Reviewer 2

Thank you for your very detailed review of our manuscript. Responses to your comments can be found in line below.

This study reports on firn melt dynamics using C-band SAR and modelled climate data.

General comments:

The manuscript is well written. More detail is required relating to some methods and results.

There are issues pertaining to the climate modelling and instrument data that needs to be addressed before the manuscript is acceptable for publication.

The interpretation of the SAR data is done with a climate model that requires work. There needs to be a rigorous definition of melt that is independent of the remote sensing used to detect melt. Snow and ice are biphasic and contain liquid water as a function of temperature. Is there other data that can independently verify the interpretation of the SAR data? The inclusion of optical albedo and surface infrared thermal satellite data would help with the interpretation.

Most of the validation data comes from the east side of the precipitation divide, but the parameters from these data are applied to the west side of the icefield that has much different temperature and precipitation characteristics. Your own statistical model indicates distance from the ocean is very important. Much more detail is required in understanding how the model choices and spatial heterogeneity of data influence this studies results.

Radiosonde and re-analysis should be consulted for lapse rate evaluation.

Detailed comments:

Many instances of undefined words need revision. For example, in the Abstract, “all elevations”, “mid-elevation”, “highest elevations”, “area of interest” are all undefined. Please review the manuscript the remainder of the manuscript for this issue. Examples include, “some regions” on line 21, “high annual snow accumulation” on line 45.

We have altered the language in the abstract (see below) to be more precise. We have left some instances in the manuscript body as is (including the examples given in the introduction), specifically where we are using summarizing statements, with specifics included in following text and/or citations.

> *High-elevation alpine firn is increasingly influenced by surface melt and meltwater retention, yet the spatial extent and timing of these processes remain poorly quantified. Here, we use*

surface melt onset and firn freeze-up dates derived from Sentinel-1 C-band Synthetic Aperture Radar data from 2015–2024 to map dry firn and hydrological transition zones, where firn is at a transition between dry and wet regimes, across the central Wrangell/St. Elias Mountains. Melt onset and freeze-up are identified from characteristic changes in backscatter associated with the presence of liquid water in snow and firn. Seasonal melt is detected across nearly all elevations in the range (0–5,670 m a.s.l.). Melt onset broadly tracks the seasonal rise of the 0°C isotherm up to ~3,000 m a.s.l., while freeze-up shows pronounced delays relative to subfreezing air temperatures at mid-elevations (2,000–3,000 m a.s.l.), indicating widespread meltwater retention within the firn. We find that dry firn covers only 3% of our study domain's glacierized area, while hydrologic transition zones cover 9% of our study domain's glacierized area. Our results highlight the pervasive influence of meltwater retention on firn hydrologic regimes in the Wrangell/St. Elias Mountains and demonstrate the utility of Sentinel-1 SAR for mapping firn water retention and monitoring changes in regional firn hydrology in data-sparse mountain regions.

The last sentence of the Abstract needs to better convey the importance of this work.

See above response

Line 28 – by climate records do you mean ice cores? There are many types of climate records.

Edited to "ice core climate records"

Line 30-32 – this sentence is obvious. It is unclear to me why this citation is necessary.

This is in response to past feedback requesting that we clarify the meaning of "cold content"

Line 44 – extensively is better than heavily.

Changed to extensively

Line 54 – Define what is "novel'.

This has been removed

Figure 1 – is there a representation of the precipitation divide that can be included on this figure? It appears the stations are all on the west side of the divide.

Unfortunately, we do not have a representation of the precipitation divide. We have, however, altered our analysis to identify dry firn and transition zones on a per-glacier basis to address the influence of different precipitation regimes on the east and west sides of the divide.

Line 94 – a pixel is a picture element on a computer screen. The resolution of the pixel is determined by the properties of the device and thus are variable across platforms. There are better descriptions of gridded remote sensing data, such as array element, grid cell, etc.

