et al., 2017b; Moon and Joughin, 2008; Jensen et al., 2016), 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),~~Jakobshavn (Thomas et al., 2011), and Helheim and Kangerdlugssuaq in the south-east (Howat et al., 2008; Luckman et al., 2006), ~~linearly~~ increasing temperatures after the 1990s increased thinning in the ablation zone, which reduced basal/lateral drag and instigated a period of rapid terminus retreat. ~~In~~Indeed, increased thinning occurred at many of the study glaciers in northern Greenland, prior to rapid retreat. Thus, it is likely that similar increased ice marginal thinning 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 for increased glacier retreat rates and feedbacks between ~~retreat, acceleration and further dynamic thinning. Another subsequent feedback mechanism may have been surface melt induced hydrofracture, either through water filled crevasses (Benn et al., 2007; Nick et al., 2010), or supraglacial lake drainages through the full ice thickness (e.g. Banwell et al., 2013; Carr et al., 2015). Examples of where this might have been the case are at Zachariae Isstrøm and C. H. Ostenfeld, where water filled crevasses are clearly present along their ice tongues before collapse. Additionally, many ice tongue and grounded-terminus outlet glaciers supported supraglacial lakes throughout the summer months (e.g. Humboldt: Carr et al., 2015) and, particularly in the northeast, they are likely to become even more common in the future (Ignéczi et al., 2016).~~ thinning, retreat, acceleration and further dynamic thinning in northern Greenland.

~~Another key impact of warmer air temperatures from the 1990s onwards across northern Greenland is the removal of sea ice from the fjords (Figure 12). Sea-ice buttressing has previously been identified as an important control on glacier calving rates, both at glaciers in northern Greenland (e.g. Higgins, 1990; Johannessen et al., 2013; Khan et al., 2014) and elsewhere (e.g. Miles et al., 2016; Moon et al., 2012, 2015). The NEGIS has been highlighted as a region particularly sensitive to sea ice changes (Khan et al., 2014; Reeh et al., 2001). Sea ice concentrations in this region decreased from 1996 to 2005 (Figure 12c),~~

~~and coincided with periods of retreat at both glaciers (Figure 4d). At Nioghalvfjerdsfjorden, in particular, it is likely sea ice removal allowed major calving to occur from 1995 (Reeh et al., 2001) until the end of our study. Elsewhere in the region, the removal of sea ice from 2005 to 2015 in the NW (Figure 12d), coincided with greater retreat from 2005 onwards at Humboldt Glacier (Figure 7n). This supports previous assertions that many outlet glaciers are highly sensitive to changes in sea ice buttressing (Amundson et al., 2010; Carr et al., 2015). Across the most northern regions of the study area, from Petermann Glacier east to Hagen Bræ, anomalously low sea ice conditions occurred between 1986 and 1995 (Figure 12b), which coincided with the onset of some retreat during this period (Figure 4c). Similar to early work (Higgins, 1990), this suggests sea ice removal from the fjords can allow the removal of calved ice away from the terminus and increase the length of the 'calving season'.~~

~~An important area of future work in northern Greenland, is understanding the role of ocean conditions in controlling outlet glacier behaviour. Elsewhere increased ocean temperatures have coincided with acceleration, retreat and thinning (e.g. Moon and Joughin, 2008; Straneo and Heimbach, 2013). Despite not being exposed to warm subtropical waters like elsewhere around Greenland (e.g. east Greenland: Seale et al., 2011), increased ocean temperatures can markedly increase basal melt rates on large floating tongues (Mouginot et al., 2015; Reeh et al., 1999; Rignot et al., 2001, 1997). Early work highlighted the importance of basal melting for the mass balance of ice shelves (Reeh et al., 2001; Rignot et al., 2001; Rignot and Steffen, 2008) and melt rates beneath the three remaining floating ice tongues (Nioghalvfjerdsfjorden, Petermann, and Ryder) are estimated to exceed ~50 $m\ a^{-1}$, which is >80% of the total melt flux at all three glaciers (Wilson et al., 2017). While ocean warming is another likely control on dynamic glacier change, we are unable to make a more objective assessment on this due to limited region wide ocean temperature data. With the availability of more spatially extensive ocean/fjord temperature data in future, more focus on the role of ocean warming on glacier change in northern Greenland is needed.~~

