Reviewer 1

Thank you for your thorough, substantive, and constructive review of our manuscript. We appreciate the time you clearly put in to give thoughtful feedback to better the manuscript! Responses to your comments can be found in line below.

This study characterizes the melt and refreeze evolution across a portion of the Wrangell and St. Elias mountains. The study offers an interesting method to characterize various zones of dry firn, wet firn, and melt by assessing the variability in the delay of wet snow/firn refreeze (as detected from Sentinel-1 SAR backscatter) compared to the 0˚C isotherm (derived using temperature lapse rates from weather stations across the region). The study is compelling and seamlessly combines remote sensing observations with in-situ observations and insights from models. The paper is also written at a very high quality, was generally easy to follow, and enjoyable to read. However, I have some major reservations about some of the results, particularly the classification of the ablation zone, and limitations associated with the melt detection algorithm.

Main comments

The level of writing of this paper is very high (definitely sufficient for publication). Still, readability would be improved with the removal or vast reduction of acronyms (S1, S1A/B, AOI, VV, VH, SEB, PDD, PR, K/H, ELA), especially for non-technical readers. I would highly recommend writing these out in full. This is ultimately not crucial and up to the discretion of the authors. Note some other acronyms not mentioned that are probably okay to use: SAR, AWS, HOBO, DOY.

We have replaced the following:

- S1 > Sentinel-1
- S1A/B > Sentinel-1a and Sentinel-1b
- AOI > study domain
- VV > co-polarized
- VH > cross-polarized
- SEB > surface energy balance
- PDD > positive degree day
- K/H > Kaskawulsh/Hubbard
- ELA > equilibrium line/equilibrium line altitude

We chose to include the use of PR as the place name "PR Col" is used frequently enough to make Prospector-Russel unwieldy in reading.

The authors claim in the introduction and conclusion to be the first study to assess melt across the region, which is not true. Wells et al. (2026) also used Sentinel-1 SAR backscatter to produce melt onset time series for all glaciers >2 km2 in the region. It may be worth comparing these results in the supplement, which use the same -3 dB threshold from mean winter backscatter but for slightly different data (Wells et al. use cross-polarized SAR, this study uses co-polarized SAR) and slightly different onset elevation determination (Wells et al. use an 'all melt' threshold and hypsometric approach per-glacier, this study averages melt onset maps during elevation binning of all pixels in the study domain).

Apologies! We have altered our language and added appropriate citations of Wells et al. (2026). We also refocused our scope around firn hydrology, specifically focusing on dry firn and the dry-to-wet transition, so have not included a direct comparison.

My main concern regards the firn melt zone classification results (as shown in Fig. 7). The accumulation area of the glaciers in this region is roughly 50-55% (Zeller et al., 2025), but this study only maps the ablation area as 12% of the area. In turn, this means that nearly 90% of the glacierized area is some classification of a firn zone, with over 70% being either wet firn, dry to wet firn, or dry firn. The authors need to motivate the physical meaning or interpretation of the transition zones, as the "wet firn to ablation" zone almost certainly contains no firn in reality. For many glaciers in the region, the "wet firn" zone itself is delineated as covering the entire glacier.

This may be the result of processing at the study domain scale, as opposed to per-glacier. As such, melt signals are mixed and aggregated into bins that span different parts of glaciers, especially across the large range of climates (maritime/coastal and continental/interior) and elevations (0 to 5000+ m a.s.l.) within the domain. While this is a major limitation of the study, it may still be okay as long as the authors make it explicitly clear that these results should be interpreted only as a domain-wide estimate and not necessarily indicative of any particular glacier (the authors don't parse results for specific glaciers, but this could maybe still be explicitly stated). In this case, it also might make sense to remove the map in Fig. 7 and just show the zones in relation to the regional hypsometry to avoid misinterpretation of the results.

My other major concern arises from caution about the melt detection algorithm, particularly over heavy debris cover. Heavy debris can result in that portion of a glacier not exhibiting a clear melt signal. The current algorithm does not detect or identify these pixels as melting, and thus altogether excludes them from the analysis. This is clear from the maps D1-D7, where the terminus of Malaspina glacier, Logan glacier, Chitina glacier, and others (which are heavily debris covered) are never mapped in the melt onset and subsequent maps. The debris covered pixel behavior is also clear in cross-polarized SAR maps on, for example, Chitina glacier (https://alaskasnowlines.streamlit.app/plot_gif?name=Chitina&rgi_id=16307) and Logan glacier (https://alaskasnowlines.streamlit.app/plot_gif?name=Logan&rgi_id=16822), where the backscatter at the debris-covered terminus remains pretty much unchanged throughout time. In the study results, these parts of the glaciers are primarily the regions being mapped as "ablation area" or "wet firn to ablation zone", even though no melt onset/refreeze interpretations where made over these areas of the glacier to begin with. One way to get around this issue would be to use some sort of "all melt" threshold to account for these lower pixels that are in fact melting but are either debris-covered or generally below the snowline, but this would likely require transitioning to a per-glacier analysis, at least to develop the spatially-distributed melt onset maps.

Lastly, in Figure 7, there is an artifact resulting from plotting (hopefully it's just a cosmetic error!), the DEM, or the mapping algorithm. The glacier areas near the edges of the figure are colored as ablation zones, cutting through other parts of the glaciers in a non-physical way, even in some accumulation areas.

Thank you for bringing up these really valid concerns. We have made two fundamental changes to our firn zone analysis to address zone misclassification and issues related to debris cover: we have removed the wet firn, wet-to-ablation, and ablation zones from consideration, and we have moved to classifying dry firn and the dry-to-wet transition on a per glacier basis using glacier outlines from RGI version 7.0. Our updated text and figures can be found below:

Methods

We combine Sentinel-1-derived freeze-up dates, in situ air temperatures, and elevation data to identify regions where delayed firn freeze-up indicates a transition between dry and wet firn regimes. Since our focus here is on firn hydrologic regimes rather than surface melt production, we use the term "dry firn" to refer to firn that does not retain persistent liquid water, even if some surface melting occurs. We identify hydrologic transition zones between dry and wet firn based on the timing of SAR backscatter recovery relative to the annual onset of subfreezing air temperatures (∆freeze). Where liquid water is retained within the firn, the return to winter backscatter is delayed relative to atmospheric cooling, reflecting progressive refreezing and downward propagation of the freezing front through the firn column (Rau et al., 2000; Winsvold et al., 2018; Scher et al., 2021). Thus, larger ∆freeze values indicate greater persistence of liquid water within the firn.

We analyze ∆freeze values across elevation for individual glaciers within the study domain, as delineated by RGI version 7.0. For each glacier, we calculate the mean ∆freeze value within 50-m elevation bins, excluding glaciers that span less than 1000 m in elevation or are entirely below 2,500 m a.s.l.. We then calculate the elevation gradient of ∆freeze for each glacier. To reduce short-wavelength variability while preserving broader elevation-dependent patterns, we smooth the resulting gradients using a Savitzky–Golay filter (Savitzky and Golay, 1964) implemented through the savgol_filter function in the Python SciPy package (Virtanen et al., 2020).

