Revision of manuscript : "A mutlisensor C-band synthetic aperture radar (SAR) approach to retrieve freeze/thaw cycles: A case study for a low Arctic environment " by Crevier *et al.*

Referee comment in blue
In black: Answers to referees.
In black and italic: Modification added to text.

Comments from the Referees:

Reviewer 1: General Comments:

The paper describes a method for estimating freeze/thaw (F/T) cycles in a low-arctic tundra environment using synthetic aperture radar (SAR) dual-polarization backscatter (HH+HV) in C-band from two constellations: Sentinel-1 and Radarsat-2, across three transition periods from August 2018 to December 2019. The paper defines a seasonal algorithm with an optimization approach to detect F/T cycles utilizing in-situ data. Results for a specific extended area were compared with high-resolution classified maps to discuss different parameters related to F/T cycles.

The paper is well-structured and written in clear, comprehensible English. The "Introduction" section provides relevant background information, including sufficient details on previous works and the goals of this study. The "Study Site and Data" section offers a good explanation of the data used in this study. However, I would have liked to see some information on rainfall and snow depth from meteorological sites near the study area in this section, as this could help clarify some of the results. The "Methods" section provides a thorough explanation of the data processing and the definition of the algorithm. The "Results" section is also well-written, with a comprehensive explanation. The "Discussion" section includes an explanation of three main parameters: the impact of snow cover on the freezing transition, the difference between thawing and freezing detection, and the effects of classified ecotypes on the F/T cycle. This section provides a great explanation of these parameters, though it would be beneficial to add a discussion of other factors, such as the relationship between rainfall or snowpack depth and SAR backscatter time-series.

Overall, the paper is in a good shape for publication, and a few specific and technical comments could improve its quality.

We thank the reviewer for the comments. All specific comments were address, thus covering the point raised in the general comment.

Specific Comments:

R1-C1 - Comment: The paper mentions several times the influence of snowpack on the F/T cycle. One question could be how snowpack thickness affects SAR backscatter during the winter season. It is recommended to discuss snowpack thickness using available in-situ data and examine its impact on SAR backscatter in C-band. Additionally, as summer seasons become wetter in Arctic regions, it would be useful to explore how SAR backscatter is affected by rainfall during the summer. These two parameters (snowpack thickness and rainfall) could be discussed further with the available in-situ data.

We agree with the reviewer that further analysis with in situ could be interesting to understand the different radar signal seen in the study. However, temporal snow depth in situ observations are not available at meteorological stations for the giving year of our study. Hence, we cannot identify the effect of snow depth change on the SAR signal throughout the season. Punctual in situ snow depth samplings were performed by our group, (Meloche et al. 2022) but as our paper is focus on the transition period, it is out of the scope to identify the link between SAR backscattering and snow depth, which would take a complete study to thoroughly analysis the relationship. In addition, it is well documented that C-Band could be sensitive to deep snowpacks, but has minimal effect on shallow snowpack which are encountered in our study site (Lievens 2019; Hoppinen et al, 2024). We thus add element of discussion related to possible snow impact on radar signal:

“Generally, it is expected that the surface thaw onset happening under wet snow would be difficult to monitor, because wet snow is mostly opaque to microwave (i.e., surface scattering) (Ulaby et al., 1986). The dielectric properties of snow are defined in two distinct phases: (1) dry snow, having a low dielectric constant related to the absence of liquid water within it; and (2) wet snow, having a high dielectric constant related to the presence of liquid water in the air-ice mixture (Langlois et al., 2007). *On one hand, the impact of snow depth in the winter season when the snow is dry should be minimal on C-band backscatter. Studies showed that C-band was not able to capture snow depth variations lower than 1 m (Lievens et al. 2019; Hoppinen et al., 2024). Snow depth observations performed by our group between 2015 and 2019 showed that maximum snow depth maximum reach around 0,35 cm*

(± 0.17 cm) (Meloche et al., 2022), which limit the possible impact of dry snow on backscattering signal. On the other hand, the C-band signal would then decrease with the presence of wet snow on the ground (Tsai et al., 2019), which decreases the penetration depth and increases the surface scattering of the air and snow interface as air temperatures rise above zero in the spring."

Similarly to rainfall during summer, the topic is a bit far from the scope of our manuscript. However, we agree that soil moisture in the beginning of the freezing season might impact the initial backscattering coefficient before freezing and impact or algorithm. We added some discussion on this topic:

"Interestingly, despite the difference in the soil moisture regime between the two sites, the backscattering trends are similar, with slightly higher σ^0 at IP13 in winter, probably related to the lower fraction of ice in the soil. *These results show a possible impact of summer water balance and soil moisture at the end of the season on the initial backscattering coefficient at the beginning of the freezing season. Our results show that even if the initial soil moisture change the backscattering at the beginning of the freezing seasons, the contrast between frozen and thawed backscattering remain large enough to use the proposed simple thresholding approach*."

R1-C2 - Comment: Section "3.3.2. Ecotype Analysis" needs further explanation. How did you apply the least squares model to estimate surface freezing and thawing values? Please provide more details.

We provided more details on the least square model used:

"A generalized least square model (GLS) was used to *predict* values of surface freezing and thawing DOY *as a function of the ecotype class*. *The gls function in R was used. This function fits a linear model using generalized least squares and considered when the ordinary least square regression assumptions are not met, i.e. errors are correlated and/or have unequal variances*. We created 3 models, one per transition season (freezing transition 2018 and 2019 and thawing transition 2019). A variance and spatial autocorrelation structure were defined in the models. F/T transition DOY derived from the models were used to establish if the differences of the timing in transition DOY between ecotype class were statistically significant."