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). 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). 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 has revealed three broad categories of terminus change for the period 1948–2015 for 18 major outlet glaciers in northern Greenland: (1) those that underwent minimal change followed by steady retreat; (2) those that underwent minimal change followed by rapid, short-lived retreat; and (3) those that underwent a period or several periods of sustained advance. Importantly, we find that Category 1 corresponds to those glaciers with grounded termini and Category 2 corresponds to those with floating ice tongues. Category 3 includes several glaciers that we interpret to be surge-type, and their potential surge-type behaviour are discussed separately in Section 4.4. Moreover, our results show that the dynamic response to a calving front perturbation/change is highly dependent on whether the terminus is grounded or floating. Here we discuss these differences between glaciers with floating versus grounded termini.~~

~~Both grounded and floating-terminus glaciers showed increased thinning in the years prior to retreat. As such, thinning may have initiated accelerated terminus velocities, thinning, and enhanced rates of retreat, as in~~Our analysis of terminus behaviour shows that the dynamic response 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). Across northern Greenland we observe two dominant calving behaviours based on terminus type: 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 change.

Independent of style (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). Increased thinning at the glacier terminus, causes downstream increases in velocity, which stretches the ice, promotes crevasse propagation induced calving, and accelerates flow inland. 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). ~~Following initial~~ Indeed, across northern Greenland our results suggest that terminus thinning ~~at~~ (~1990s) could have been the ~~terminus, grounded~~ initial criterion for instigating enhanced calving and terminus retreat in the following two decades (1996 to 2015).

Following an initial change in terminus conditions (~1990s), outlet glaciers in northern Greenland ~~(Category 1)~~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 ~~6b). During these steady retreats, annual ice velocities increased by 27–110%, and surface thinning rates increased (Figure 7). In several cases, there was a clear inland propagation of accelerated flow following retreat (e.g. Heilprin and Tracy Glaciers: Figure 7a, d). Steady and continuous retreat accompanied by prolonged acceleration and~~

~~thinning is analogous to~~5). Like grounded-~~terminus~~ outlet glaciers elsewhere, e.g. Helheim and Kangerdlugssuaq ~~(Howat et al., 2008, 2005, 2007)~~(Howat et al., 2008, 2005, 2007) and in west Greenland (McFadden et al., 2011)~~. Sustained~~ , periods of steady and continuous retreat at grounded-terminus ~~retreat likely caused a large and~~ outlet glaciers in northern Greenland were accompanied by increased annual ice velocities (27-110%), and dynamic thinning (Figure 6). Thus, 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~~, which~~ of most grounded outlet glaciers in northern Greenland, allowed acceleration and thinning to propagate inland and continue for a longer period ~~before the glacier~~as most glaciers may have not reached a stable geometry ~~(McFadden et al., 2011; Nick et al., 2009).~~(McFadden et al., 2011; Nick et al., 2009: Section 4.3).

