

Response to comments on “The terrestrial ice margin morphology in Kalaallit Nunaat (Greenland)” (essd-2025-2424) by Steiner et al.

Response to RC2 (Anders Björk):

The Steiner et al team deliver the first Greenland-wide quantification of land-, lake-, and marine-terminating margins and a spatial census of terrestrial margin morphologies for both GrIS and Greenlandic PGICs. This is a major accomplishment, and a very useful scientific contribution for numerous future process and change detection studies. The paper's immediate reproducibility makes it a foundational dataset and method for ice margin research in general.

This manuscript is clear, well-structured, and methodologically careful. The authors combine established datasets with sensible preprocessing, and a distribution-based slope classification, validated against Pléiades DEMs. Uncertainties and limitations are quantified and transparently handled, and all code/data are made available.

I really applaud the authors for doing this work and for taking the time to develop the method. I am confident, that it will be a method and procedure, which will be used on many datasets in the future, and provide critical knowledge and understanding of our ice margins and their changes.

Thank you very much for the constructive reading and encouraging response. We address all points raised comment by comment below.

I have one major point, which requires attention:

My major point of concern with the study in its current form is the use of the PROMICE ice mask (Citterio & Ahlstrøm, 2013). This particular outline represents a manually derived ice margin based on aerial photographs collected in the period 1978-1987, and not a year-2000 margin as the authors interpret. This discrepancy results in a potential large glacial retreat between the timing of the margin and the timing of the DEM used for the analysis. The authors do initiate a series of measures to counter the supposed offset from 2000-2012, but the actual offset in timing is much larger.

My concern is that too many cells have been excluded as a result of this, and only regions where retreat since the mid-1980s have been minimal are included. Under all circumstances, a 100 meter buffer from the 1980s margin, will many regions be inadequate as reported retreat rates are often in the order 5-20 meters / year. This concern is illustrated by figure 4d, where some of the excluded 1km grid cells, show a frontal retreat (between ice mask and DEM) of more than 500 m. Here most of the margin is excluded, and as a result, knowledge of ice margin slope of the rapid retreating ice margins are omitted.

There are a number of ways to go about this, but unfortunately I don't see any that does not require substantial extra work. There are newer datasets available that offer an ice margin, closer in time to the ArcticDEM. One option is "OpenLand" from the Danish Climate-data Agency. This outline is from 2017-21 <https://dataforsyningen.dk/data/4771>. Another option is a beta-dataset from GEUS – the new PROMICE-2022 ice mask, which is currently under review, but with data available <https://essd.copernicus.org/preprints/essd-2025-415/>, however this is only covering the ice sheet and not the PGICs. This could however be combined with one of the newer PGIC outlines like the Randolph Glacier Inventory which match closer in time to the ArcticDEM.

If the authors argue that the 1980s outline is sufficient, based on the extensive three step approach with visual inspections, I would like to see a more comprehensive analysis of the effects of the excluded ice margins: How much of the margin is visually inspected? What are the cut-off values for a cell to be discarded? What would be the effect of a different buffer size?

I would expect the excluded cells to be in the lower elevation parts of the terminating margins (the glacier front), which will skew the results more towards lateral margins, with potential substantial implications for the overall results and conclusions.

Thank you for pointing out the serious issue on the mask timing. Even more embarrassingly, the error made was here was going two ways. While we have initially used the PROMICE mask from the 1980s (as we were working with older Korsgaard DEMs, where the temporal overlap works well), the final mask we employed was the CCI product, that was published together with the product for PGICs (Rastner et al., 2012) and hence – with all its deficiencies – is also of comparable quality. We regret this lapse in the documentation of the data used. The advantage of the CCI mask is that it does align closer to the time step of the DEMs (having been produced from imagery between 1994 and 2004). This doesn't absolve us however of (a) the general issue of quality, (b) the mismatch especially around the termini of outlet glaciers (also those terminating on land) and (b) remaining temporal offset to the DEMs and the adequacy of the buffer. We appreciate your suggestion of the additional datasets, which we have now also considered to make the analysis more robust. Considering these aspects we would like to outline below how we address the issues raised more concretely:

- a) We understand the concern that a relatively small buffer removes many potentially interesting pixels, but we also found that an increased buffer (200 m, 500 m) makes the detection of the near-vertical sections increasingly difficult as they are often very short, result in then very few pixels and in the approach we chose are overshadowed by many shallow pixels on the ice. We now provide a sensitivity analysis and show this in a separate section of the methodology for well known sections of the margin. This naturally comes at a trade-off and is especially problematic when the margin isn't placed accurately and no ice at all is captured in the buffer. For this we have shown on 41 locations across Greenland (Supplementary Material) that this buffer works well. However, considering the restructuring of the manuscript, reducing the parts on the margin lengths and emphasizing the aspect of mapping the morphology, we have now expanded this both in scope and scrutiny, and place the discussion into the main manuscript, to have a more solid discussion of the uncertainty of the product. We now place 200 such profiles across the margin, randomly placed and extract the morphology. From this we determine the true positives, where the margin was obviously captured. We would also like to highlight that we do provide grid cells where the margin is obviously so misplaced that we do not calculate the morphology. We furthermore now emphasize in the manuscript that the margin morphology at outlet glacier termini needs to be handled with caution, due to its rapidly changing nature (see for example Figure 1). This introduces to some degree skewness you mention. We address this for the overall product by showing for each basin, where in the elevational distributions the mismatch is larger. This reduces the number of locations where we extract the morphology, with the current quality of the masks and us being reluctant to manually adjust it (which would hamper reproducibility in equal quality) we believe this is acceptable. We now also provide a more detailed discussion of the patterns of morphology across Greenland at the scale beyond small sections.

- b) We now also quantify the amount of margin that was visually inspected and deemed insufficient and provide a quantitative measure when this was done so (following the mask and imagery, with an obvious mismatch beyond 100 m).
- c) As noted, the outline we used does match the ArcticDEM more closely than the PROMICE outline from the 1980s, hence we believe the buffer chosen in general is acceptable. However, we agree that there are many cases when there is a mismatch. The suggestion of the alternative margin products has now prompted us to evaluate the differences and discuss the pros and cons of using one or the other, which like you also note, is in any case of essence as potential future iterations will definitely need to be carried out with a new margin mask. We believe that checking individual sites in such a large product is always somewhat problematic as a definite quality check and the perfect match is unlikely possible. Figures 1 to 3 show a couple of examples, where we superimpose all masks against the imagery from 2000. The SDFE data (the dataset you kindly suggested, i.e. from 2017-2021) seems to have excellent quality at many margins and would undoubtedly be the best temporal fit for the ArcticDEM. Unfortunately, it has also many missing sections and some glaciers seem to have been mapped rather randomly (see Figure 1 and Figure 3). Since its documentation is not available like for any of the other masks, we feel it may be unwise to use it for a product where future iterations are foreseen. The PROMICE 2022 dataset, still in review, is likely the currently best option for the ice sheet, but we are faced with the mismatch in time and the possibility that parts of the mask are within the actual ice sheet on the ArcticDEM and we lack the PGIC data. The CCI data obviously has many erroneous parts, but given the location with the buffering, congruent with the product we use for PGICs is in our eyes the most pragmatic and consistent choice. However, to quantify the sensitivity of this choice, we now extract morphologies with the different margins and show the ability to capture the margin on the DEM for sections of relative stability across all decades, as well as for lower regions of outlet glaciers that show more rapid changes.

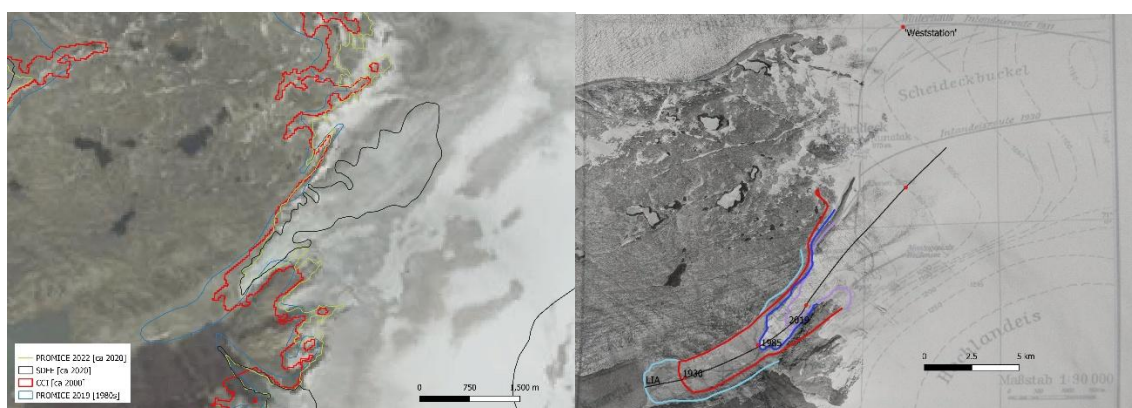


Figure 1: (left) The four available masks on a glacier in Western Greenland where a co-author carried out field research (imagery 2000). Note that the SDFE data is accurate at the lower margin, but only available for the tongue and no adjacent areas. (right) Same glacier with manual delineations, imagery (1980s)

