Dear Editor

Many thanks for overseeing the latest round of reviews of our paper: '*Unravelling the long-term, locally-heterogenous response of Greenland glaciers observed in archival photography*'. We are very pleased to see that Referee #2 (Anders Bjork) is happy with our latest version, but sorry to see that Referee #1 was not able to provide a 2nd review. We are nevertheless grateful to the anonymous third referee.

Referee #3 is generally very positive and we are grateful for their acknowledgement of the 'huge effort' that we have put in to 'extend the record of glacier change in this region back in time'. We are pleased that they also recognise one of the focuses of our paper which is to explore heterogeneous glacier behaviour. As before, we deal with each of the comments made by referee #3 in turn, using red text to identify relevant statements from the reviewer and black text to indicate our response.

Referee #3

L61: The "data sparseness" mentioned here is nicely illustrated by Goliber et al. preprint in TC (https://tc.copernicus.org/preprints/tc-2021-311/).

Thanks for directing us towards this work. We have now added reference to this paper.

L260: Clarify that these are mean annual max/min temperatures. I was unclear on this until I saw Figure 7. Also, how are the positive degree days calculated?

We now replace: 'Annual air temperatures (minimum and maximum) as well as positive degree days (calculated from these data)' with: 'Mean annual minimum and maximum air temperatures, as well as positive degree days (calculated from these data)'. Positive degree days were calculated by counting the number of days in a year when the maximum temperature record exceeded zero degrees.

2.4: First there is a description of manually delineated margins, then a description of centerline positions. Clarify, were both methods used, and what was the purpose of each?

We apologise for the lack of clarity here. We manually digitised the margins of each glacier at each time-step and then constructed centrelines using the method outlined in our manuscript. We then looked at where the centreline intersected the frontal margin at each timestep to investigate change. In the text, we replace: 'Specifically, we use contemporary velocity data to define a centre-line and measure a single length change from these centre-line positions.' with 'Specifically, we use contemporary velocity data to define a centre-line and measure a single length change at locations where the centre-line intersects delineated frontal margins.'

Figure 5/Table 2: In Table 2, southern glaciers 22-24 have advance/retreat listed in 1966-1985, but that is not shown for these glaciers in Figure 5. Also, L301-302 state that the southern glaciers have no data from 1930-1985, which is contradicted by Table 2.

Thankyou for this comment, figures 5 and 4 are correct however the table and the text was misleading. For glaciers 22-24 and glaciers 15-16 we do have orthomosaics created based on data from BAARE expedition (1930s) and from 1985 mission, however we do not have data from 1960s Corona mission. The data in table 2 refers to change in the glacier frontal position between 1930-1985. Since we can see how this is confusing in the current version of the manuscript we moved all five glaciers to the bottom of table 2 and added a separate heading for this part of the table. The sentence in L301-302 has been changed to "Indeed we do not have any data for the period of 1930-1985 for glaciers 20 and 21. We are also missing the 1966 time step for glaciers 22-23 where we do have data from 1930s and 1985 for those glaciers, and so parts A and B of Figure 5 are blank."

Figure 6: It took me several minutes to figure out that the plots in the center were showing the same data as those at the left, but with an extended y-axis to show the full error bars. Please clarify this in the figure caption.

You are correct and we apologise for omitting this from our figure caption. This has now been amended.

L437: Specify that warming waters could contribute to the mass loss of marine-terminating glaciers (not all glaciers in your study).

We agree that when we refer to SST, bathymetry and the role of sea ice, we only mean these are relevant for marine terminating glaciers. As a result, we replace the following sentence:
'Such observations suggest that glacier response is defined not only by climatic variables (e.g. air temperature, SST) but also by a) ice velocity (and changes in this over time), b) ocean circulation at a calving front, c) underlying topography (i.e. bed elevation beneath an ice mass) and bathymetry, d) the presence, concentration and role of sea ice, and e) ice thickness.'
With:
'Such observations suggest that glacier response is defined not only by climatic variables (e.g. air temperature, SST) but also by a) ice velocity (and changes in this over time), b) ocean circulation at a calving front, c) underlying topography (i.e. bed elevation beneath an ice mass) and bathymetry, d) the presence, concentration and role of sea ice, and e) ice thickness. Of course, the role of SST, ocean circulation, bathymetry and sea ice are only relevant controls with respect to marine terminating glaciers.'

L446/generally: Many studies that have looked at the effect of warming ocean temperatures on glacier behavior have assessed temperatures at depth, not just SST. While your data focus on SST, it would be good to mention this as well.

Thank you for this suggestion. We now draw attention in our discussions to this fact. We add the following sentence to the end of paragraph 2 of section 4.1:

'It is, however, important to note that the focus of Wood et al. (2021) is on subsurface water temperatures that occurred as a result of the spreading of ocean heat caused by changes in the North Atlantic Oscillation (NAO). We do not have data that enables us to explore subsurface temperatures in this way'.

In the following paragraph, when summarising the controls on glacier frontal position, we now also refer to the role of subsurface temperature changes as well as SST changes.

L458-460: the items listed here would benefit from supporting citations as there has been much work on all of these topics as pertains to glacier response.