~~In contrast to periods of steady retreat, terminus changes at floating ice tongue glaciers (Category 2) were characterised by short-lived (<6 years), high-magnitude retreat events that averaged -4536 m a~~$^{-1}$ ~~(Figure 6a), and the dynamic response was more variable. In most cases rapid, large calving events were followed by either minimal and/~~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, in most cases large calving events, appeared not to perturb the force balance by neither increasing longitudinal stretching, nor driving stresses on inland grounded ice (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 ~~8).~~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., 2008)~~(e.g. Joughin et al., 2008, 2004) 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. ~~For example, little dynamic change was seen at C. H. Ostenfeld and Petermann Glaciers in response to entire ice tongue collapse or large calving events.~~ At ~~other~~some glaciers ~~(Steensby and Hagen Bræ)~~ short-lived acceleration ~~(< 13%) occurred near~~ was followed by reduced retreat, and deceleration (e.g. Hagen Bræ), which represents a rapid re-adjustment at the terminus ~~following ice tongue collapse, before a rapid return to pre-retreat velocity. On these glaciers, the minimal/short-lived dynamic response suggests~~ , and that ~~the stress perturbation associated with losing substantial sections of the ice tongues was minimal. In contrast to episodic calving events~~ calving at ~~the majority of~~ floating ~~tongue glaciers, gradual and~~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 ~~at Zachariae Isstrøm (ZI)~~ was accompanied by a longer period of glacier acceleration and thinning~~, similar to the response of grounded northern Greenland glaciers, and conforms~~ (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). With the exception of ZI~~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). ~~The behaviour of glaciers with floating ice tongues contrasts strongly with grounded-terminus glaciers, which underwent a much larger dynamic response to small magnitude retreats (Table 1).~~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

~~Variations~~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.~~(Carr et al., 2013; Howat and Eddy, 2011; McFadden et al., 2011; Thomas et al., 2009; Carr et al., 2017). In this study, the differences between periods of retreat, acceleration, and thinning between floating and grounded-terminus glaciers suggests basal topography may control the time taken for glaciers to return to a point where retreat slows and velocities return to pre-retreat levels. In the case of grounded-terminus glaciers (Category 1), prolonged acceleration and thinning following retreat suggests a long period of re-adjustment took place and was not complete 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 (~15 km of their grounding zones) beneath most grounded-terminus glaciers (e.g. Tracy, Heilprin, and Harald Moltke Bræ: Figure 7).~~

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). However, there are exceptions: retreat rates on Tracy Glacier substantially exceed those on Heilprin, despite the latter having steeper (i.e. higher gradient) inland-sloping basal topography (Figure 6: Porter et al., 2014). In this case, the deeper bed topography at Tracy Glacier (Figure 7d) promotes the intrusion of warm water to the glacier front (Porter et al., 2014), and basal topographic pinning points at Heilprin Glacier may have provided greater lateral drag and inhibited accelerated retreat down its deep sloping bed.~~(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).

~~In contrast to~~Unlike grounded-~~terminus glaciers, Category 2 glaciers with~~ termini, floating ice tongues ~~experienced a comparatively short-lived dynamic response to changes at their~~ 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~~. Ice tongue buttressing can importantly influence~~ becomes grounded, at which point basal drag becomes an important control, and basal topography at and immediately inland of the grounding line ~~retreat. It would appear that several~~becomes more significant.

At most glaciers with floating ice tongues in northern Greenland ~~provide limited buttressing, whereby ice loss at the tongue does not result in~~, 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).

