

## **Review of tc-2021-256: Unravelling the long-term, locally-heterogenous response of Greenland glaciers observed in archival photography**

This manuscript presents orthorectified aerial and satellite imagery of the margin of the central-eastern portion of the Greenland Ice Sheet. Glacier terminus positions are digitized from the newly processed imagery, providing measurements of glacier extent in 1930 and 1966. These are combined with glacier terminus position measurements from satellite imagery from 1985, 1995, 2005, 2015, and 2019 to produce a ~90-year record. The glaciers are divided into categories of: marine-terminating, land-terminating, ice sheet outlets, and local glaciers. Their terminus position changes are interpreted in the context of changes in regional air temperature, positive degree days, sea surface temperature, and reconstructed surface mass balance. Finally, the heterogeneity between glaciers as well as within different portions of individual glaciers is discussed.

Processing the archival photography from the 1930/31 British Arctic Air Route Expedition and the CORONA satellite mission is a big undertaking. I'm very pleased to see this imagery being utilized to provide longer-term context for the recent changes that glaciers have undergone. Another strength of the paper is the focus on lesser-studied glaciers, including land-terminating ice sheet outlets and peripheral glaciers and ice caps, which shows clear differences between the behavior of these different types of glaciers. Finally, the exploration of heterogeneity between neighboring glaciers and heterogeneity within individual glaciers themselves (i.e., different branches or portions of the same glacier) is a strength.

There are, however, several improvements that can be made to strengthen the paper and I have noted these below in general and editorial comments. One overarching comment that I would like to emphasize is that the discussion needs improvement in order to better support the point that “full understanding of the behaviour and response of the Ice Sheet requires us to consider changes that are taking place at the scale of individual glaciers” (abstract). The paper does an excellent job of showing the heterogeneity among glaciers in the data, but the discussion is weak on interpreting this heterogeneity. I understand that, without observations at most of these glaciers (e.g., bathymetry, oceanographic data), it is not possible to draw conclusions about why some glaciers are stable while others retreat. This paper hypothesizes that bathymetry and subglacial topography is likely what is stabilizing some glaciers, but this has been shown in previous work (e.g., Catania et al., 2018). The discussion in the paper needs to be strengthened by showing what can be learned from focusing on the lesser-studied glaciers and by extending the record of glacier behavior back in time, beyond what has already been shown in past literature. In other words, the discussion can be improved by focusing on the novel aspects of the archival data. For example, one question that the authors can consider addressing is: if air and sea-surface temperatures exhibit similar anomalies from the long-term baseline in the 1930s and 1940s as they do in the 2000s and 2010s (Figs. 7 and 8), why do marine-terminating and GrIS outlets respond with so much more retreat in the latter period (Fig. 2)? This is a novel question that could be addressed with the archival data of southeast Greenland that could not have been addressed before.

I would just like to emphasize, again, that the archival photos processed for this study add crucial and novel measurements that help contextualize glacier changes that occurred over the last couple of decades. The processing of the data is thorough, and the results are presented clearly. I feel that, with some improvement to the discussion, this paper can provide an impactful contribution to our understanding of glacier change.

## General comments

1. One of the conclusions of the study is that it is important to study glacier-to-glacier heterogeneity in order to get a full understanding of the behavior and response of the ice sheet. While I agree with this sentiment, I feel that this paper frames past work incorrectly. For example, lines 478-480 state that “there has been a temptation in the past to differentiate between regions.” I disagree that past work that focused on regional aggregations of glacier behavior did so simply because it was tempting to do this. The goal of grouping regionally is to understand whether there are broad patterns to glacier behavior and their response to external forcing. And, while there have been previous studies that have grouped glaciers regionally, there are also studies that have shown significant heterogeneity between neighboring glaciers (e.g., Bjørk et al., 2012; Carr et al., 2017). I have two suggestions:
  - a. Change the wording throughout the manuscript to more accurately state that the goals of the past regional studies was to investigate broad-scale patterns, while this present study focuses on glacier-to-glacier heterogeneity.
  - b. Add to the introduction an overview of past studies that have looked at glacier-to-glacier heterogeneity, explain what they had found, and then go on to describe how this present study builds on that previous work.
2. An estimate of observation errors for SST and SMB should be added to the manuscript. Currently, Figures 7, 8, and 9 show the standard deviation of the data around the mean (gray shading) but this does not take into account errors in each individual measurement. I appreciate that it is difficult to assess the errors on these data but, at the very least, a rough estimate should be incorporated such that the gray shading includes both the scatter in the measurements and the errors on the measurements themselves.
3. I suggest combining Figures 7, 8, and 9 into one. This would make it easier to compare air temp, SST, and SMB.
4. Some of the text in the discussion section presents results without any interpretation and the manuscript would be clearer if this text were moved to the results section. I've tried to note this in my editorial comments below but I may have missed some. I suggest the authors go through the manuscript to move any text that does not include interpretation from the discussion section to the results section.
5. In general, more explanation is needed throughout the discussion to substantiate some of the interpretation. I've noted this in editorial comments below.
6. The interpretation of the behavior of Glacier 14 needs to be clarified. First, the text on lines 442-446 states that the bathymetry data in front of Glacier 14 shows that the stable portion of the terminus is located where the bed is deeper. Although the bed may be deeper in front of the terminus, the data doesn't show what the topography is just upstream of the terminus. There could potentially be a steep ridge there and the bathymetry data that's available does show a shallowing towards the terminus. Second, the text on lines 446-449 goes on state that the observed stability is in opposition to the fact that calving rates tend to be higher for termini in deeper water. This is slightly confusing because terminus stability arises from stable calving and melt rates. In other words, the calving rate can be high but as long as it doesn't increase (and melt rates don't increase), the terminus will not retreat (velocity also has to remain steady). So, it isn't the calving rate itself but changes in the calving rate that are important. Finally, this paragraph hypothesizes that the western part of this glacier is "subject to dynamically-driven mass loss" even though the terminus position is stable. This interpretation is not supported and I would like to see more explanation for why the authors think this is the case. The evidence presented is that the western portion has faster ice flow and is grounded in deeper water

(although I question this) but I don't see why this leads to the claim that this glacier is dynamically losing mass.