We are sorry, but we're not clear what it is that the reviewer wishes us to add references to. This passage (lines 458-460) reads:

'*...show 2-3 times more retreat than these. Two of these are part of Glacier 8 (see Figure 8) which has several outlets. The two southernmost ones showed rapid and large-scale retreat between 1930 and 1966, but then displayed very little change over the years since then. In contrast, Glacier 10 showed relatively modest retreat from 1930 to 2015, but then large-scale and rapid…*'

This passage is a description of the behaviour of our glacier. However, we wonder if the referee means the material on lines 441-445, which currently reads:

'*Such observations suggest that glacier response is defined not only by climatic variables (e.g. air temperature, SST) but also by a) ice velocity (and changes in this over time), b) ocean circulation at a calving front, c) underlying topography (i.e. bed elevation beneath an ice mass) and bathymetry , d) the presence, concentration and role of sea ice, and e) ice thickness. Of course, the role of SST, ocean circulation, bathymetry and sea ice are only relevant controls with respect to marine terminating glaciers'*.

We believe the referee is requesting citations related to each of the points we make here, which we now add. As a result, the passage reads:

'*Such observations suggest that glacier response is defined not only by climatic variables (e.g. air temperature, SST) but also by a) ice velocity (and changes in this over time; King et al., 2020), b) ocean circulation at a calving front (Wood et al., 2018), c) underlying topography (i.e. bed elevation beneath an ice mass) and bathymetry (Catania et al., 2018), d) the presence, concentration and role of sea ice (Carr et al., 2013), and e) ice thickness (Barr et al., 1998). Of course, the role of SST, ocean circulation, bathymetry and sea ice are only relevant controls with respect to marine terminating glaciers'*.

Figures 8, 9: Use a perceptually uniform colormap for velocities (see https://matplotlib.org/stable/tutorials/colors/colormaps.html for Matplotlib examples; see doi.org/10.1038/s41467-020-19160-7 for reasoning). Also it appears that the colormap is not discretized although the colorbar is, which makes interpretation more difficult.

Thankyou for this comment, in this version of the manuscript we used colour maps magma and viridis (https://bids.github.io/colormap) for velocities and bathymetry respectively. And the colour bar is no longer discretized.

L560-567: I think that you state the importance of bed topography too strongly in the conclusions given the highly speculative nature of your discussion. The reference to Catania et al. (2018) is important, but unlike here, that paper specifically focused on the influence of bed topography on glacier behavior, as have others (e.g. Carr et al., 2015; Felikson et al., 2021).

Again, there seems to be some confusion over line-numbering. The line numbers refer to the reference list. However, the referee refers to oru mention of Catania et al. (2018) in the conclusions. We refer to this paper on line 523. Shortly before we mention this paper we state:

'*...we propose that the great variability in the retreat of marine terminating glaciers (both in terms of the magnitude and timing of retreat) is strongly controlled by the presence or lack of shallow ridges which act to pin glaciers as they retreat. We envisage an undulating submarine/subglacial topography which has meant that some glaciers have showed periods of much greater or lesser retreat, and some are apparently stable in their position. Such a situation lends itself to the possibility of future periods of comparatively rapid retreat of glaciers that appear to be stable, and likewise future stabilisation of other glaciers that may currently (or in the past) have shown more significant retreat*'.

We are *assuming* that it is in this passage that the referee feels we are overstating the importance of bed topography. To address this, we change the wording slightly so that the passage now reads:

'*...we propose that the great variability in the retreat of marine terminating glaciers (both in terms of the magnitude and timing of retreat) may be controlled by the presence or lack of shallow ridges which act to pin glaciers as they retreat. In our interpretation, we envisage an undulating submarine/subglacial topography which has meant that some glaciers have showed periods of much greater or lesser retreat, and some are apparently stable in their position. Such a situation, if accurate, would lend itself to the possibility of future periods of comparatively rapid retreat of glaciers that appear to be stable, and likewise future stabilisation of other glaciers that may currently (or in the past) have shown more significant retreat*'.

In relation to our mention of the Catania paper, we accept that the wording used seems to imply that their and our work is similar and thus the two pieces of work are comparable. In order to try and reduce this interpretation, we replace:

'Catania et al. (2018) showed similar results for western Greenland which gives us greater confidence in our interpretation here'.

With

'Catania et al. (2018) also provided such insights for western Greenland and so we have greater confidence in our interpretation here'.

Generally, this manuscript would also benefit from introduction/discussion of past studies that have also highlighted heterogeneous glacier behavior.