We agree that the classical definition of a pixel is a picture element on a computer screen. However, it is the commonly used term within the SAR community for the grid cells used in this application, so we use it for consistency.

Line 96 – is there a citation for the 3dB value. If not, a justification for its use is required. Reconcile the RS definition of melt to physical definition of melt.

We have added a citation for the 3 dB value. We have also altered the first sentence of the paragraph to explicitly distinguish direct measurement of liquid water from SAR backscatter detection:

> *Rather than directly measuring liquid water, the SAR-based melt detection method we use relies on the contrast between dry snow and melting snow backscatter values.*

Line 112 – there needs to be meta data included that documents the time of capture of the RS data. Any trend in time of capture or variation in time of capture can have unevaluated effect on the interpretations.

We address this in L84:

> *Additionally, we only use path/frame from descending Sentinel-1 orbits, which are acquired before 10:00 local time, to eliminate biased earlier melt detection for pixels with afternoon image acquisitions (all scenes in our study area are acquired before 10:00 or after 18:00). Sentinel-1 path/frames and scenes used in this study are provided in Appendix A.*

Line 116 – median filters will smooth data – what is the effect on detecting melt across spatial distributions?

We recognize median filters will smooth data. Smoothing the data is our intention to reduce the effects of speckling in our final melt onset maps.

Line 117 – How are slopes determined? If with a DEM then analysis is required to show how robust the method is. DEMs are notoriously inaccurate over snow and ice.

We have added the following comparison of slopes determined from the 30 m Copernicus DEM (what we use in this study) and slopes determined from the 10 m ArcticDEM downsampled to 30 m:

> *We also remove steep (<30°) glacier slopes, which tend to have chaotic and changing ice surfaces that are not conducive to SAR timeseries analysis (Shi and Dozier, 1995), using a*

mask based on the Randolph Glacier Inventory Version 7.0 (RGI 7.0 Consortium, 2023) and the Copernicus DEM (European Space Agency (ESA), 2014). To evaluate the sensitivity of the 30° slope threshold used in this analysis to our choice of DEM, we compared slopes derived from the 30 m Copernicus DEM with slopes derived from the 10 m ArcticDEM resampled to the same 30 m grid. The comparison was restricted to glacierized pixels where both DEMs contain valid data. Differences between slope fields showed no systematic bias (median difference = 0.0°; mean difference = 1.25°). Although localized differences occurred in areas of complex topography (RMSE = 7.07°; standard deviation = 6.96°), the two DEMs produced similar total areas of steep terrain. Areas classified as >30° slopes represented 21.5% of glacierized terrain using the Copernicus DEM (9,702 km2) and 23.8% using ArcticDEM (10,724 km2). Differences between the two classifications were limited to 6.2% of glacierized pixels, with ArcticDEM identifying a greater extent of steep terrain (+1,022 km2) relative to Copernicus.

Line 122 – Define physically meaningful - the sentence is difficult to interpret and confusing. How does the SD compare to a "drop" of 3dB? SD is a measure of variation around a central tendency.

We have altered the text as follows:

Pixels where the standard deviation of winter backscatter values is >3 dB (the established melt detection threshold) are excluded from analysis because a 3 dB drop in backscatter is not a deviation from the winter normal range in these areas

Figure 2 – increase font size.

Done

Section 2.6.

Provide background information on HOBO temperature loggers. Make, model, precision, integration, shielded, movement (x,y,z) over the study period, etc.

We have updated the caption for Table 1 as follows to include background information on the temperature loggers:

Ground-truth data used in this study. Locations of all stations are shown in Fig. 1. Air temperatures at Prospector-Russel Col were measured using a Vaisala HMP155 temperature sensor inside a solar radiation shield. The sensor experienced no movement over the study period. Sensor accuracy and technical data are available at https://docs.vaisala.com/v/u/B210752EN-K/en-US. The Kaskawulsh/Hubbard Divide AWS and Kaskawulsh equilibrium line AWS both used the HOBO S-THB-M002 Temperature/Relative Humidity Sensor (accuracy: ±0.21°C from 0° to 50°C; precision:±0.02°C from 0° to 50°C) mounted inside a HOBO RS3 Solar Radiation Shield.