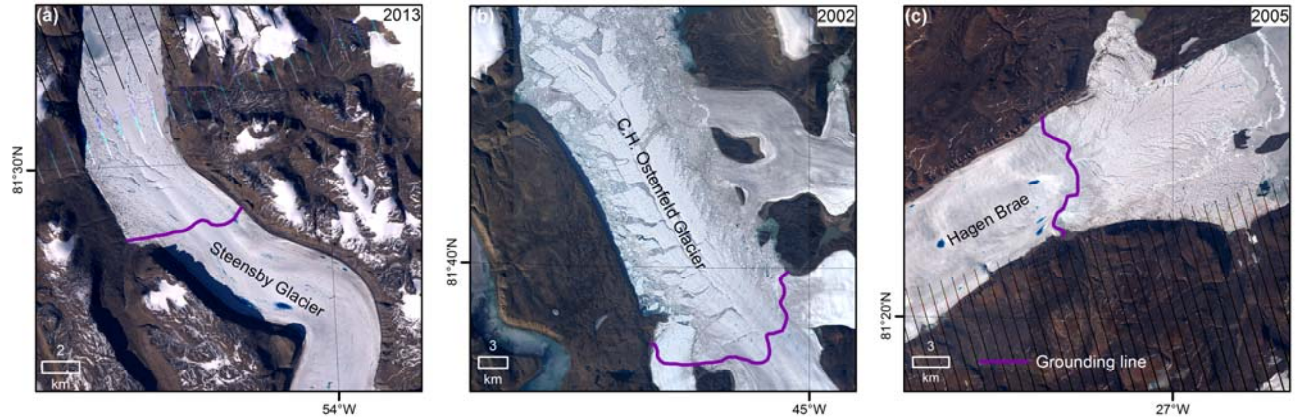


Figure 11: Landsat imagery of three glaciers which terminate in floating ice tongues in northern Greenland before their ice tongue collapse. (a) Steensby Glacier in 2013, (b) C. H. Ostenfeld Glacier in 2002, (c) Hagen Bræ in 2005. Purple lines denote the location of the grounding line ~~retreat or impact inland ice discharge. The response of these glaciers is also dependent on their bed topography and, in most cases, their~~ .

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 ~~currently rest on relatively~~ 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 ~~their basal topography. Such relatively flat basal topography at Hagen Bræ and C. H. Ostenfeld (Figure 8c,i) could have prevented unstable grounding line retreat, and associated acceleration and thinning, following the loss of their floating ice tongues. In a similar way, the flat sections of basal topography under~~basal topography beneath the grounding lines of Petermann Glacier and Nioghalvfjerdsfjorden ~~could~~may also control their future response to ice tongue collapse ~~(Figure 8b, g),~~, as their grounding lines would need to retreat ~20 km inland ~~in order~~ to sit on a retrograde slope~~.~~ (Figure 8b, g). In contrast, ~~there has been prolonged thinning, acceleration and retreat following~~ ice tongue ~~loss~~collapse at ~~ZI, which can also be explained~~Zachariae Isstrøm, was followed by ~~basal topographic controls.~~continued acceleration, retreat, and more dramatic thinning (Figure 7b). Here, ~~once the glacier became grounded, unstable retreat down a large basal over-deepening~~the deep retrograde bed-slope that extends ~20 km inland of the grounding line ~~(Figure 8h) could have caused the positive dynamic feedback response of acceleration and thinning~~, is likely responsible for continued retreat (Khan et al., 2014; Mouginot et al., 2015). ~~Overall, the different dynamic responses of floating and grounded-terminus glaciers to perturbations at their terminus, and their distinct basal topographic characteristics, highlights bed topography as a key control on the behaviour of glaciers in northern Greenland.~~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).

~~Fjord width and pinning points have both been identified as key controls on glacier response to forcing (e.g. Carr et al., 2013; Enderlin et al., 2013; Howat and Eddy, 2011; Jamieson et al., 2012), and could also At Hagen Bræ, for example, the ice tongue is confined by, and strongly attached to, its fjord walls, and retreat away from an island pinning point may have reduced back stress on inland grounded ice, and contributed to its accelerationMore limited dynamic responses at C. H. Ostenfeld and Nioghalvfjerdsfjorden may be due to the unconfined nature of the tongue within the fjord, and ice islands holding the tongue in place at Nioghalvfjerdsfjorden.~~

~~Overall, the minimal/short-lived dynamic response of most glaciers with floating ice tongues (Figure 8) suggests there was limited buttressing forces acting on their terminus, and little resistance provided by the fjord walls. Instead, the calving of grounded ice which is strongly attached to the bed and fjord walls, is likely to have caused a larger stress perturbations due to the greater reduction of basal/lateral stresses at grounded-terminus glaciers (McFadden et al., 2011). The transfer of stresses is propagated inland, and drives accelerated ice flow and surface thinning, which may account for their more pronounced dynamic response to terminus retreat.~~

4.4 Glacier surging

~~In contrast to the majority of glaciers in northern Greenland, we identify four outlet glaciers which underwent sustained advance (Category 3) and suggest these are likely to represent surge-type glaciers. 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.~~

~~Ryder Glacier has the most complete record of a potential surge-type glacier in northern Greenland, and showed two clear periods of advance over the last two decades (1995 to 2015), and two further advances before 1995 (Figure 6, Figure 9h). Recent periods of advance were accompanied acceleration, and some surface thinning ~30 km inland of the grounding line, which provide strong evidence for it being surge-type. While our elevation data are limited, previous studies~~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. Our results provide substantial 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.