7. Similar to my previous point, the text on line 455 states that Glacier 15 is undergoing "surface thinning" and is "losing the greatest amount of mass" however this is not supported. Please add justification for these claims.
8. The data availability statement does not comply with the requirements of the journal. The journal data policy states that if the data is not made publicly accessible in a FAIR repository, an explanation needs to be provided for why this is the case ([https://www.the-cryosphere.net/policies/data\\_policy.html](https://www.the-cryosphere.net/policies/data_policy.html)). My strong recommendation is for the orthophotos from the BAARE and CORONA, as well as the derived terminus positions from all of the imagery (including those from Landsat), be placed in a FAIR repository, with a DOI obtained and referenced in the Data Availability section.

### **Editorial comments**

[line 279] Change "Thss" to "This"

[lines 308-309] The sentence "Those outlets ... greater variability" repeats what has already been said earlier in the paragraph about marine-terminating glaciers. I suggest removing this sentence.

[lines 309-310] I suggest moving this sentence to the discussion because it does not directly describe results.

[lines 311-312] These sentences should be moved to the paragraph where Figures 2 and 3 are described.

[line 329] I suggest renaming this section to "Surface mass balance"

[line 365] I suggest changing "controllers" to "external forcings"

[lines 365-371] This paragraph should be moved to the discussion. It can be combined with the existing text in Section 4.1.

[lines 380-382] Please add the start and end years that define each of these periods discussed in this sentence

[lines 383-384] Please add some discussion of this differences in air temperature from this study and what was shown by Hanna et al. (2021). Is this just the difference between Greenland-wide air temperature versus the trend in the southeast? Or is there a difference between the air temperature reconstructions for the same region?

[line 385] Please explain why this increase is seen as important. Was there a threshold crossed? Is it the largest observed increase in XX years? I also suggest mentioning the positive degree days in the contemporary period and discuss their behavior.

[lines 391-392] More discussion is needed to explain why the interpretation is that warming waters are responsible for glacier retreat, rather than rising air temperatures.

[line 400] Add the word "detail" following "more"

[lines 402-404] This sentence, which states that SMB is a driver of marine-terminating glacier change in recent years, seems like it contradicts the previous paragraph, which states that ocean temperature has been responsible for the retreat of these glaciers since the 1990s. I suggest combining the previous paragraph with this sentence and clarifying the interpretation of whether one or both drivers are responsible for frontal changes during various periods.

[line 405] Remove the hyphen between "local" and "heterogeneity"

[lines 430-438] This paragraph presents results rather than interpretation. I suggest moving this text from the discussion to the results section.

[line 430] Please specify: "2-3 times more retreat" ... more than what?

[line 453] Should "down" be changed to "due"?

[lines 439-441] The first sentence needs to be rephrased because I think it incorrectly presents the conclusions of Wood et al. (2021). In fact, the second sentence of this paragraph contradicts the first. I suggest replacing the first two sentences with the following: "Although the behavior of many of Greenland's marine-terminating glaciers has been speed up and mass loss as a consequence of warming ocean waters (Wood et al., 2021), there are glaciers that have exhibited small or no retreat."

[lines 439-455] This paragraph hypothesizes the response of glaciers in terms of dynamic thinning and links that to glacier ice speed and calving. However, I'm not clearly seeing the link. For example, it is stated that the eastern portion of glacier 15 is sitting on a shallower bed and has slower ice speed and, therefore, the terminus retreat is due to calving and there is less dynamic thinning. Why would calving-driven retreat and slower ice speed necessarily imply that there is relatively less dynamic thinning? This link needs to be explained in greater detail.

[line 443] I believe that "Glacier 15" should be replaced with "Glacier 14" here

## References

Bjørk, A. A., Kjær, K. H., Korsgaard, N. J., Khan, S. A., Kjeldsen, K. K., Andresen, C. S., et al. (2012). An aerial view of 80 years of climate-related glacier fluctuations in southeast Greenland. *Nature Geoscience*, 5(6), 427–432. <http://doi.org/10.1038/ngeo1481>

Carr, J. R., Stokes, C. R., & Vieli, A. (2017). Threefold increase in marine-terminating outlet glacier retreat rates across the Atlantic Arctic: 1992-2010. *Annals of Glaciology*, 58(74), 72–91. <http://doi.org/10.1017/aog.2017.3>

Catania, G. A., Stearns, L. A., Sutherland, D. A., Fried, M. J., Bartholomaeus, T. C., Morlighem, M., et al. (2018). Geometric Controls on Tidewater Glacier Retreat in Central Western Greenland. *Journal of Geophysical Research: Earth Surface*, 29(1), 1–15. <http://doi.org/10.1029/2017JF004499>