We define the hydrologic transition zone as the contiguous region of negative ∆freeze gradients containing the greatest number of elevation bins on each glacier. Negative gradients indicate decreasing ∆freeze with elevation, representing a shift from lower-elevation regions with persistent liquid water retention toward higher-elevation regions characterized by earlier seasonal refreezing. The resulting firn-zone map therefore delineates spatially coherent zones of inferred hydrologic transition based on elevation-dependent variations in seasonal refreeze timing on a per-glacier basis. These zones represent changes in SAR-observed meltwater influence rather than direct observations of firn stratigraphy or classical melt facies.

Results

Based on the behavior of firn freeze-up across our study domain (Fig. C1), we find that 3% (702 km2) of the glacierized area in our study domain is in a dry firn zone, and 9%

(2,142 km2) is in a hydrologic transition zone (Fig. 6). We find hydrologic transition zones to be concentrated on the continental side of the range and/or on the flanks of high peaks, with hydrologic transition zones on the continental side tending to be higher in elevation than those closer to the coast (Fig. 7).

Discussion

Our results indicate that firn meltwater processes must be taken into account across both coastal and inland sectors of our study domain, and underscore the importance in continuing to develop robust and spatially distributed meltwater percolation models for use in alpine environments; liquid water plays a central role in shaping near-surface physical properties across the majority of Wrangell/St. Elias. In fact, areas of dry firn are restricted to the highest peaks in the region, accounting for only 3% of our study domain. The limited extent of dry firn has direct implications for the preservation of ice core paleoclimate archives, as meltwater percolation and refreezing in wet firn can disrupt stratigraphy and preclude ice core drilling. As a result, opportunities to recover regional ice core records in Wrangell/St. Elias are already limited (Holland et al., 2026), and are likely to diminish with ongoing atmospheric warming.

We find hydrologic transition zones to occur anywhere from 1,925 m a.s.l. to 4,225 m a.s.l., with the 10-90 percentile range being from 2,467–3,393 m a.s.l. (Fig. 7). The lower bounds of our hydrologic transition zones are characterized by high ∆freeze values that indicate the persistence of liquid water within the firn into the fall, consistent with in situ observations of a firn aquifer near the Kaskawulsh/Hubbard Divide at approximately 2,640 m a.s.l. (Ochwat et al., 2021). Note that a delay in summer-to-winter backscatter rebound (high ∆freeze) does not necessarily imply a firn aquifer; a similar backscatter response can be expected from percolation and delayed refreeze even if an aquifer never forms.

We define our hydrological transition zones as spatial transitions between higher areas of dry firn and lower areas of wet firn. However, we interpret these spatial transition zones as also reflecting a temporal transition: sites within these zones appear to be in the process of evolving from dry to increasingly wet firn states (e.g. increased percolation and delayed refreeze). This interpretation is supported by in situ observations and firn pack modeling at Eclipse Icefield (Fig. 1) which suggest the site is undergoing a temporal transition from a mostly dry firn pack to one that can and does support persistent liquid water into the fall and winter (Kindstedt et al., 2025). If wetting of the firn continues to the point of saturation, this transition could support the eventual development of a firn aquifer. Even barring aquifer development, continued firn wetting will alter firn column structure and the timing of seasonal discharge from firn at these elevations.

The method applied here is able to identify zones of hydrological transition; however, it does not provide information on other aspects of melt production and storage, such as melt season intensity, total melt production, or the partitioning of meltwater between storage in the snow/firn column and runoff. Such factors are necessary to quantify the contribution of surface melt to glacier mass balance and assess downstream hydrological impacts. Notably, the variability in ∆freeze between 3,000–3,400 m a.s.l. suggests variation in melt season intensity, total melt production, and/or meltwater transport without a corresponding shift in melt onset, underscoring that onset alone is not a sufficient descriptor of seasonal melt *dynamics. Nevertheless, in a region defined by pronounced seasonality, melt onset remains a valuable metric that establishes temporal context for subsequent melt, percolation, and refreezing processes. Future work should focus on the quantity and duration of meltwater retention in the firn, thereby enabling a more complete assessment of meltwater generation and its implications for both local glacier evolution and regional hydrology.*

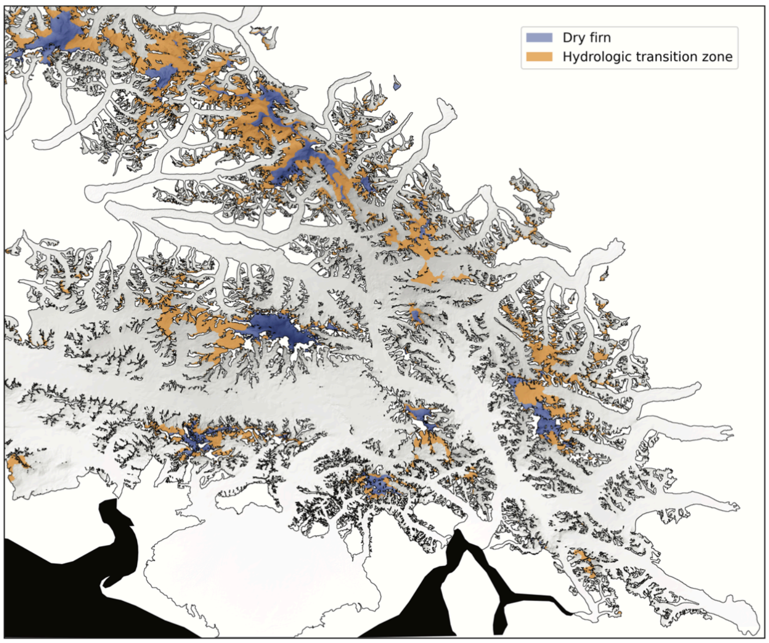


Figure 6. Hydrologic transition zones across the study area from 2018–2022 derived from Sentinel-1 freeze-up timing, air temperature, and elevation. Glacierized area are shown in hillshade overlain with dry firn (blue) and hydrologic transition zones (orange). The Gulf of Alaska is shown in black.

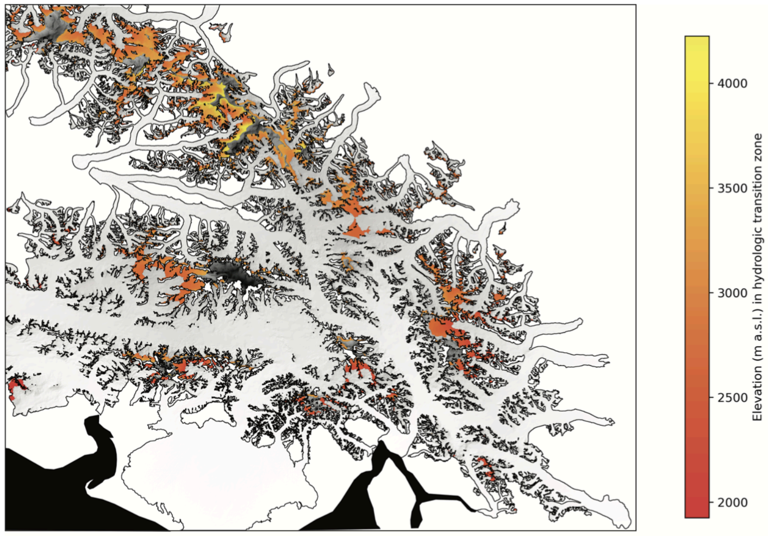


Figure 7. Elevation of hydrologic transition zones across the study area from 2018–2022 derived from Sentinel-1 freeze-up timing, air temperature, and elevation. Glacierized area are shown in hillshade overlain with hydrologic transition zones colored by elevation. The Gulf of Alaska is shown in black.

