Dear reviewer,

Thank you for agreeing to review this manuscript and taking the time to provide general/specific/grammar/typo comments. Your comments certainly helped improve the manuscript and we hope our specific responses adequately address the comments/concerns. Detailed responses for each comment are below; black font is the original comment, blue text is the direct response to the comment, and red text is the updated and/or new text added to the manuscript.

Sincerely,

Dakota Pyles and co-authors

In this manuscript, Pyles and co-authors present a dataset of frontal ablation at Svalbard's tidewater glaciers. The dataset is comprehensive and highly resolved, and I expect it to be of great value to the science community. The manuscript is well written, detailed, and clearly illustrated with high-quality figures. I commend the authors on an overall enjoyable and insightful read! I have some minor recommendations and questions that I hope will improve the manuscript:

General comment:

The tone of language is at points -- in particular in the abstract and introduction -- a bit informal/florid or leans toward editorializing. Examples of this are: "...the manual labor cost inherent to mapping..." (L14) - manual labor is not strictly speaking inherent to mapping, so I would just simplify this to "...the manual labor cost of mapping..."; "...from the extensive ITS_LIVE velocity database, ..." (L 15), change to "from the ITS_LIVE velocity database, ..."; "unprecedented" (L19, L61) - I would just remove the word or replace with "high"; "is strongly recommended" (L 40) - reword?; I also recommend following the general guideline of avoiding the terms "novel" or "new" (the science should speak for itself, L 12 and 62). I would encourage the authors to go over the full text with this in mind.

We agree with the critique and have adjusted the example comments to less informal wording. However, regarding the usage of “unprecedented” and “new/novel”, this study is delivering an unprecedented dataset, in particular for Svalbard; to our knowledge, the previously best temporal resolution for a frontal ablation study was by Fahrner et al. (2025) at 3-monthly intervals and only for 49 glaciers on Greenland. Also, to our knowledge, this is the first study to use a deep learning segmentation model to map calving fronts for frontal ablation application and the described methodology is new/novel. While we understand letting the science speak for itself, we also think these new benchmarks should be acknowledged as such.

Specific comments:

L 44: the statement on "decadal timescales" appears in conflict with the L 48 statement on annual/seasonal resolution by Minowa et al and Fahrner et al - rephrase?

We split the paragraph into two smaller paragraphs, while updating some of the language to show that both long-term and shorter-term studies exist, both with limitations.

Though recent studies have computed frontal ablation of tidewater glaciers on regional extents (Kochtitzky et al., 2022b; Temme et al., 2025), the estimates are often calculated on multi-annual or decadal timescales, leaving a knowledge gap in the temporal evolution, and consequently, the process understanding of frontal ablation. The coarse temporal resolution is largely due to the demanding nature of frontal ablation computation. Ice discharge (velocity and thickness), climatic mass balance (CMB), and frontal area change datasets are required to fully resolve and partition the frontal ablation components. However, much of the data is difficult to obtain and aggregate on consistent spatio-temporal scales. Of the most time- and labor-intensive tasks, Kochtitzky et al. (2022b), McNabb et al. (2015), and Minowa et al. (2021) manually mapped ~4,500, >10,000, and 3,969 terminus positions, respectively, to estimate mass change at the terminus.

