

## 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.

We are very grateful for this careful and constructive review of our manuscript. We also appreciate that you think the data we present is of use to the wider scientific community on outlet glacier behaviour in northern Greenland. To address the comments of both reviewers we have undergone a large re-structure of the manuscript, in the hope of significantly improving it over its previous version. We have made a real effort to simplify the structure, and focus the paper on the behaviour of glaciers in the region depending on their terminus type. Several modifications to figures have been made, while Table 2 and Figure 6 are still present in the manuscript we have added new figures to show velocity and surface elevation change through time alongside terminus change, and separate figures to display the basal topography at each glacier, more clearly than the previous centreline profile plots of bed elevation. Within the text, a large number of changes have been made when restructuring the manuscript and for that reason a tracked changes document compared to the original submission will look relatively chaotic. Several of the more specific comments outlined below may no longer be present, and several that are, lie on substantially different line numbers than in the previous version. We hope to have sufficiently signposted to all changes using the new line numbers at which these exist within a revised manuscript. Below are referee comments in black, and our responses to each comment are in blue.

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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.

On reflection, we agree with the referee's comment on the limitations of the climate data and our analysis of it in this manuscript. We also agree that it may detract from the better quality long term terminus change record and assessment of geometric controls that are instead the focus of this paper. We have taken your suggestion to remove 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. In line with the tidewater glacier cycle literature we have instead switched the focus of this section to climate-forcing initiating an initial terminus instability (e.g. glacier thinning), before the role of glacier geometry becomes a more important control on continued retreat and dynamic glacier behaviour.

**#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.

This is a very good point, and we realise the need to put dynamic glacier behaviour in northern Greenland, into better context with fundamental differences expected between glaciers with grounded or floating termini across the region. 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. The differences in dynamic behaviour between these two terminus types is then our justification for our new categorisation of glaciers within the region. Following some of the comments from referee 2 we simplify our previous categorisation to now just compare glaciers based on whether they terminate in a floating ice tongue or are grounded. 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.

We appreciate the advice on improving the writing of the manuscript and the book recommendation. We agree that there are sections of the manuscript where our phrasing and organisation could be improved. 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.

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#### Specific comments by page/line number:

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

Changed to 'is poorly constrained'

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

1/20. 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 2/3. 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.

2/27 – 3/2 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 are grateful for the suggestion as to how to simplify/shorten this section of the text. We have taken it as written and changed it on 5/25-28.

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

We have amended this to 'incrementing the number of breaks' now on 6/18

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

We have reworded the last couple of sentences at the end of 2.2.3 to improve the description of the process. 6/18-22.

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

7/6. 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.

7/7 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.

9/1-4 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.

9/19 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.

We have moved 1948-1975 to the second half of the sentence. Now on 10/13

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.

This has now been changed to 'were followed by gradual glacier acceleration in the subsequent decade'. Now on 16/5-6

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.

We hope to have clarified this on 16/8-10

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).

17/16-32 Removed dramatic and clear throughout this paragraph.

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

This section 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.

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' now on 22/23

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

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.' Now on 22/28-29

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 (23/8) 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 Nioghalvfjærdsbræ (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 Nioghalvfjærdsfjorden 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. However we have re-ordered these processes on 23/33 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 24/17-19 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 25/28-29 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 25/11.

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

26/3-5. We have changed this sentence to now read 'In particular, C. H. Ostfeld 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?

27/31. 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 this table.

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.