Technical data are available at https://www.onsetcomp.com/sites/default/files/resources-documents/11427-O%20S-THB%20Manual.pdf. Neither of these sensors experienced any movement over the study period. All listed HOBO sensors refer to the HOBO U23-001A Pro v2 Temperature/Relative Humidity Data Logger (accuracy: ±0.25°C from -40 to 0°C, ±0.20°C from 0 to 70°C; precision: 0.04°C) mounted inside a HOBO RS1 Solar Radiation Shield. Technical data are available at https://www.onsetcomp.com/products/data-loggers/u23-001a. Listed HOBO sensors experienced horizontal (downglacier) movement of approx. 100 m per year and vertical movement of approximately -5 to -10 m per year.

The highest station is well below 6000 m, so not 0 – 6000 m. And the data records are of various lengths, with PR-Col being the shortest. The lapse rates will be of various heights depending on the lengths of the data records. There are going to be calibration issues related to the PR-Col station that need to be discussed. Typically radiometric instruments need to be calibrated every two years. Explain/discuss.

We have corrected the elevation range to 0 – 5640 m. The PR Col station covers less than two years time, so calibration is not a major concern for the dataset. We have altered the text to clarify the use of the short PR Col station:

To track the 0°C isotherm, we first calculate daily regional lapse rates (Fig. B1) from 0 to 5,640 m a.s.l. using temperature data from three HOBO sensors (Kaskawulsh Lower, Kaskawulsh Middle, Kaskawulsh Upper) and two AWS (Kaskawulsh/Hubbard Divide and Prospector-Russell Col). We use the Kaskawulsh Upper HOBO data rather than the nearby (within 100 m elevation) Kaskawulsh equilibrium line AWS data because the HOBO sensor is located on glacier ice while the AWS is located on a bedrock nunatak, and the HOBO sensor provides more recent data (Table 1). We select the series of stations going from the lower Kaskawulsh Glacier to Prospector-Russell (PR) Col for its spatial coverage over nearly the entirety of the elevation range within our study domain, and because its temporal coverage began nearly two years earlier than measurements on the nearby Dän Zhùr Glacier (Fig. 1). Note that the PR Col temperature record only covers the time from April 2021 through February 2023; lapse rates outside of this period only utilize data from 0 to 2,603 m a.s.l.. We perform a least squares linear regression on overlapping mean daily temperature values from all five selected stations (August 2017 – February 2023). Finally, we use the resultant daily lapse rates to compute isotherms at 2°C intervals from -20°C to 20°C for comparison with our melt onset and freeze-up results. A comparison of isotherms computed from Kaskawulsh vs. Dän Zhùr data over their period of overlap (July 2019 – February
150 2023) is provided in Appendix B.

Table 1: Add months to the Time period covered field.

Done

Lines 150-154 – What are the criteria for these classifications?

The classification process if detailed in L157-184

Line 167 – “transitional” should not be a quote.

The quotes have been removed

Line 171 – citation for filter and usage?

Edited to: *To reduce short-wavelength variability while preserving vertical gradients, we apply a Savitzky–Golay smoothing filter (Savitzky and Golay, 1964) using the savgol_filter function in the Python SciPy package (Virtanen et al., 2020).*

Section 2.8:

This section requires a substantial amount of work. To gain a better understanding of the factors that influence glacier melt models I suggest you read some papers found here: https://scholar.google.com/citations?user=86dWcwkAAAAJ&hl=en