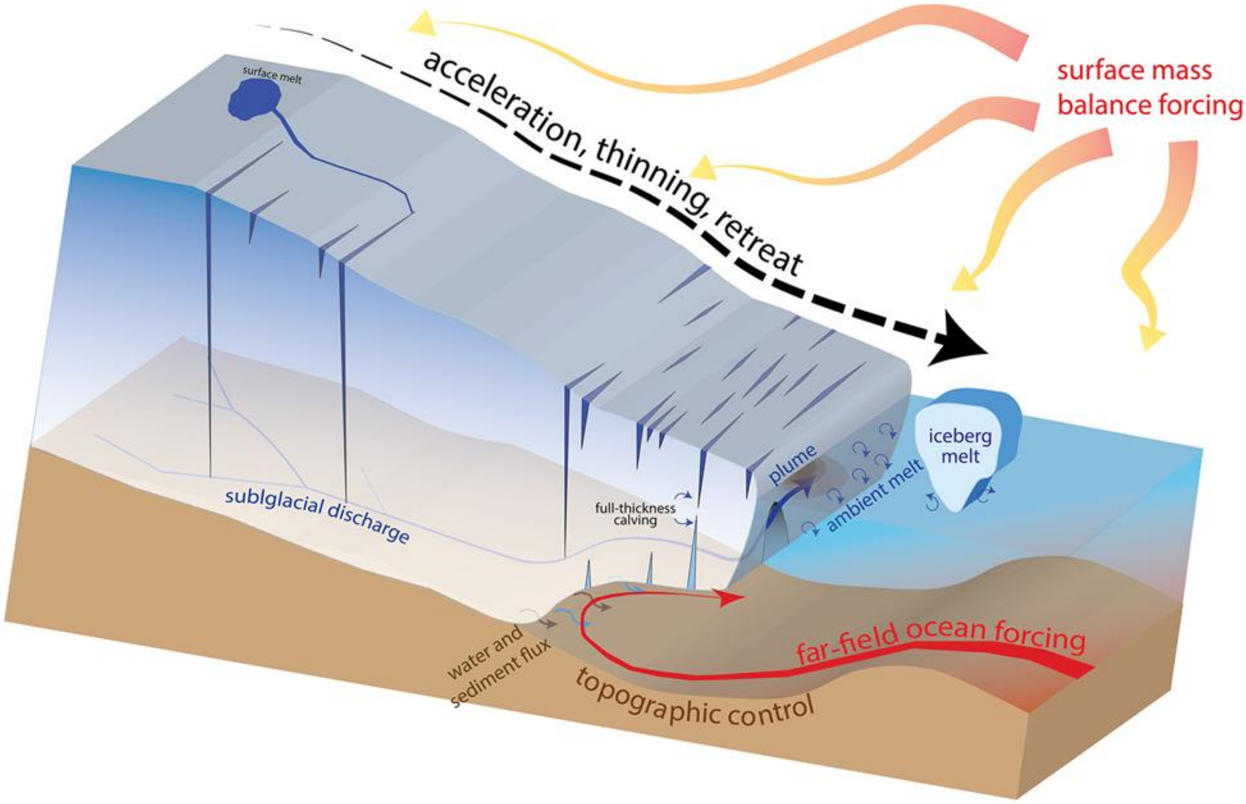
In contrast, several studies have achieved annual or seasonal frontal ablation estimates, each with different methodological or spatial limitations. While Osmanoğlu et al. (2013, 2014) provided annual frontal ablation analysis for King George Island and Livingston Island in the South Shetland Islands archipelago, they did not account for mass changes due to variations in the calving fronts. To our knowledge, McNabb et al. (2015), Minowa et al. (2021), and Fahrner et al. (2025) are the only regional scale studies that partitioned ice discharge and terminus mass changes at annual or seasonal resolution. However, each study calculated frontal ablation for only a subset of tidewater glaciers within its broader study region; McNabb et al. (2015) considered 27 Alaskan glaciers with large, active calving fronts and aggregated frontal ablation annually over 1985-2013, Minowa et al. (2021) derived annual estimates for 38 major glaciers in the Patagonia icefields between 2000-2019, and Fahrner et al. (2025) delivered a seasonal (3-monthly) frontal ablation dataset for 49 tidewater glaciers on the Greenland Ice Sheet from 1987-2020.

L 64: Could you clarify why you are not using the Li et al (2024) frontal positions for this study?

We already began working on this work before the study by Li et al. was published. In hindsight, we could have used the Li frontal positions, but this work was the culmination of a joint project with our colleagues (Dreier et al., 2025, 2026; explained in the sentence just before the line of this comment) who have been developing a DL segmentation model for this large-scale frontal ablation application within the structure/funding of the project.

Fig 2: While this figure is visually striking, I found it a little hard to interpret. I was trying to figure out which elements were schematic illustrations of the quantities used in the dataset, and which were artist's rendering/ aesthetic additions. I would urge the authors to simplify this and only include what is needed to make sense of the dataset/ processing chain.

We understand the concern; however, we received permission from Ginny Catania to use the base figure in her paper (Catania et al., 2020), which came with all of the artist renderings and aesthetic additions that may be unnecessary relative to our specific processing chain. Since the base figure already had these processes and annotations on it, we cannot reasonably remove them. For example, this was the base image provided in Catania et al. (2020):



Still, these additions/renderings are useful visualizations when viewing a tidewater glacier as a complete system with many of its processes that influence frontal ablation (i.e. surface melt, subglacial discharge, water and sediment fluxes, meltwater plumes, topographic controls, ocean forcing, ambient melt, etc.). This figure was not designed with the intent to show the particular processing chain we implemented, but rather show a relevant schematic of a tidewater glacier and its processes, along with an overview of the frontal ablation equation. This is why we added the fluxgate and two frontal positions, as well as the full equation and color-coded equation terms at their relevant spatial position on the figure. We hope this is understandable.

L 165: Could you clarify in the main text what the OpenStreetMap is used for?

We added a sentence in second paragraph of Sect. 3.1.3 about what the OpenStreetMap coastline is used for.

Before updating the termini, initial regional-scale zone labels are produced using the Svalbard coastline extracted from OpenStreetMap (OpenStreetMap Contributors, 2024); all non-ice area (from RGI v6) inland of the coastline is defined as land, while all area within a 10 km buffer of the coastline's convex hull is defined as ocean.

Fig 3: I found the overall layout of this Figure, with the different insets and zoom-ins somewhat confusing and was wondering whether it could be laid out slightly differently, or maybe panel a should be made its own figure?

The second reviewer also had some design suggestions for Figure 3 that we implemented to make the figure less confusing. Panels were reordered to put the Svalbard zone label map in panel “a” and we moved the Kronebreen processing to panel “b”. We also included the extent/context box of the

Kronebreen panel "b" in the larger Kongsfjorden panel "c" for easier interpretability. We decided to keep the former panel "a" in the figure because the former panel "c" heavily relies on it for a before/after processing visual comparison, rather than making panel "a" its own figure. We also reordered/adjusted the figure description, as well as in-text references to the figure's various panels.

