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.

We are very grateful for your detailed and constructive comments on our manuscript. We have undergone a major restructure of the manuscript in the hope of improving it substantially from its previous version. In doing so, we hope to have refocused the paper, removed some of the excess information, and improved the readability. While there is a lot of information put forward, to some extent this region is a complex one, and cannot be explained by a single factor alone. That said, throughout we have tried to focus more on the role of terminus type in controlling the differences in behaviour in northern Greenland, and the influence of topography. 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. Despite the volume of data that we have presented, we do feel that it is of value to the scientific community, as it provides a new record of outlet glaciers change in northern Greenland. As well as this, referee 1, did point out that in some cases there needed to be more detail on specific glaciers, and so in several places we were cautious about removing any of the detail on individual glaciers.

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.

We appreciate your feedback on the categorisation of glaciers within the manuscript, and this 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.