We agree that a more complete treatment of surface energy balance processes, particularly albedo and longwave radiation parameterizations, would be required for a predictive melt model. However, the objective of the energy balance calculation presented here is not to develop a comprehensive glacier melt model, but rather to evaluate whether melt under below-freezing air temperatures is physically plausible given observed meteorological conditions. We have revised the text to clarify this distinction:

> *To compare the relative contributions of radiative and turbulent fluxes to the surface energy balance across elevations, we apply the surface energy balance model of Matthews et al. (2020), previously developed for a similar glacierized alpine environment in the Himalaya, to AWS data from three sites: PR Col (5,640 m a.s.l.), the Kaskawulsh/Hubbard Divide (2,603 m a.s.l.), and the Kaskawulsh equilibrium line (1,800 m a.s.l.; Fig. 1; Table 1). Our surface energy balance modeling is not intended to predict or reproduce observed melt rates, but rather to evaluate the physical plausibility of melt occurring during periods of below-freezing air temperatures. The model is used as a first-order physical constraint: if available energy is sufficient to produce melt despite sub-zero air temperatures, this supports the interpretation that air temperature alone is insufficient to determine melt occurrence in high-elevation glacier environments. Therefore, simplified parameterizations are used to estimate whether the net surface energy balance can become positive under observed meteorological conditions. This approach is appropriate for identifying whether melt is energetically possible, while recognizing that uncertainties in albedo, cloud radiative effects, and atmospheric emissivity introduce uncertainty into the magnitude of calculated melt energy.*

Incoming shortwave radiation is measured directly at all three AWS sites and combined with a prescribed constant albedo of 0.8 (old, clean, dry snow; Cuffey and Paterson, 2010), applied uniformly across sites and time, to calculate ES . Although snow surface albedo can vary widely (0.5–0.98; Cuffey and Paterson, 2010), higher elevations are generally characterized by dry, minimally metamorphosed snow and thus higher albedo. As a result, our estimates of the relative contribution of shortwave radiation to surface energy balance at PR Col compared to the lower sites are likely conservative. The effects of cloud-enhanced shortwave radiation through multiple scattering were not explicitly represented. This process may increase incoming shortwave radiation under partial cloud cover; however, resolving these effects would require a more sophisticated radiative transfer scheme beyond the scope of this diagnostic analysis.

Net longwave radiation is estimated using the Brutsaert (1975) clear-sky emissivity parameterization based on measured air temperature and relative humidity. The Brutsaert (1975) formulation estimates clear-sky emissivity from near-surface atmospheric variables and does not explicitly represent cloud contributions to atmospheric emissivity. Consequently, longwave radiation estimates may be biased low under cloudy conditions, where atmospheric emissivity is enhanced. Because the analysis focuses on identifying conditions favorable for melt rather than estimating melt volumes, we interpret modeled melt energy as a first-order estimate of available energy. Turbulent heat fluxes are calculated using the bulk aerodynamic method (Hock, 2005), with identical parameterizations applied at all sites. We run the model with 2-minute timesteps to resolve diurnal variability and then downsample output fluxes to daily means.

The energy balance requires a more mature treatment of albedo. Albedo has been measured in the St. Elias, see: https://www.sciencedirect.com/science/article/pii/S1873965216300500

Also, see section 4d of this paper which you have cited elsewhere: https://journals.ametsoc.org/view/journals/clim/33/8/jcli-d-19-0405.1.xml

Albedo contribution to glacier melt can be found here: https://www.nature.com/articles/s43247-025-02503-x

Much more detail regarding the Brutsaert (1975) model needs to be included. For example, longwave radiation if largely the result of the bulk atmosphere in the bottom 1 km. If surface temperature is used without modification for lw radiation, then the values will be much larger than actual. Clear sky e will be much lower than cloudy sky e. Thus the amount of lw will be greater in all sky conditions compared to clear sky. There is a recursive shortwave radiation relationship between high albedo snow and clouds – thus somewhat counterintuitively the downwelling solar radiation can be larger under partial cloud cover than during clear sky. Has this effect been accounted for?