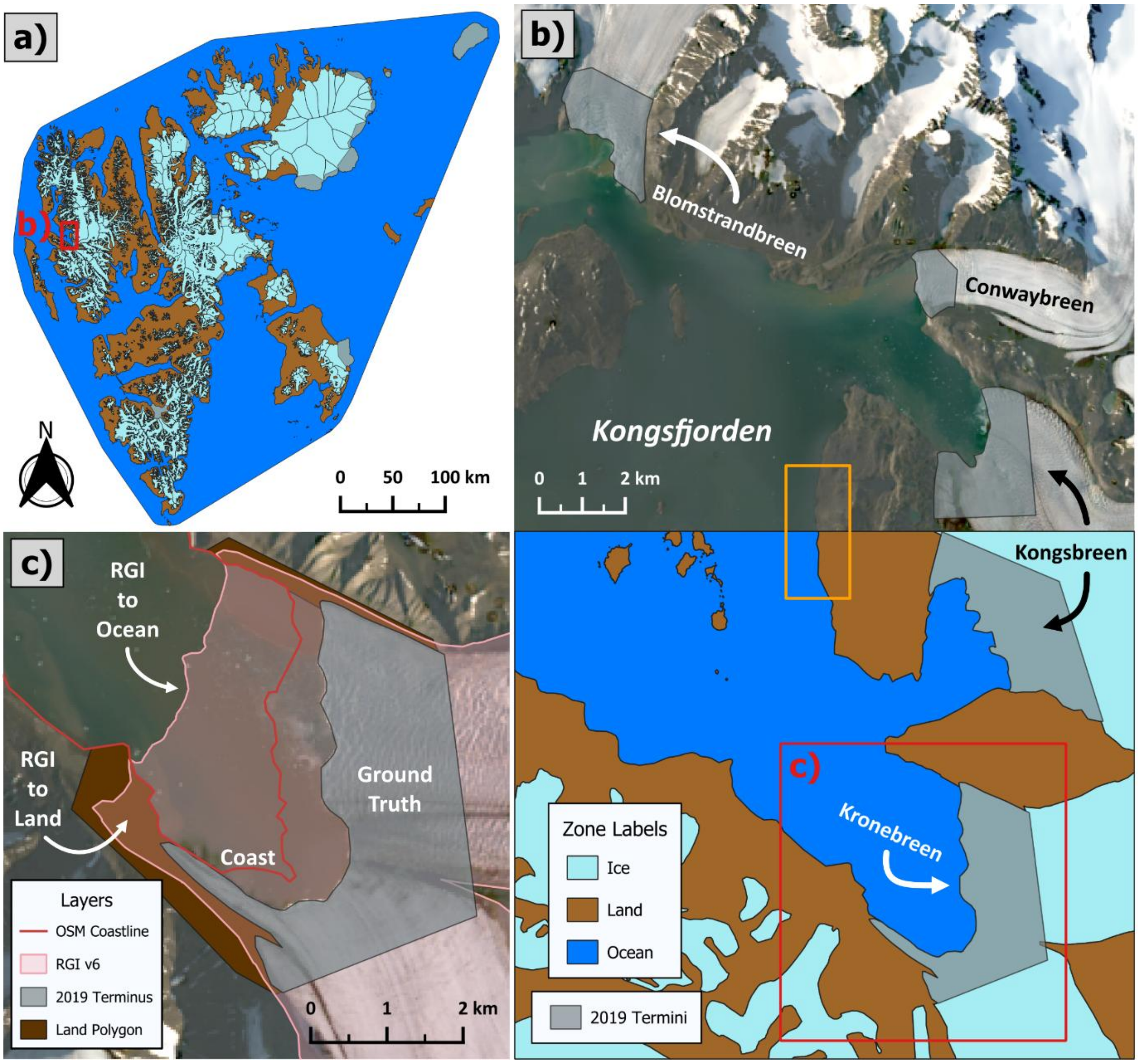


Figure 3. a) Full Svalbard regional extent of the updated ice, ocean, and land zone labels. A red inset map of the zoomed window in (b) focuses on the Kongsfjorden where Kronebreen (panel c) is located. **b)** Spatially contiguous top and bottom subpanels (see land-ocean area within orange box) of the Kongsfjorden and its four tidewater glaciers, showing zone label accuracy with respect to the reference optical image. The top panel shows the termini polygons manually delineated by Kochtitzky et al. (2022b) in 2019, with the Landsat-8 image (July 28, 2019) they used for front mapping plotted as background. Bottom panel is the resulting zone labels at the terminus after applying the layers and processing steps in (c); compare Kronebreen in panels (c) and (b) for a before/after example. **c)** An overview for updating the RGI v6 ice extent at the Kronebreen terminus to the ground truth front position mapped by Kochtitzky et al. (2022b), which results in updated ocean and land zone labels around the glacier outlet area. The OpenStreetMap coastline (© OpenStreetMap contributors, https://www.openstreetmap.org/copyright) provides a reference for maintaining the land-ocean interface during zone label updates, and assists in illustrating the enclosed RGI v6 areas (pink) that become land/ocean. The workflow is applied to all 147 tidewater glacier basins.

L 261: Is the smoothing of the polygon boundaries necessary beyond an aesthetic improvement? Would it be worthwhile to also provide the unsmoothed polygons in the dataset?