We agree that considering other work that has focussed on heterogeneous behaviour is important. However, as we arrive at this idea through the focus of our work, we would like to refrain from discussing this in the introduction at all. Instead, we modify our discussion. The final paragraph of the discussions previously read:

'*Such diverse observations highlight how even dividing the ice sheet up into regions masks the complexity that is inherent in individual glacier behaviour. Even glaciers that exist adjacent to each other can show markedly differing patterns of retreat. An individual glacier has a unique mixture of processes that might control its rate of retreat and thus it is oversimplistic to just to state that mass balance or dynamic changes dominate in a region. In particular, we propose that our long-term study of multiple glaciers suggests a very important role for subglacial and submarine topography and in particular the importance of shallow ridges that dictate the retreat rates of marine-terminating glaciers. Such an interpretation is not new. Catania et al. (2018) showed how fjord geometry is an important control on how glaciers respond to climate. However, their work was focussed in West Greenland and explored changes over the past 30 years. The novelty of our work is not only the exploration of previously unstudied, smaller outlets in East Greenland, but also that we are able to identify such processes taking place over a timescale that is three times as long, thanks to the data we are able to extract from archival imagery. This greater length means that we can see that there was an earlier and a later warmer period, and that the glaciers responded differently in each, such that much more retreat took place in the later period. If topography is indeed the control on this, then it demonstrates the significance and ability to be a major moderator of climate-driven changes*'.

…but now it reads:

'*Such diverse observations highlight how even dividing the ice sheet up into regions masks the complexity that is inherent in individual glacier behaviour. Even glaciers that exist adjacent to each other can show markedly differing patterns of retreat. Significant variability in the behaviour of Greenlandic outlet glaciers has been identified previously (McFadden et al., 2011; Moo; Csatho et al., 2014; Porter et al., 2018), whereby variations in rates of frontal retreat, surface thinning and velocity may be apparent even when a region as a whole is*

losing mass. An individual glacier has a unique mixture of processes that might control its rate of retreat and thus it is over simplistic just to state that mass balance or dynamic changes dominate in a region. In particular, we propose that our long-term study of multiple glaciers suggests a very important role for subglacial and submarine topography and in particular the importance of shallow ridges that dictate the retreat rates of marine-terminating glaciers. Porter et al. (2018) used a statistical approach to explore the spatial correlation in the behaviour of adjacent Greenlandic glaciers and showed that local controls are more important than regional influences. They also found that there was a good correlation between rate of thinning and ocean heat content, and also that glaciers grounded in deeper water were more sensitive to oceanic controls on mass loss. Similar to our findings, they also showed that taking account of the presence of shallow sills was important, and further called for an improved understanding of bathymetry. Catania et al. (2018) also revealed how fjord geometry is an important control on how glaciers respond to climate. However, their work was focussed in West Greenland and explored changes over the past 30 years. The novelty of our work is not only the exploration of previously unstudied, smaller outlets in East Greenland, but also that we are able to identify such processes taking place over a timescale that is three times as long, thanks to the data we are able to extract from archival imagery. This greater length means that we can see that there was an earlier and a later warmer period, and that the glaciers responded differently in each, such that much more retreat took place in the later period. If topography is indeed the control on this, then it demonstrates the significance and ability to be a major moderator of climate-driven changes.'

In addition, we also modify the final 3 sentences of our conclusions. Previously it read:

'*In our efforts to better understand the complexity of the response of the Greenland Ice Sheet to a warming climate, we propose that it is increasingly important to consider the variability between outlet glaciers because of the variation in responses that we have identified here. In addition, our work has also highlighted how difficult it is to analyse overall glacier response from investigations of frontal variations alone. An important future direction would be to focus on surface elevation change and also to explore the subglacial topography of these outlets to predict likely future 'jumping' periods of retreat, or indeed stabilisation*'.

…but we have now modified it to read:

'*In our efforts to better understand the complexity of the response of the Greenland Ice Sheet to a warming climate, we propose that it is increasingly important to consider the variability between outlet glaciers because of the variation in responses that we have identified here. We also support, and further stress the need for much improved knowledge of fjord geometry, as initially called for by Porter et al. (2018) because of its probable importance in controlling the heterogeneity in glacier behaviour. In addition, our work has also highlighted how difficult it is to analyse overall glacier response from investigations of frontal variations alone. An important future direction would be to focus on surface elevation change and also to explore the subglacial topography of these outlets to predict likely future 'jumping' periods of retreat, or indeed stabilisation*'.

There are a number of typographical errors throughout the manuscript. I've listed those that I identified below; please review the manuscript for any further changes.

• L57: ETRS1 → ERTS1 (may also mention that this mission is now known as Landsat-1 to improve name recognition)
Sentence now changed to read: '*Since the launch of the first Earth Resources Technology Satellite (ERTS1;now known as Landsat-1) in 1972 (Ives, 2011)...*'

• L70: utilse → utilize
Corrected as suggested. We actually find three such occurrences in our manuscript, and so we modify them all.

• L79: "poorly understudied" is redundant; use "poorly studied" or "understudied"
We modify to 'poorly studied'.

• L128 and elsewhere: use CORONA consistently
All occurrences of Corona changed to CORONA.

• L125: lead → led
Corrected.

• L189 and L214: ArcticDEM
Corrected.

• L282 and elsewhere: I think, Bjork → Bjørk (per other references in the manuscript)
Corrected - we identify 4 incorrect spellings.

• L297 and L303: terminii → termini
Corrected.

• L334: temperature remain → temperatures remain
Corrected.

• L529: it's → its; to just to → just to
We cannot locate the occurrence of 'it's', but we do make the second suggested correction.

• L568: reagion → region
Corrected.