Line 214 – define generally

We were using ‘generally’ to make a qualitative statement here – our goal being to acknowledge some visual agreement between melt onset and PDDs even though we cannot identify any specific PDD threshold that corresponds with melt onset. We have removed the statement and moved the comparison of melt onset with PDDs to Appendix E.

Line 218 - nice

Removed ‘nice’

Line 221 – dramatic

Removed ‘dramatic’

Line 217-224 – unclear. Revise for clarity. Eg., positive relationship with elevation – this appears to be backward.

Rephrased as follows:

> *Melt onset occurs later as elevation increases, closely tracking the upward migration of the 0°C isotherm until around 3,000 m a.s.l., providing validation for SAR-based melt detection…*

Line 226-227 – explain why freeze up is so late. How is freeze up determined? With which data?

This information can be found in the methods:

> *We identify freeze-up, or refreezing of the snow and firn, as the first of at least two consecutive dry scenes following a period of seasonal melting. The penetration depth of C-band SAR in wet snow (e.g. during the summer melt season) is only a few centimeters; however, as the snow and firn refreeze, Sentinel-1 can penetrate meters to tens of meters (Baghdadi 110 et al., 1997; Tsai et al., 2019). Freeze-up timing inferred from increases in SAR backscatter may therefore reflect multiple processes, including surface refreezing, drainage, and firn structural change. As such, we use the term freeze-up to represent an integrated firn column response to changes in structure and liquid water content rather than a discrete physical threshold in surface conditions.*

Figure 4 is difficult to read and needs to be revised to better convey the meaning. As currently presented I can’t evaluate this figure.

See our response to your comment about defining “generally” above. Figure 4 was meant to make a broad qualitative statement, but we have moved it to Appendix E, since it is not part of our main results.

Figure 8: to my knowledge net radiation has not been measured in the St. Elias. I assume that net radiation here is modelled. If modelled from the parameters provided earlier in the manuscript, then these values will be inaccurate. A calculation of error is required.

Yes, all the elements in this figure are modelled with the intent of providing a first-order estimation of whether melt production is physically plausible under sub-freezing temperatures (as opposed to predicting or reproducing observed melt rates). Please see the caption below.

> *Figure 8. Modeled components of the surface energy balance (SEB) at Prospector-Russel Col (a), the Kaskawulsh/Hubbard Divide (b), and the Kaskawulsh ELA (c). The net SEB is shown by a black line, while individual components are shown in the stacked line plot. The gray shaded area in panel (a) indicates the period of time when wind speed measurements used to calculate the sensible and latent heat fluxes were unavailable at PR Col. Because the analysis focuses on relative flux contributions using identical model parameterizations across sites, systematic uncertainties are expected to affect all sites similarly and are therefore not shown.*

Line 255 - indeed

Removed 'indeed'

Line 265 – percolation and refreeze models exist – see work by Shawn Marshall and others.

Percolation and refreeze models do certainly exist, but they don't perform particularly well, especially when considering spatial variability in percolation and refreeze. We have rephrased as follows to better reflect this:

> *We find only 12% of the glacierized area in our study domain to comprise dry firn (3%) and hydrologic transition zones (9%). Our results indicate that liquid water plays a central role in shaping near-surface physical properties across the majority of Wrangell/St. Elias, and underscore the importance in continuing to develop robust and spatially distributed meltwater per- colation models for use in alpine environments.*

Line 268 – drilling of what?