Beyond an aesthetic design choice, the smoothing of the polygon frontal boundaries produces a geometry that is more aligned with the shape of the extracted zero contour front lines (described in Sect. 3.1.5), which were also smoothed with a Savitzky-Golay filter. Therefore, the area of the polygons should be closely or closer optimized to the geometry of the smoothed, monthly-averaged calving fronts. We do acknowledge we could have kept all frontal information in raster format, however for consistency and nicer visualizations we made both the monthly calving fronts and polygon terminus boundaries with a more natural shape than the pixelated footprint of the segmentation prediction rasters. When optimizing the polygon smoothing to closely match the calving front shape, we also took care to pick smoothing thresholds/parameters that best preserved the polygon area of the rasterized version.

An additional consideration of smoothing the extracted calving fronts was that the “zig-zag” pixelated footprint of the raster artificially inflates the front length, compared to a more natural frontal geometry. The front length is important input to the frontal area change and uncertainty equations (i.e Eqs. 2 and 4). As explained above, the polygon boundaries are processed after the smoothed calving fronts and closely approximate the smoothing of the front lines.

L 340-375: I struggled a little to follow this argument; would it be worth adding a schematic to illustrate this process, or adjust Fig 7 to help with this?

We rewrote much of this section to be clearer and included a pop-out schematic to illustrate the process on panel (a) for an orientation point that is equal to 0.

The primary purpose of the orientation point is to define a consistent normal flow direction for each flux segment. To compute ice discharge through a flux segment, the sampled ice surface velocity is projected onto the selected segment normal. Because each flux segment has two possible perpendicular directions, the downstream flow direction is ambiguous. The orientation point resolves this ambiguity by consistently identifying the downstream side of the fluxgate. For each flux segment, the local tangent vector (m_{tan}) is computed as the difference between the segment’s midpoints. The tangent angle (θ_{tan}) is then calculated from this vector, and two normals $\left(n^{(+)}, n^{(-)}\right)$ are defined:

$$m_{tan} = m_2 - m_1 \tag{6a}$$

$$\theta_{tan} = atan2\left(m_{tan,y}, m_{tan,x}\right) \tag{6b}$$

$$n^{(+)} = \begin{pmatrix} -sin\theta_{tan} \\ cos\theta_{tan} \end{pmatrix}, \qquad n^{(-)} = \begin{pmatrix} sin\theta_{tan} \\ -cos\theta_{tan} \end{pmatrix} \tag{6c}$$

The orientation point defines an orientation vector (v_{orient}) between the orientation point (o) and the segment midpoint (m_{mid}). Depending on the orientation flag, the vector is directed either from the segment midpoint to the orientation point (orientation = 0) or from the orientation point to the segment midpoint (orientation = 1):

$$o = (x_o, y_o), \qquad m_{mid} = \frac{(m_1 + m_2)}{2} \tag{6d}$$

$$v_{orient} = \begin{cases} o - m_{mid}, & if\ orientation = 0 \\ m_{mid} - o, & if\ orientation = 1 \end{cases} \tag{6e}$$

The candidate normal (n) whose direction is most closely aligned with the orientation vector is then selected:

$$n = \underset{n^{(\pm)}}{argmax} \left(n^{(\pm)} \cdot v_{orient}\right) \tag{6f}$$

This ensures a consistent sign convention for ice discharge across all flux segments because the orientation point consistently identifies the downstream side of the fluxgate.