Specific comments (these are mostly suggestions)

L9: The way it's written, it almost sounds like one needs freeze-up timing, air temperature, and elevation to classify the dry firn zone. The dry firn zone should basically be the elevation above the melt extent. I'm curious if you compare the dry firn zone delineated from your method to the maximum melt extent/melting pixels that you detect (maybe with some threshold to avoid a few individual pixel outliers).

Rewritten to: *"We find that dry firn is confined to the highest elevations, covering only 3% of our area of interest"*

When we talk about dry firn, we are referring to firn that does not retain persistent liquid water, rather than snow/firn that never experiences surface melt. In fact, since we only calculate freeze-up and ∆freeze values for pixels that experienced melt onset, you can see in Fig C1 that parts of our dry firn zone do indeed experience melt. We have added the following language to Section 2.7 to clarify our use of "dry firn":

> *Since our focus here is on firn hydrologic regimes rather than surface melt production, we use the term "dry firn" to refer to firn that does not retain persistent liquid water, even if some surface melting occurs.*

There's also a very interesting study by Noël et al. (2018) that assesses past and ongoing changes in the firn structure of the Canadian arctic. This probably supports some of the statements you make in the introduction here.

Noel et al. (2018) has been added as a citation for relevant statements about firn warming, decreased pore space, and decreased meltwater buffering in the intro.

Fig. 1b: somewhere specify that you are only showing elevation of glacierized land. Maybe add a coastline to the map.
Done

I'm not sure how important the overall study domain area and percentage glacier cover is. Instead, it's more interesting to highlight foremost the amount of glacierized area itself and possibly the number and size of glaciers.

We do include the amount of glacierized area (29,190 km^2). We do not include the number/size of glaciers because our study domain is not defined based on glacier boundaries, so some glaciers are partially included.

L68: Remove 'dramatic'

Done

L77: I would similarly suggest writing 'co-polarization (VV)' and 'cross-polarization (VH)' to make this more readable to a non-technical audience.

Done

L83: possibly write: "...we only use path/frame from descending Sentinel-1 orbits, which are acquired before 10:00 local time, to eliminate biased … acquisitions (all scenes in our study area are acquired before 10:00 or after 18:00)."

Done

L95: Could you explain the rationale for using Nov-Mar scenes for the reference period? I think using Dec-Mar or Jan-Mar might make more sense given the slow refreeze of firn aquifers (especially, for example, on Donjek glacier). This would align with the statement on L227. To be clear, I don't think this needs to be re-done as I don't think this would make a difference in the results since the melt signal is so much larger than the refreeze signal, but I am curious about the rationale here. It *could* be worth showing a histogram of the difference between the mean winter backscatter from Nov-Mar compared to from Jan-Mar for one glacier or one path/frame.

Initially we were using Jan-Mar scenes for the reference period, but using Nov-Mar allowed us to analyze pixels that didn't have 4 Jan-Mar acquisitions (see plots in response to L110), and the mean winter backscatters were consistent across both methods for pixels with both.

L96: It could be worth mentioning that you may classify areas below the snowline where the surface is ice as ‘dry’ scenes despite the fact that they are melting. This logic is sound in accumulation areas or anywhere above the firn line.

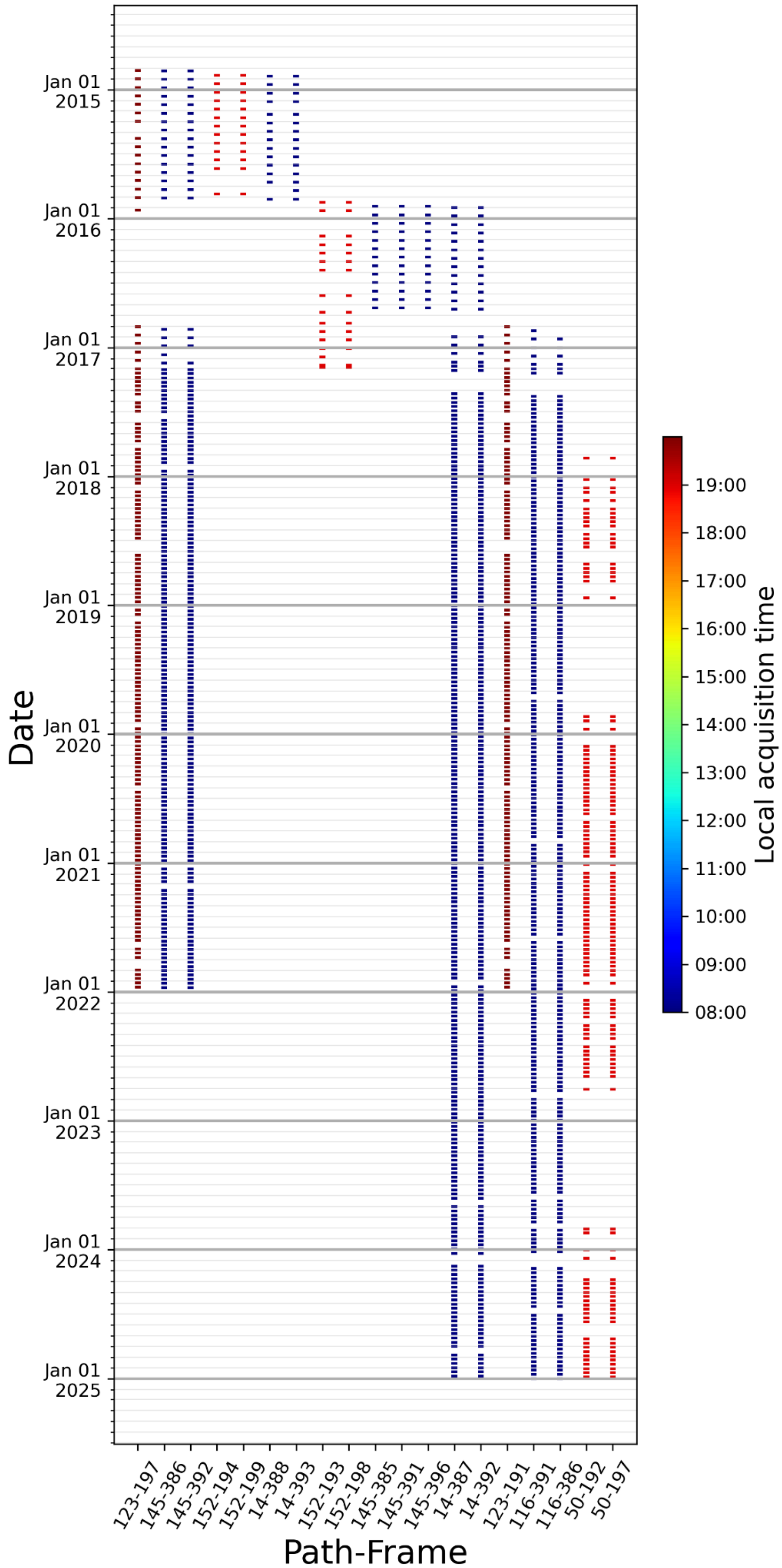
We have rewritten the section as follows:

> *The SAR-based melt detection method we use relies on the contrast between dry snow and melting snow backscatter values. Following Scher et al. (2021) and Nagler and Rott (2000), we use a timeseries of backscatter values from each pixel to classify that pixel as either dry or melting at the time of acquisition. A schematic of our melt classification method is shown in Figure 2. Because melt is identified individually for each pixel relative to its dry-snow backscatter value, we first produce a reference dry-snow image from at least four wintertime (Nov-Mar) scenes. Pixels are classified as melting when their backscatter value is ~3 dB lower than their dry-snow average; otherwise, pixels are classified as dry. Sentinel-1 can penetrate meters to tens of meters in dry snow (Baghdadi et al., 1997; Tsai et al., 2019), so our method is most reliable in the accumulation zone, where tens of meters of dry wintertime snow and firn can be found. However, limiting analysis to the accumulation zone requires some prior knowledge of where the equilibrium line altitude is, a feature which is itself difficult to identify. We therefore do not apply any elevation- or zone-based filters, instead taking local context into account during interpretation of our results.*
>
> *To establish melt onset each year, we identify the first of at least two consecutive melting scenes in each pixel's backscatter timeseries and set melt as the date of image acquisition. We consider the uncertainty in melt onset date to be the number of days passed since the last dry Sentinel-1 observation before onset. We exclude pixels where melt onset is identified to be later than day 244 (September 1 in non-leap years).*

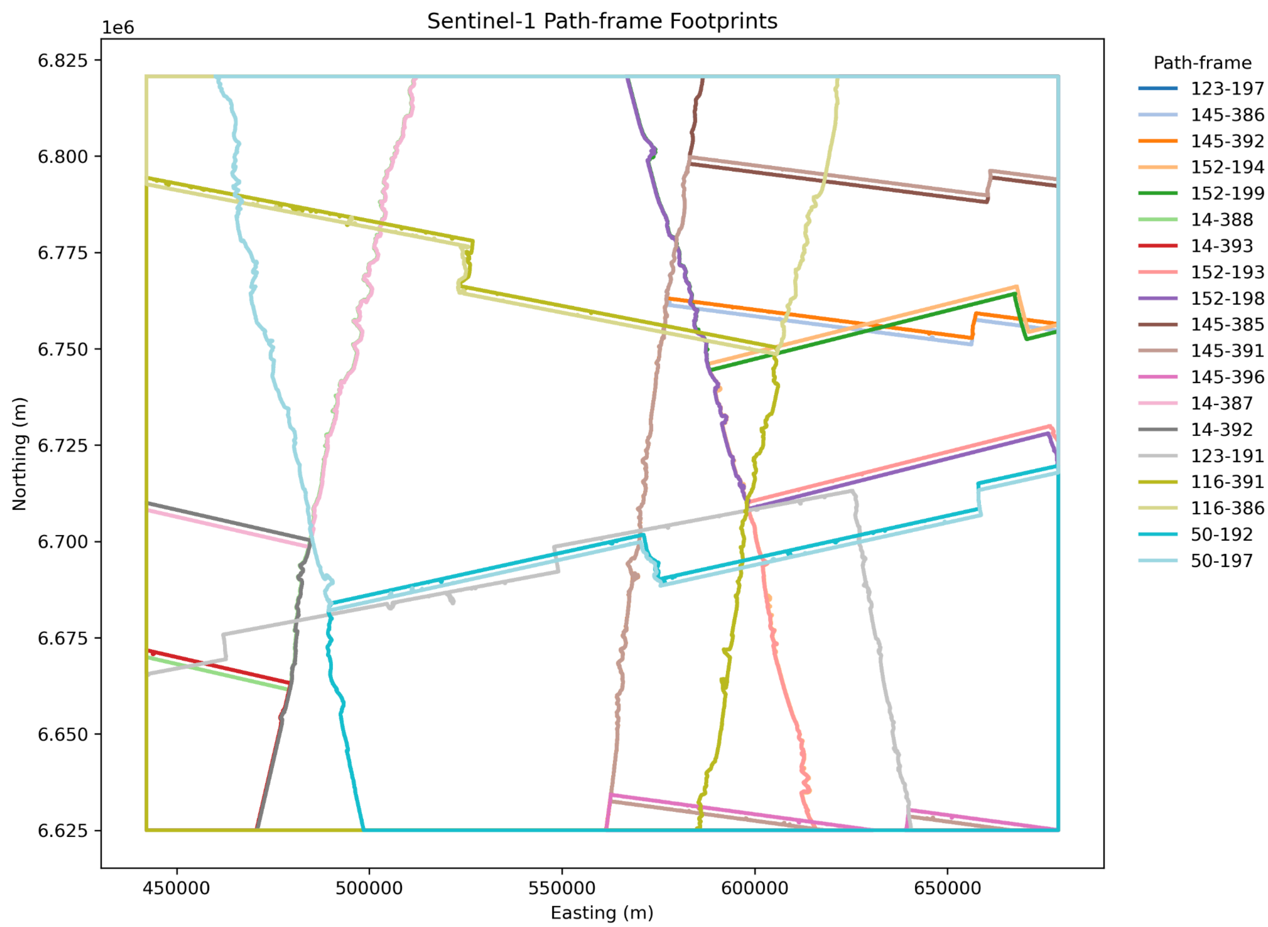
L105: I appreciate the clarity of what the backscatter signal physically indicates.

L110: I’m curious what the Sentinel-1 scene gaps look like (i.e., where you may have >12 days uncertainty in melt or refreeze dates). It would be interesting to plot a horizontal bar for each of the 6 path/frames from 2015-2024, with the bar shaded where scenes are available/used. It might be worth simply ignoring years without sufficient scenes (or, without sufficient scenes around the melt onset or refreeze time) for a given path/frame, instead of including this potentially biased result in the averaging of all years and prescribing a very high uncertainty.