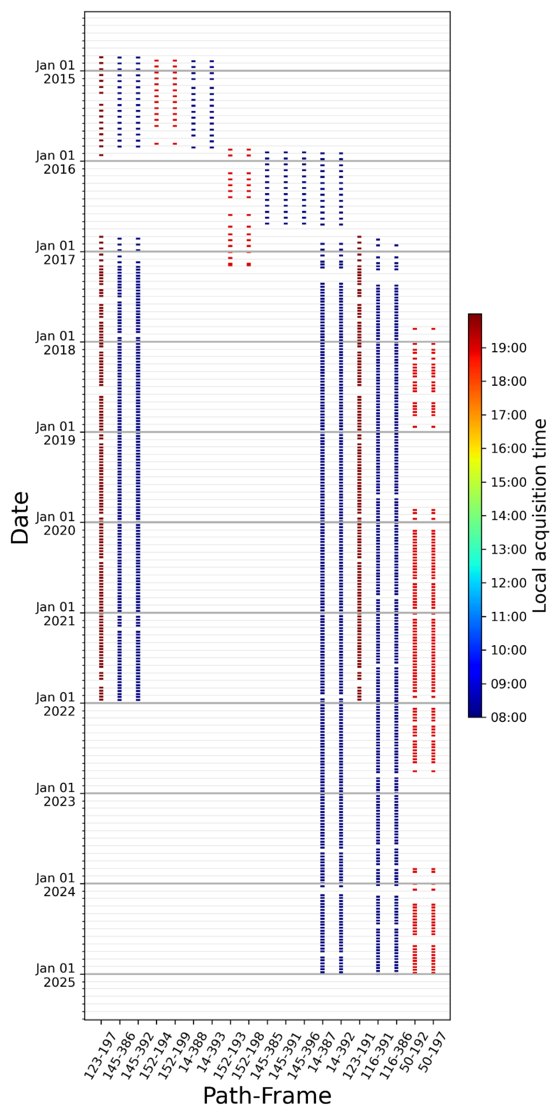
Rephrased as follows:

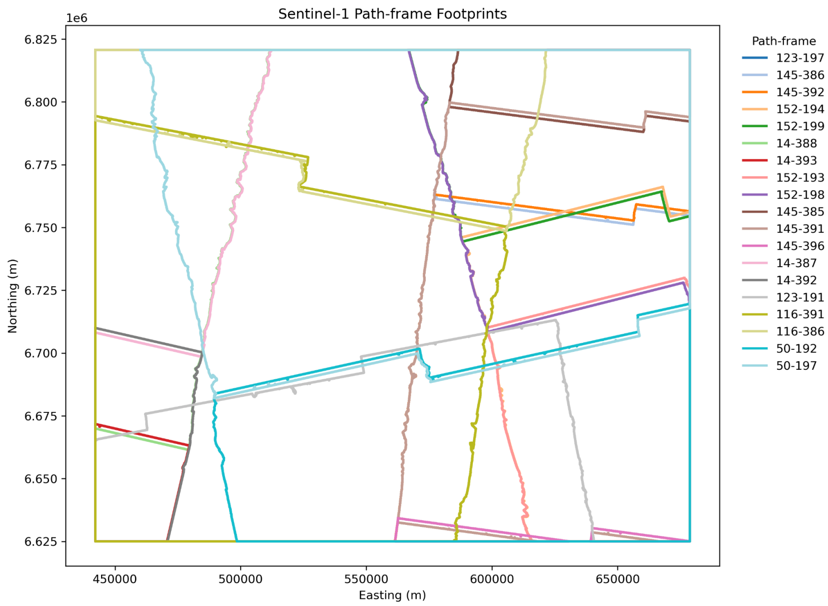
> *The limited extent of dry firn has direct implications for the preservation of ice core paleoclimate archives, as meltwater percolation and refreezing in wet firn can disrupt stratigraphy and preclude ice core drilling*

Appendix A

Table A1 – Include dates. If difficult to include individual dates then include average date each year and standard deviation. Separate by number of scenes for melt and refreeze. The reader needs to be able to evaluate if the number and timing of observations influences the results.

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




Sentinel-1 Path-frame Footprints
1e6
6.825
6.800
6.775
6.750
6.725
6.700
6.675
6.650
6.625
Northing (m)
450000
500000
550000
600000
650000
Easting (m)
Path-frame
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