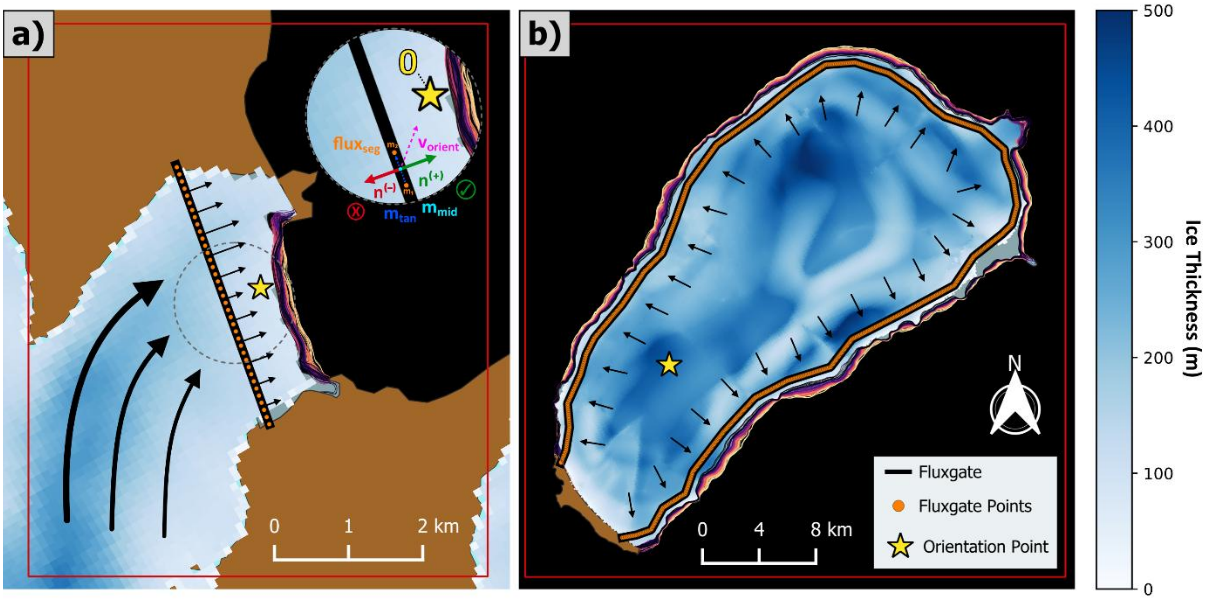


Figure 7. Fluxgates, flux points, and orientation point geometry styles. The fluxgate and orientation point are placed behind the most retreated terminus position. Thickness and velocity parameters are point-sampled at the flux points. Red outlines are the glaciers RGI boxes. Ice thickness data are derived from Fürst et al. (2018a). **a)** Fjord-style morphology where the orientation point equals 0 and is placed within the glacier domain, with ice flow towards the point. Large arrows represent possible flow directions to the fluxgate and small arrows show normal flow vectors perpendicular to flux segments. The pop-out schematic (within the dashed grey circle) illustrates an example of the normal orientation selection process, showing the accepted (green check) and rejected (red x) candidate normal directions for a single flux segment. **b)** The Kvitøyjøkulen ice cap representative of an island-style glacier with morphologically unconstrained flow and an orientation point of 1; ice flows away from the orientation point and toward the terminus (arrows).

L 386: It wasn't quite clear to me here whether you are using the Fuerst et al data or method here - could you please clarify?

We are using the bedrock topography map for Svalbard from Fürst et al. (2018a; i.e. the dataset) and differencing it from the Copernicus GLO-30 DEM to produce an ice thickness map. We also cited the two papers linked to the methodological development of their ice thickness methods (Fürst et al., 2017, 2018b) for additional context. As such, this description clearly states what is being used and cites the relevant studies:

An ice thickness map (H_{ref}) is generated for Svalbard by differencing the surface reference Copernicus GLO-30 Digital Elevation Model (DEM; European Space Agency and Airbus, 2022) from the ice-free bedrock topography of Svalbard (Fürst et al., 2017, 2018a, 2018b). Similarly, ice thickness uncertainties are obtained from the error map provided in Fürst et al. (2018a).

L 423: How do you handle days without a velocity measurement?

Days without a velocity simply are not problematic since we just take the mean of available daily velocity acquisitions per month. The analogous question is, how do we handle given months that don't have any daily velocity measurements, which we discuss in the supplementary material (Sect. S2).

L 460: Could you provide a short justification for using this reduced density of ice?

We added a short justification (air bubbles/porosity) within the sentence and from the original sentence the reference to Cuffey and Paterson (2010) is a commonly cited source for such a reduced ice density, as well as the sliding coefficient of 0.95.

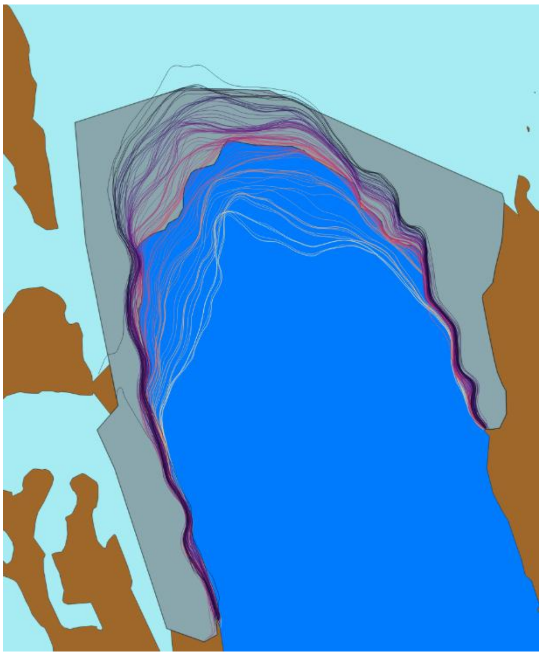
We assume a bulk ice density (p_{ice}) of 900 kg m^{-3} to account for the presence of air bubbles and porosity within glacier ice, and a sliding coefficient (γ) of 0.95 (Cuffey and Paterson, 2010) to account for depth-averaged velocity $(\bar{v})$, where $\bar{v} = v\gamma$.

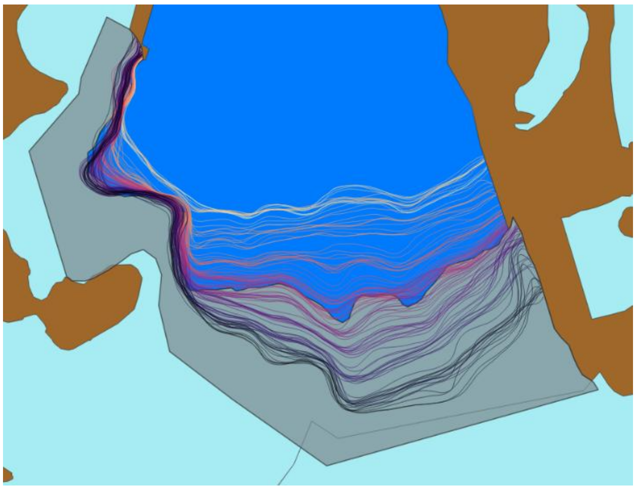
L 556: Are all the study polygons located in the ablation zone, in which case a negative CMB would be expected? Could you please comment on this?