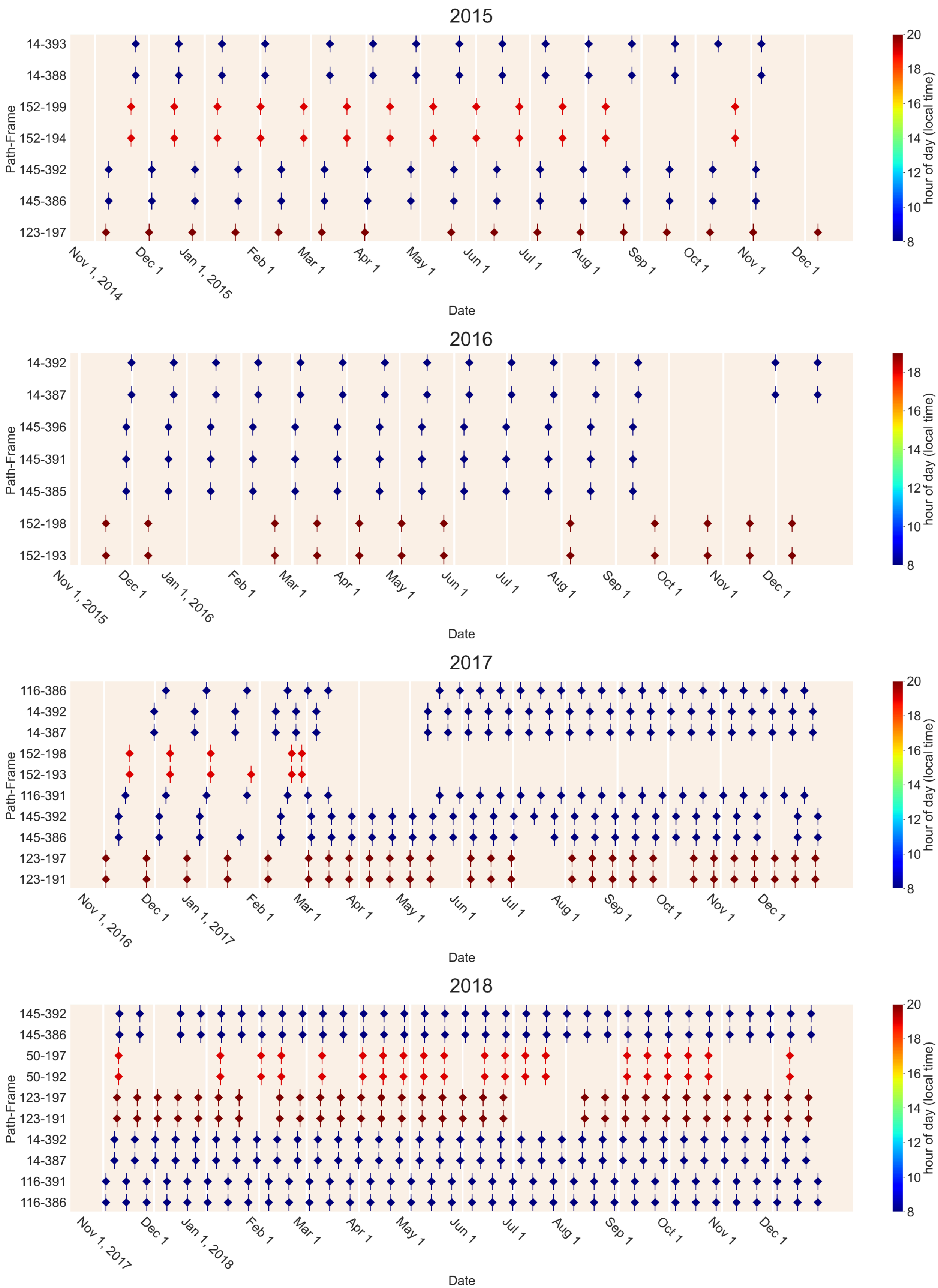
We’ve added the following two figures to Appendix A to increase transparency about both the spatial and temporal coverage of our Sentinel scenes:

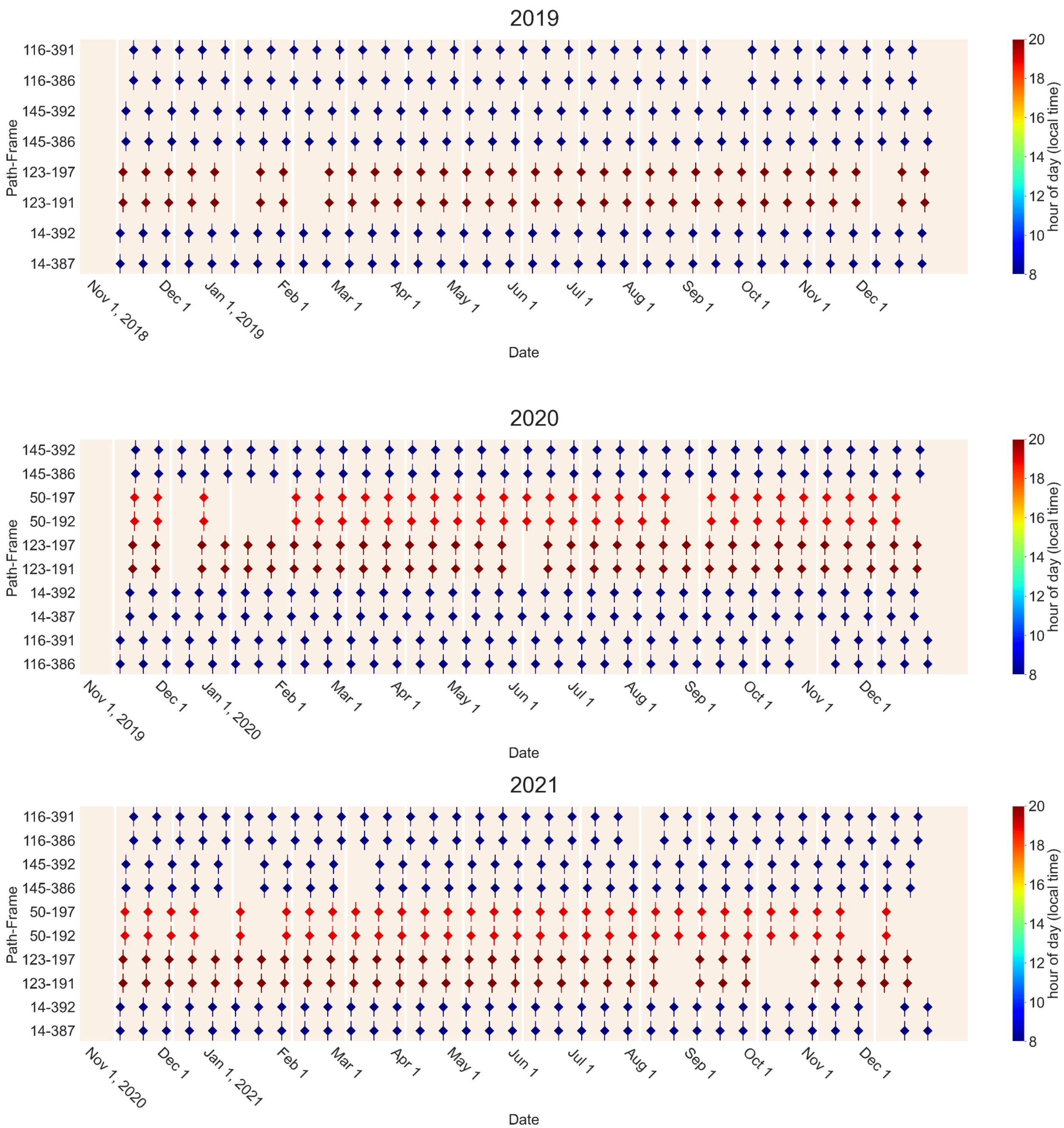


Date
Jan 01 2015
Jan 01 2016
Jan 01 2017
Jan 01 2018
Jan 01 2019
Jan 01 2020
Jan 01 2021
Jan 01 2022
Jan 01 2023
Jan 01 2024
Jan 01 2025
123-197
145-386
145-392
152-194
152-199
14-388
14-393
152-193
152-198
145-385
145-391
145-396
14-387
14-392
123-191
116-391
116-386
50-192
50-197
Path-Frame
Local acquisition time
19:00
18:00
17:00
16:00
15:00
14:00
13:00
12:00
11:00
10:00
09:00
08:00