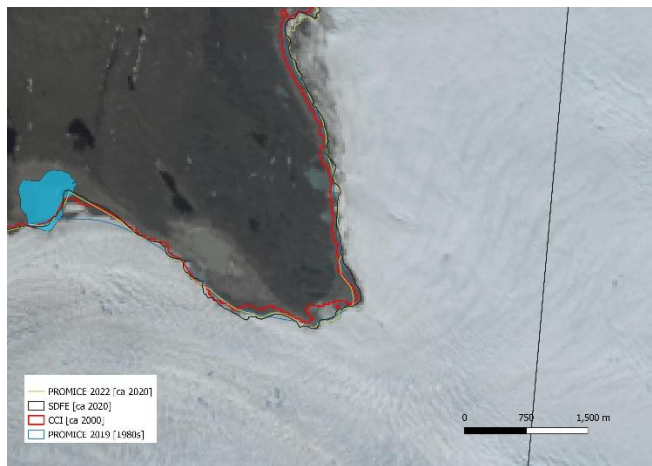


Figure 2: Margin section in central Western Greenland, showing sections of relatively close alignment for all margins, also suggesting relative stability. Imagery from 2000, which should match the CCI margin.

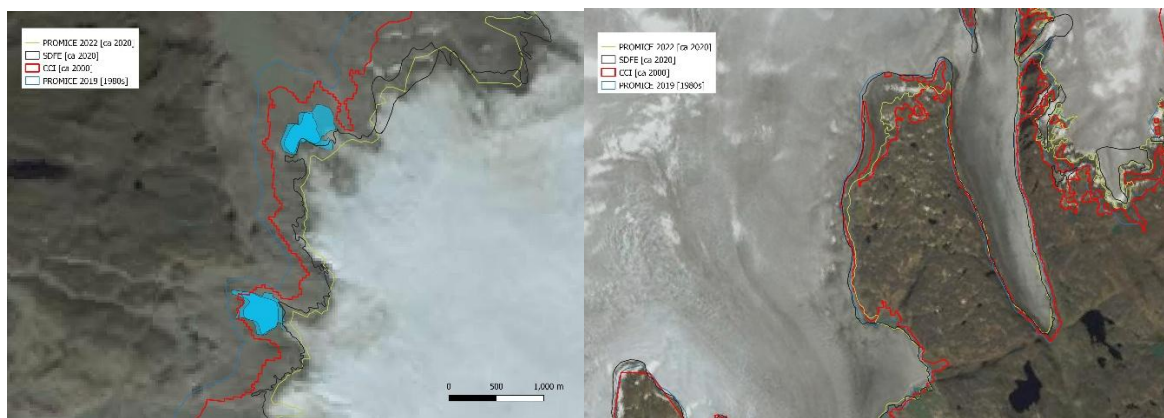


Figure 3: (left) Margin in western Greenland, where for some reason the CCI margin is especially off. (right) Margin in Eastern Greenland, where both the CCI but also the newest PROMICE 2022 product show artefacts where there is clearly no ice in the top center part, relatively good match for all products on the glacier tongue except for the lowest terminus and mismatch for the CCI product on the ice cap on the right. Note the SDFE margin only being available for some parts of the ice cap.

Many scientists would want such a study to also include change over time, and given the multitude of datasets available, it is indeed also possible, eg using the AeroDEM (Korsgaard et al, 2016) which corresponds exactly in time to the 1980s PROMICE-ice mask. However, I don't see it as a prerequisite for publishing this study. The work in itself, and the dataset, is sufficient to warren a major scientific contribution, and I am confident that several later change-studies will develop from this paper.

We absolutely agree with this sentiment but felt that for the amount of further methodology, this would have gone beyond the reasonable space here. Notably, it would require to treat the ArcticDEM product somewhat differently. We would need to take apart the DEMs according to their timesteps, which luckily is possible with the ArcticDEM dataset. However that would leave

us with only a subset of regions for the specific times (late 2000s/early 2010s vs early 2020s) as all of Greenland is not covered every time. It would then likely also require to use two different margins for these distinct steps, especially for faster changing regions. We believe that this is where now the new PROMICE 2022 becomes interesting. In response to reviewer 2, we have now also expanded the section on the analysis steps that can be taken with this product further down the line, and now also include this aspect there in more detail.