The glacier domains are not explicitly defined as ablation zones but extend from the terminus to the inland fluxgate and therefore predominately sample the lower portions of each glacier. Although some domains may include accumulation-area ice, the mean monthly climatic mass balance is nevertheless negative for all 147 glacier domains over the 2015–2024 period.

L 571: The increase in tidewater termini length: might improved data coverage/quality over time contribute to this increase in the termini length? (Part of my question here is because I thought it a surprising finding - I would expect shortening of the termini as they retreat more onto land?)

The increase in combined tidewater glacier terminus length from 834 to 900 km over the study period is expected, albeit maybe counterintuitive, as you pointed out. Many of the glaciers exhibit strong localized retreat along their termini, often where the velocity is greatest and the ice is least stable and consequently calving frequently. Particularly for fjord style glaciers, the ice can remain attached to the fjord walls while the middle of the glacier is rapidly retreating; naturally this produces longer calving fronts. For a quick screenshot example, see the frontal evolution of these glaciers:





In the left image, the ice remained bounded to a constant position on both sides of the glacier, but heavily retreats in the center, creating a longer calving front. On the right image, the left end of the terminus stayed in a relatively constant position, compared to the right end which retreated along the fjord wall; still, the terminus length increased later in the study period (i.e. darker fronts).

Wording/Typos/Grammar etc:

L 27: "the ice-water-air interface" - these are actually (3) different interfaces; rephrase?

We rephrased this sentence to:

Glaciers terminating in bodies of water lose mass through frontal ablation at the ice-water and ice-air interfaces.

L 34: "total mass loss" -> "total ice loss" ?

Done.

L 80/89: The two sentences on diverse geometries feel repetitive and could be tightened?

We updated these sentences to be less repetitive, while retaining the motivation for using Svalbard as the study region. Also, we split the single large paragraph into two separate paragraphs when we begin to describe Svalbard's glaciers.

Svalbard's tidewater glaciers and outlet areas vary in size, shape, flow style, and setting. From the 151 tidewater glaciers distinguished in this study, 53 have a terminus length less than 2 km, 56 are between 2-5 km, and 42 are greater than 5 km. In total, ~900 km of terminus length was exposed to frontal ablation in 2024, an increase from ~835 km in 2015. The AF, BE, and KV subregions are distinguished by large ice cap style glaciers whose termini splay outward to the ocean, while the VF, NW, NE, and SS regions have more traditional fjord-style glaciers with constrained flow. Several glaciers are protected by natural land inlets or isles, while most have an unobstructed ocean interface. In addition, marine-terminating glaciers in Svalbard have historically exhibited surge-type behavior, particularly on the largest island, Spitsbergen (Błaszczyk et al., 2009; Dowdeswell et al., 1991; Farnsworth et al., 2016; Jiskoot et al., 1998; Szafraniec, 2020). Given the diverse glacier geometries, outlet areas, flow types, and observed behavior of Svalbard's marine-terminating glaciers, the region is an ideal test site for this frontal ablation pilot study.

L 129/134 and elsewhere: I was a little confused by the use of "inference" vs "prediction"? Are these terms referring to the same thing? If so, I would just use one of them, if not, maybe the difference could be clarified?

We understand why this can be confusing, especially as this is not a machine learning paper. Generally, inference refers to running the trained model on new data to produce outputs and the prediction is the output produced during inference. However, for simplicity, we opted to remove the four cases of "inference" in the paper and replaced the word with more accessible options such as: "to generate segmentation predictions", "when processing the imagery", "before generating predictions", etc. All occurrences in the manuscript have been fixed.

L 140: It may be worth spelling out "Randolph Glacier Inventory (RGI)" here, not just in the Fig 1 caption?

The other reviewer also had a comment about updating this section and clearly stating the RGI version being used. We updated the sentence to:

A critical step for processing frontal area changes is defining a consistent sampling geometry for each Randolph Glacier Inventory version 6 (RGI) basin that contains at least one marine-terminating glacier.

L 176: reword: "...the segmentation model, which is pre-trained ..." (?)

Done.

L 177: what do you mean by "unseen domain" ?

We updated the sentence to be clearer that Svalbard was the unseen domain (i.e. the model has never seen SAR images of Svalbard's tidewater glaciers):

To improve the performance of the segmentation model, which is pre-trained on calving fronts outside of Svalbard (Gourmelon et al., 2022), training data are developed for fine-tuning the model on the unseen Svalbard domain.

L 234: "consensus" seems maybe the wrong term?

We replaced "consensus" with "mean".

L 304: "Like the cross-sectional area definition, ..." -> I struggled to make sense of this wording - could be clarified?

Yes, this was a casual reference to the cross-sectional area that was defined a few sentences earlier. To make the reference/language more direct we updated the sentence to:

Consistent with the calculation of the cross-sectional area, the uncertainty $\left(\sigma_{S_g}\right)$ is estimated by summing the discrete ice column area errors for all flux segments across the fluxgate.

L 305: "We assume no uncertainty in the widths ..." -> rephrase: "We assume the uncertainty in the widths is small ..." (?)