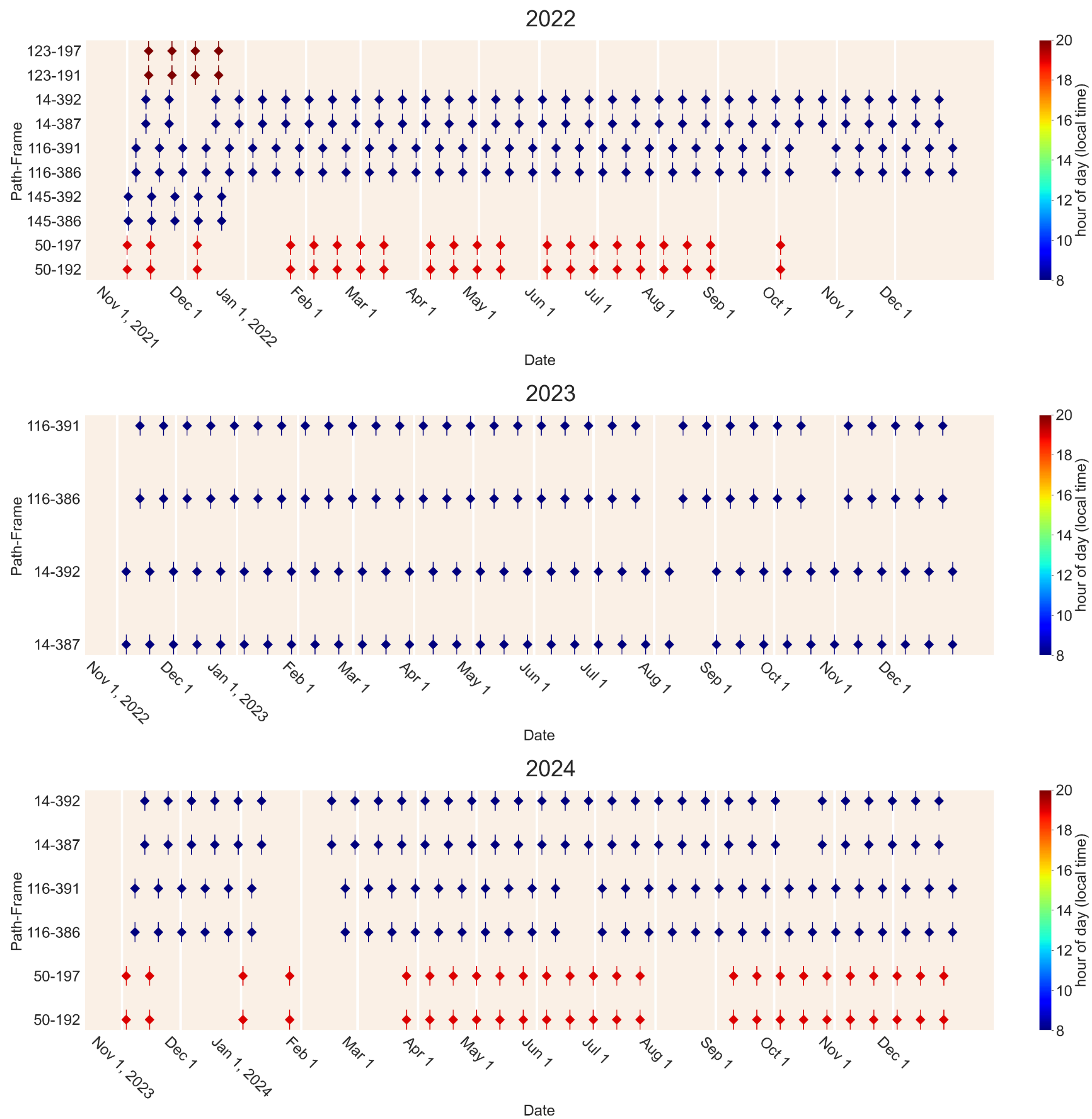


For your own benefit, here are temporal coverage plots for each individual year:


2015
14-393
14-388
152-199
152-194
145-392
145-386
123-197
Path-Frame
Nov 1, 2014
Dec 1
Jan 1, 2015
Feb 1
Mar 1
Apr 1
May 1
Jun 1
Jul 1
Aug 1
Sep 1
Oct 1
Nov 1
Dec 1
Date
hour of day (local time)
2016
14-392
14-387
145-396
145-391
145-385
152-198
152-193
Nov 1, 2015
Jan 1, 2016
2017
116-386
14-392
14-387
152-198
152-193
116-391
145-392
145-386
123-197
123-191
Nov 1, 2016
Jan 1, 2017
2018
145-392
145-386
50-197
50-192
123-197
123-191
14-392
14-387
116-391
116-386
Nov 1, 2017
Jan 1, 2018



2019
Path-Frame
116-391
116-386
145-392
145-386
123-197
123-191
14-392
14-387
Nov 1, 2018
Dec 1
Jan 1, 2019
Feb 1
Mar 1
Apr 1
May 1
Jun 1
Jul 1
Aug 1
Sep 1
Oct 1
Nov 1
Dec 1
Date
hour of day (local time)
20
18
16
14
12
10
8
2020
145-392
145-386
50-197
50-192
123-197
123-191
14-392
14-387
116-391
116-386
Nov 1, 2019
Jan 1, 2020
2021
116-391
116-386
145-392
145-386
50-197
50-192
123-197
123-191
14-392
14-387
Nov 1, 2020
Jan 1, 2021



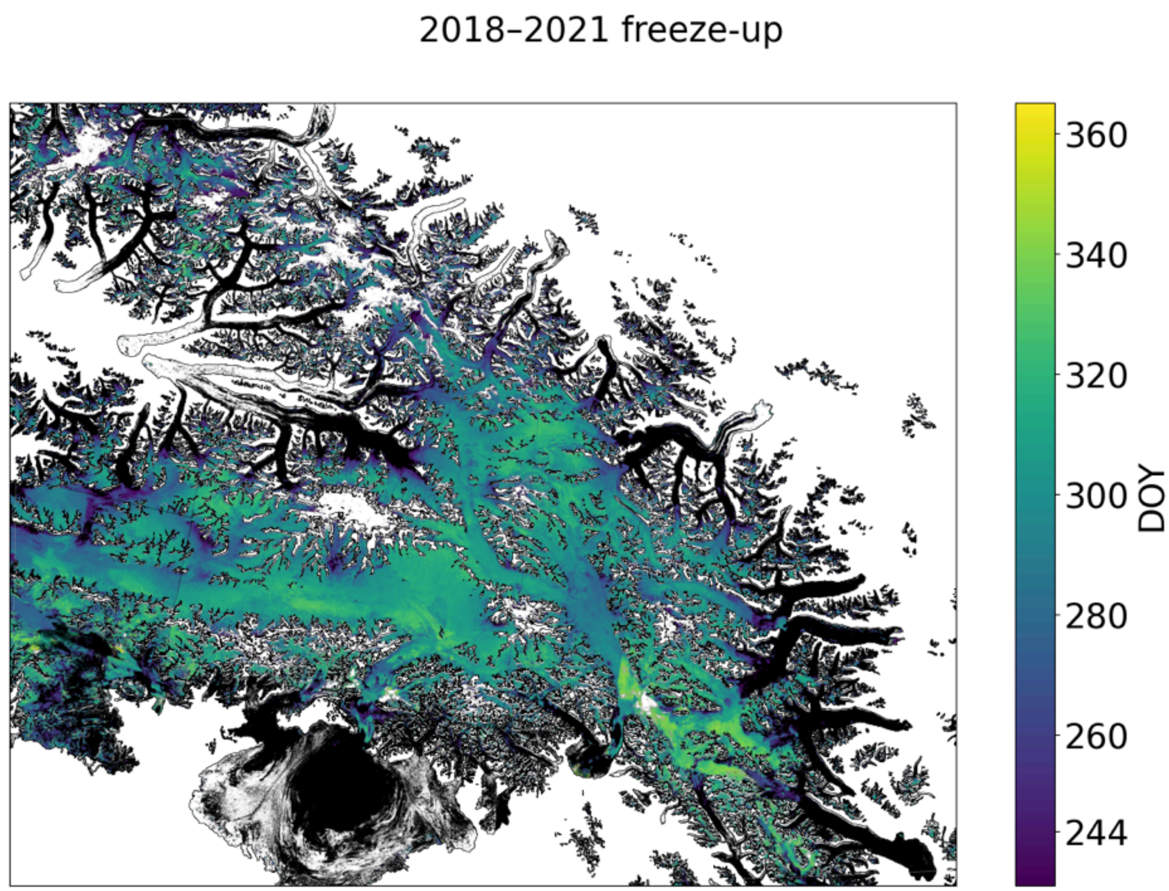
We did exclude years with large gaps (both spatial and temporal) in coverage in our averaging; that's why we report averages only for 2018-2021:

> *From 2018–2021 (years with >45% Sentinel-1 coverage over the glacierized portion of our study domain), we find melt onset across much of Wrangell/St. Elias to occur on average between day of year (DOY) 125 and 175 (approximately May 5th to June 25th, Fig. 3)*

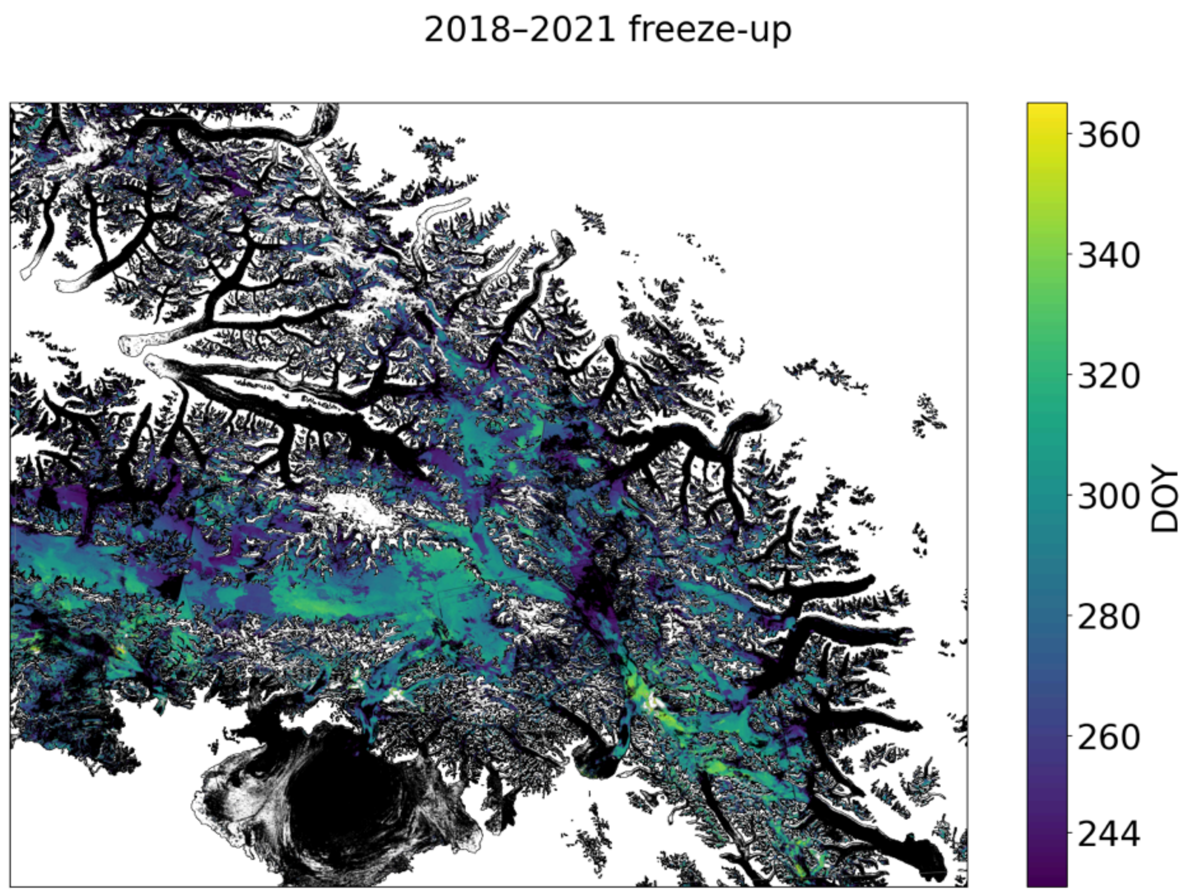
I'm also curious if you could use ascending scenes that pass in the evening to help get better resolution for the refreeze dates. While you mentioned this is biased and cannot be used for melt onset compared to the morning scenes, the slow, sub-surface refreezing process is not as susceptible to diurnal surface melt patterns. This could help give you better temporal resolution and extend the coverage of the middle of your area of interest to the earlier years without S1B data. This would at least be worth doing a quick investigation upon, to see if the refreeze dates from ascending scenes show systematic bias to the ascending scenes or not.

This is a good and interesting point that evening scenes may be valuable to use for freeze-up detection! Unfortunately, because of the way our freeze-up detection builds on our melt onset detection, we have been unable to incorporate evening scenes into our freeze-up detection without introducing artifacts and unrealistic early detection over much of our study domain, especially along frame boundaries. We agree though that this would be worth investigating in more detail in the future.

No evening scenes:



With evening scenes:



L115: Any reason why the scenes were not downloaded directly in dB scale?

When we were writing this part of the code, downloading in dB wasn't yet an option for ASF RTC processing.

L117: I would probably rephrase this as removing high-angle or very steep terrain.

Rephrased to: *"We remove steep (>30°) glacier slopes, which tend to have chaotic and changing ice surfaces…"*

L144: I would be curious to see what these lapse rates look like

We have added the following to Appendix B:

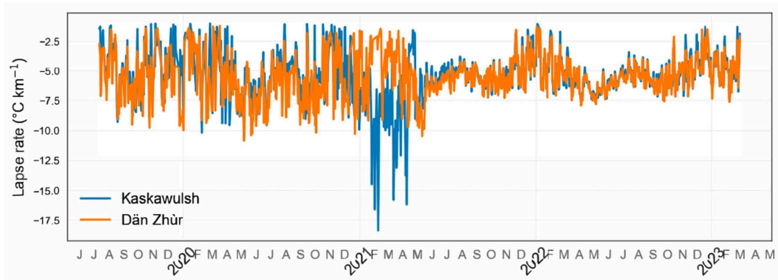


Figure B1. Lapse rates computed from Kaskawulsh and Dän Zhùr air temperature data over their period of overlap (July 2019 – February 2023). In situ data were used to calculate lapse rates. Station locations shown in Figure 1, and station information in Table 1.