Two glaciers in northeast Greenland show strong evidence of being surge-type: Storstrømmen and L. Bistrup Bræ.~~quiescent phase of surge-type glacier (e.g. Kamb et al., 1985; Meier and Post, 1969; Sharp, 1988). Despite the cyclic terminus behaviour and coincident changes in velocity that are indicative of a surge-type glacier, the long active phase (~ 7 years), followed by a short quiescence (~2–3 years) is in stark contrast to previously identified surge-cycle timescales, during which the quiescent is usually far longer than the surge (e.g. Dowdeswell et al., 1991; Sevestre and Benn, 2015). Additionally, velocity increases were not dramatic during the surge (~8%). Thus, whilst this glacier is regarded to be surge type (Joughin et al., 1999; Rignot et al., 2001) and our evidence supports that, the short quiescence and small velocity increase are not typical of surge-type glaciers.~~

~~Alongside Ryder Glacier, we find further support for two other surge-type glaciers in northeast Greenland. Terminus changes recorded at Storstrømmen and L. Bistrup Bræ (Figures 6 and 9) confirm previous work that identified a surge event at Storstrømmen in the 1970s (Reeh et al., 1999).~~ Interestingly both glaciers began to advance at a similar time, despite separate drainage catchments, and advance continued until 1985 at Storstrømmen, and 1998 at L. Bistrup Bræ (Figure ~~6c~~5). Unfortunately, velocity and surface elevation change datasets do not cover this period. However, dynamic changes at both glaciers between 1992 and 2016 were indicative of periods of quiescence. Both glaciers~~ clearly~~ show inland thickening, which coincides with slower glacier flow, and a terminus region of greater thinning, coincident with acceleration and retreat (Figure ~~9, 10). This confirms previous work that these glaciers are indeed surge type~~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 (Moon et al., 2012; Rignot and Kanagaratnam, 2006), and 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 is similar in duration to a previous period of advance and acceleration from 2004 to 2006. This glacier fits the conventional definition of surging, i.e. a short active phase, which included ~~a clear~~an order of magnitude increase in velocity (e.g. Meier and Post, 1969). However, it has a short surge-cycle (< 10 years) compared to most other glaciers in the Arctic (Carr et al., 2017a; Dowdeswell et al., 1991; Kamb et al., 1985), and underwent overall retreat from the late 1980s to 2015 (Figure ~~6), suggesting that climate-ocean forcing may be overriding its cyclical behaviour. Academy and Hagen Bræ glaciers have been previously identified as potentially surge type (Rignot and Kanagaratnam, 2006; Thomas et al., 2009), but we find no evidence to support this between 1948 and 2015. Brikkerne Glacier is the final glacier within Category 3 that advanced between 1969 and 1978. However, our limited data on this glacier makes its surge behaviour less clear and the glacier could have instead been controlled by external forcing, or had a much longer surge cycle than can be seen from this record.~~ 5), suggesting that 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, Ryder Glacier is an exception to most outlet glaciers in the region and appears to be behaving non-linearly to climate-forcing (Figure 7i). Ryder has been referred to as surge-type in the past (Joughin et al., 1996, 1999; Rignot et al., 2001), largely due to a 'mini-surge' event in 1996 (Joughin et al., 1996). Indeed, it has shown some surge-like behaviour: 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). 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. 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, 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, 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. 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, 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.

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