Following the approach of Minowa et al. (2021) assuming uncertainty of the calving front to be within ±100 m and using a mean glacier front length of 5.84 km (defined as the 859 km decadal mean total front length, divided by the 147 glaciers), the average front width uncertainty may be estimated as ~1.7% (100 m / 5,840 m) of the front width. Compared to the relative frontal area change uncertainty (mean: 38%; median: 23%), which includes the propagated cross-sectional area and frontal displacement rate uncertainties (see Eq. 4), the contribution by potential front width uncertainty is relatively small and therefore we did not account for it.

We reordered the flow of text around this section describing the frontal area change uncertainty and updated the manuscript as follows:

Consistent with the calculation of the cross-sectional area, the uncertainty $\left(\sigma_{S_g}\right)$ is estimated by summing the discrete ice column area errors for all flux segments across the fluxgate. The frontal area change uncertainty $\left(\sigma_{A_{front}}\right)$ is then given by standard error propagation of products, assuming independent uncertainties:

$$\sigma_{A_{front}} = \frac{W_f}{W_g}\sqrt{\left(\dot{L}\sigma_{S_g}\right)^2 + \left(S_g\sigma_{\dot{L}}\right)^2} \quad (4)$$

As the fluxgate width is fixed to finite points along the gate (see Sect. 3.2.1), the width of the gate (W_g) has no uncertainty. Likewise, following the approach of Minowa et al. (2021), uncertainty in W_f has a negligible contribution (1.7%) compared to the other propagated components in Eq. 4 and is therefore not considered.

Fig 6a: Is the map inset needed here, since you have the same inset in panel b?

We updated Figure 6 to include only one inset map, north arrow, scalebar, etc. We also rearranged and slightly updated the figure description as such:

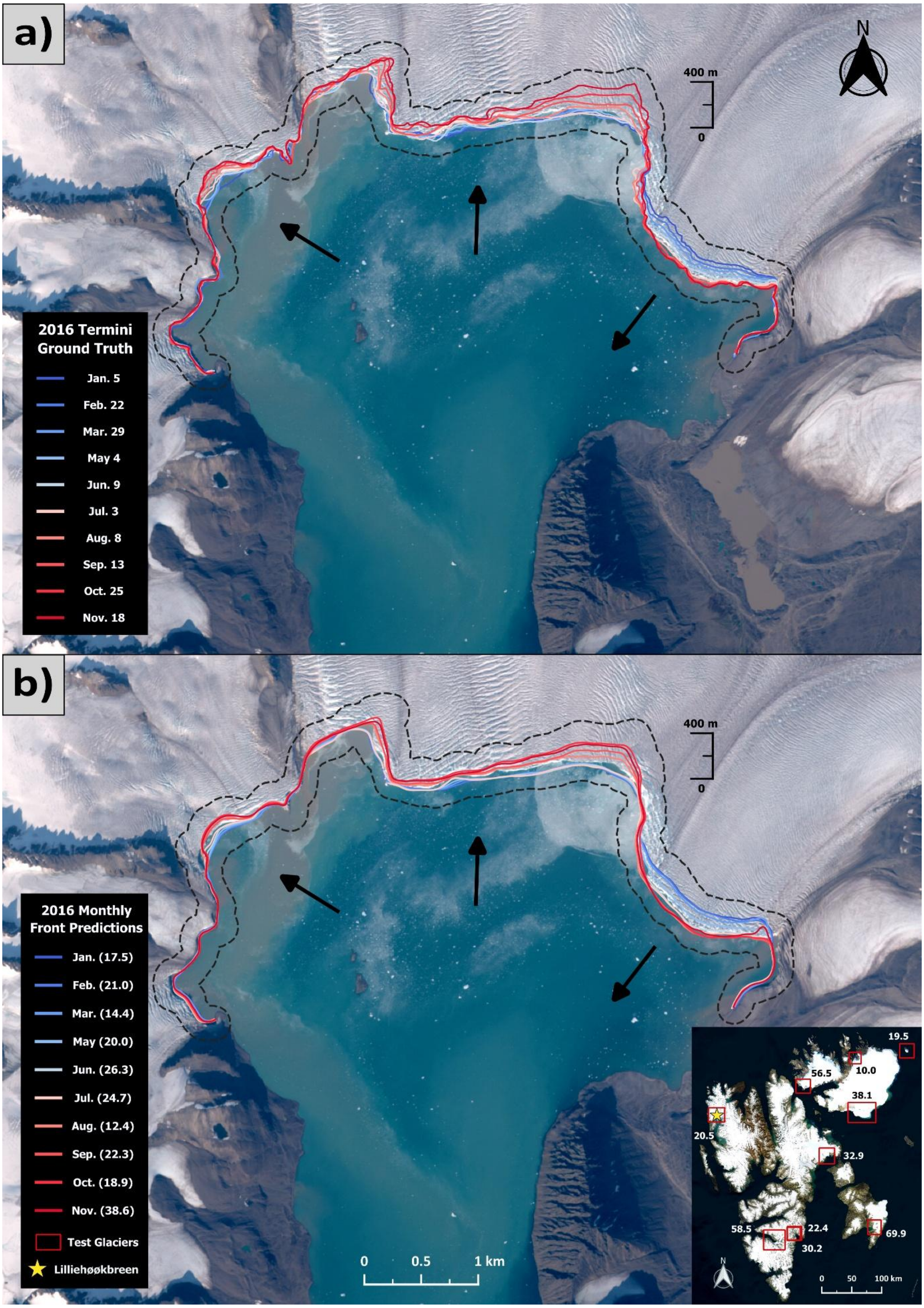
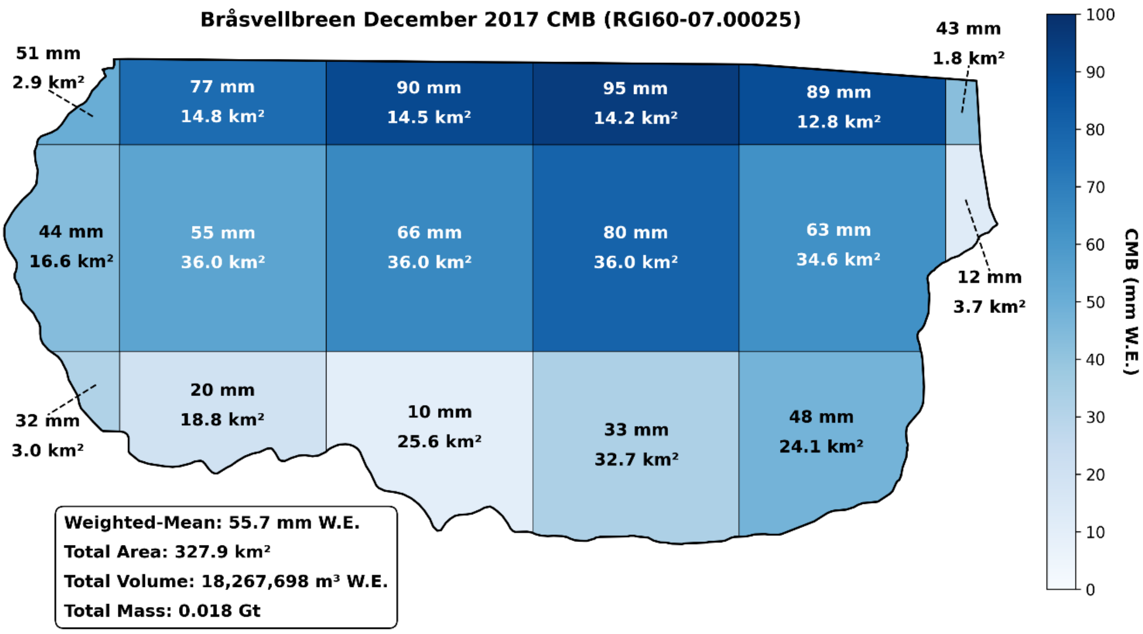