L146: Very cool to see!

L150: I was initially a bit confused reading these definitions. The 'dry to wet firn' and 'wet firn to ablation zone' are simply transition zones between the other zones, but this list doesn't offer any insight into how these are classified or any additional physical intuition about these sites. I would perhaps rephrase the way this is brought up (e.g., something like, …we define 3 primary glacier zones and 2 transition zones which account for the complex nature of…), or define them more concretely like the other zones are.

This zone classification has been replaced with one of a smaller scope. See response to major comments above.

L161: "winter dry snow backscatter" is actually backscatter from ice, debris, or ice lenses in firn that is beneath the snow. I would just say "winter backscatter" since the SAR is not reflecting off of the dry snow itself. Can also probably remove the word "values".

Rephrased to: *"In areas where liquid water is retained within the firn, the return to winter backscatter is delayed…"*

We've also included the following in our discussion:

> *Below 1,400 m a.s.l., ∆freeze < 0 days, meaning winter firn conditions are reached before air temperatures drop below 0°C. In this case, winter conditions refer to dry snow underlain by bare ice rather than by dry firn.*

I'm also curious how you identify pixels that never have a SAR melt signal due to either heavy debris very low on the glacier or the 3% of dry firn zone.

We identify those pixels as any that do not show the characteristic backscatter drop.

L166: Nice–this adds a lot of useful context! Some mention of stable vs. transitional zones would have been useful before the listed zones because it was a bit confusing as someone unfamiliar with the study/method.

See response to L150

L170: Super cool. I would reorganize this and the following paragraph a bit to explain the vertical gradient calculation before explaining what a high/low vertical gradient means in terms of firn zone stability.

See response to L150

L171: Am I understanding the method correctly: you bin the Δfreeze into 100m elevations, and then do a 1D filtering on the elevation-dependent Δfreeze signal? Is the elevation binning and profiling done per glacier or for the entire study region at once? Does the elevation binning not already smooth the signal enough?

We've changed our scope and methods some (see response to L150), but you were understanding correctly!

L176: What does "bands <200 m thick" refer to? Is this referring to any detected firn melt zone that doesn't span at least 200 m elevation range?

This has been removed – see response to L150

Could temperate and cold firn play a role in some of these differences across the region? (not suggesting any changes, just curious about this)

Yes, I'd say whether firn is cold or temperate plays a role in determining whether it can sustain meltwater in liquid form, so it probably has an impact on differences we see in freeze-up. In what we're calling the dry-to-wet transition zone, I could certainly see variations in freeze-up timing and rate being linked to temperate vs cold firn.

Fig. 5: I like this figure a lot. Why not include 2023 for (b) and (c)?

2023 is not included in any of the panels because our in situ data for calculating Δmelt and Δfreeze only goes through February 2023.

L248: Outsized

Corrected

L254: This is very interesting to observe in the data–I'm glad you pointed it out.

L262: I appreciate the discussion here, particularly tying in some of the nuances and work from previous studies.

L283: Zeller et al. (2025) and Bevington and Menounos (2025) produce ELAs for basically all glaciers across the study area you assess. How do those compare with your mapped zones?

This would be interesting to compare, but is no longer relevant after narrowing our focus to dry firn and the dry-to-wet transition.

L284: Feels strange to spell out and specify 'ELA' here after using it so many times already.

This has been removed

L285 and Fig. 5: I'm a bit confused why the "freeze-up" is detected so late at low elevations. Many of the pixels at low elevations return to within 3 dB of the winter mean backscatter very early in the season, after the snowline has retreated above them. What prevents your algorithm from defining these as "dry" pixels after the snowline has retreated?

Good catch! Freeze-up at most of our low-elevation pixels *is* detected early in the season (Figs D1-D10, black areas return to dry conditions some time before Sep 1). But this didn't come across in Fig. 5 because of a relic line of code that excluded freeze-up days before DOY 244. This has been resolved! See the updated results text and Fig. 4 (previously Fig 5) below. Updated discussion text can be found in our response to major comments above.

Results

Freeze-up across much of Wrangell/St. Elias from 2018–2021 occurs on average between DOY 260 and 340 (approximately September 17th to December 6th, Fig. 3).

Freeze-up does not mirror the downward migration of the 0°C isotherm in the fall (Fig. 4). Below 1,400 m a.s.l., ∆freeze < 0 days, meaning winter firn conditions are reached before air temperatures drop below 0°C. ∆freeze increases with elevation until 2, 400 m a.s.l.. Freeze-up is most delayed relative to 0°C air temperatures between approximately 2,400 and 2,900 m a.s.l. (∆freeze > 100 days). ∆freeze decreases with elevation from 2,900 m a.s.l. to 3,500 m a.s.l.. Between 3,500 m a.s.l. and 5,000 m a.s.l., 25 < ∆freeze < 50 days.

When considered together across all elevations, our five terrain characteristics explain 25% of variability in freeze-up date, with an average prediction error of 24 days. Distance from ocean shows the greatest predictive capacity for freeze-up (negatively related) below 3,000 m a.s.l., while its importance is reduced relative to elevation and slope angle above 3,000 m a.s.l. (Fig. 5).

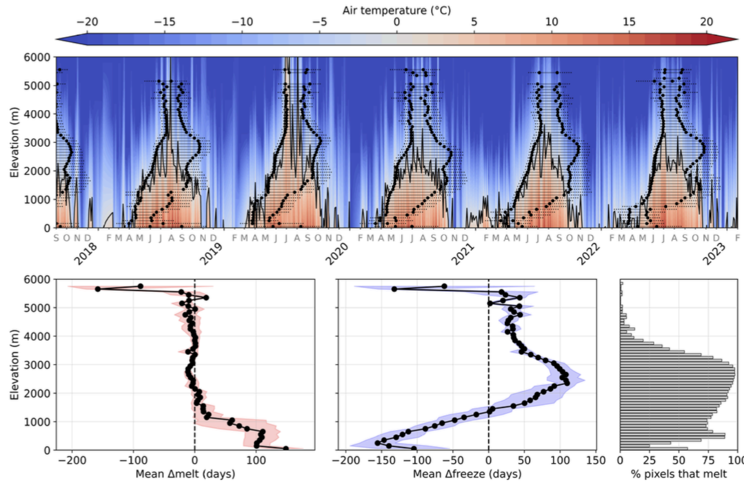


Figure 4. Mean melt onset and freeze-up relative to seasonal migration of the 0°C isotherm. Panel (a) shows melt onset and freeze-up dates (black solid circles) averaged over 100 m elevation bins plotted with spatially integrated air temperatures (colorbar). Air temperatures were estimated from lapse rates computed using data from five in situ stations ranging in elevation from 1,192–5,640 m a.s.l.. The black line represents the 0°C isotherm. Panel (b) shows the offset between Sentinel-1 melt onset and the DOY of 0°C air temperatures across elevation bands ($\Delta melt$). Panel (c) shows the offset between Sentinel-1 freeze-up and the DOY of 0°C air temperatures across elevation bands ($\Delta freeze$). $\Delta melt$ is averaged across 2018–2022. $\Delta freeze$ is averaged across 2017–2022. Standard deviations are shown by the shaded red (melt) and blue (freeze) envelopes. Panel (d) shows the percentage of pixels in each elevation band that melt.

References

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