Figure 6. Background for both panels is a Sentinel-2 image obtained on August 2, 2016. **a)** Our 10 manually mapped terminus positions from SAR images at Lilliehøøkbreen glacier over the evaluation period in 2016. Arrows indicate a retreat over the year on the left and middle thirds of the glacier and

a frontal advance on the right third. The dashed black line provides a consistent visual reference for comparing the panels. **b)** The 10 monthly-averaged ice front model predictions, forming pairs with the ground truth positions by the corresponding month. The model captures the observed contrasting retreat/advance pattern during 2016. The width-averaged spatial uncertainty per pair is provided in meters in the legend. The inset map shows the geographic location of all glaciers included in the spatial uncertainty analysis, with the map background given by the Bing Satellite ©. Mean pair spatial uncertainties are annotated in meters on the inset map per testing glacier.

L 487: "m^3 W.E. (Fig. 8)" -> the figure legend gives the total mass in Gt rather than the volume in "m^3 W.E." - could this be made consistent or clarified?

We updated the figure to also include the volume in m^3 W.E. We initially only included the mass in Gt because that is the final value that comes from the CMB correction, after converting with the density of water and adjusting units from kg to Gt.



L 606: unit of Gt a^-1 (100 km)^-1 - as on L 608

Done.

L 655: remove "heavily" ?

Done.

L 663: reword: "mass loss due to frontal ablation *has* rapidly *increased* since 2000 ..."

Done.

L 696: "both *study* results"

Nice catch, and we agree the original grammar was not correct, but also the given suggestion is not the best option either; we reworded the sentence to this:

Though AF Basin 3 is the overwhelming contributor to frontal ablation mass loss in Svalbard, results from both studies, combined with our more recent decadal rate, suggest that the rate of mass loss is stable since the destabilization in 2012.

L 701: These values should be negative, to be consistent?

These values are correct to be written positive because at the beginning of Sect. 5.1 we wrote:

For consistency, we flip the signs of our frontal ablation rates, as equations were defined with contrasting sign in the studies.

The only cases where we have negative signs on values in this section is for terminus mass change, which can be negative (glacier retreat) or positive (glacier advance). The values that your comment is referencing are frontal ablation values from Kochtitzky et al. (2022b) and this study, both defined as positive for comparability.

L 734: "...and *its* implications..."

We chose to remove the “implications” part of the sentence and rewrote the sentence as:

We conclude by reflecting on the new methodological framework developed in this study and outlining recommendations for future studies to improve the process understanding of frontal ablation.