R1-C3 - Comment: In Figure 4, is there a data gap for Radarsat-2 from November 2018 to May 2019? How do you explain the 88% reduction of Sentinel-1's standard deviation in summer (HV), and the 84% and 69% reductions of Radarsat-2's standard deviation in winter and summer (HH and HV)? Did you check the trends for other pixels? A comparison between different pixel classes (vegetated vs. non-vegetated) in response to incidence angle normalization could be useful.

Indeed, the number of acquisitions from Radarsat-2 is reduces between November 2018 to May 2019 (see figure R-1). Unfortunately, we were not able to explain this reduction of observations. However, we do not think it would change the results of our proposed method, and it still allow us to show the good concordance between Sentinel-1 and radarsat-2 observations in the Arctic and the possible synergy between both sensors to increase temporal resolution of SAR observations.

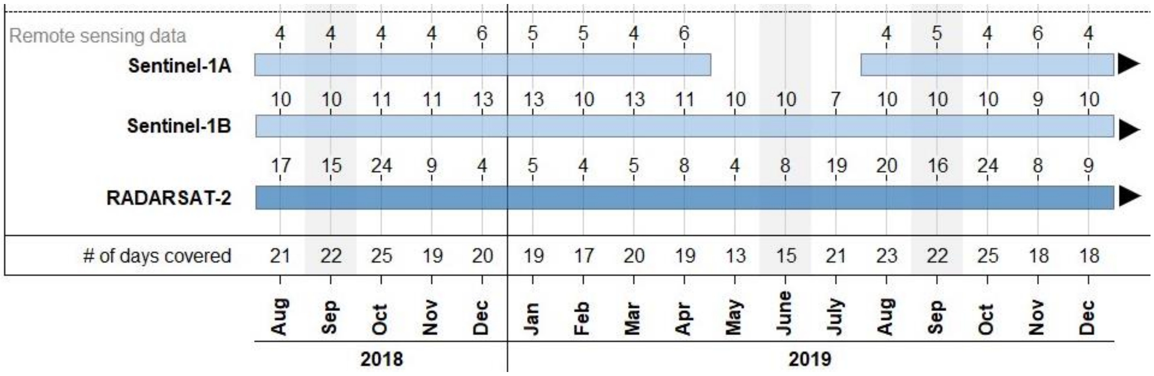

Figure R1 : Number of observations for the different satellites during the study period.

For the higher standard deviation reduction, we were not able to identify the reason why the standard deviation reduction is higher for HV than HH. Chen et al (2022) have reported that the used of regressions factors (similar to what we did) suggests better normalization results than the widely used cosine-square correction method for horizontal transmit and horizontal receive (HH) images and a slight improvement for horizontal transmit and vertical receive (HV) images.

See also comment **R3-C4** for more comments.

R1-C4 - Comment: It would be interesting to apply the same threshold (Total H = 0.62) to a newer or older dataset to assess its applicability. For example, the 2020-2021 F/T transition cycle could be analyzed using either both datasets or only the publicly available Sentinel-1 data, though soil temperature data may not be available.

We agree that it would be interesting to apply our threshold to a new set of data. However, at the moment of the redaction of the manuscript no other in situ datasets were available.

R1-C5 - Comment: I agree that C-band can penetrate vegetation up to a height of 5 cm, but by the end of the summer season, when some vegetation reaches a height of 30 cm (Table-1), the C-band backscatter may backscatter from somewhere between the soil and the top of the vegetation, potentially not reflecting the transition phase. How do you address this challenge?

C-band signal can saturate for very dense canopy in temperate or tropical forest. However, in tundra, the effect of vegetation on the signal is minimal. Indeed, the transmissivity of vegetation in tundra region remains low (Liu et al, 2023) which confirm that the soil is the main contributor to the signal. As the FT signal is very strong in fall, it is clear that the signal come from the frozen soil. We add some elements in the discussion:

"*Another possible impact on freezing identification is the presence of vegetation (Cohen et al., 2024). However, vegetation high and biomass in our study site is low with limited impact on backscattering as shown from studies using ASCAT (Liu et al. 2023). Hence, if vegetation senescence in fall as an impact on backscattering, the effect is much lower than the soil FT processes as shown by the accuracy over 93% obtained in this study.*"

R1-C6 - Comment: In the conclusion section, the authors describe the area as a shallow snow-covered terrain. Please refer to the first comment and provide snowpack information based on meteorological data in the study area section to support this.

Our group have performed several in situ snow depth measurements to confirm that the regions is shallow snow-covered terrain (see R1-C1 and Meloche et al. 2022). We thus add a reference for the shallow snow-covered terrain:

"The surface F/T product created from this study demonstrates how, on one hand, the SAR backscatter can be used for surface F/T detection in low vegetation and shallow snow-covered terrain *(Meloche et al. 2022)*, and on the other hand, how it could be used as complementary data to improve modelling of the soil thermal regime."

Technical corrections:

R1-C7: Comment: Line 94: remove the period after Figure 2.

"done"

R1-C8: Comment: Line 149: Is it maximal vegetation height or average vegetation height. It should be consistent with Table-1.

The vegetation height was estimated based on the type of vegetation in the ecotype like Meloche et al. (2022) did. Hence, we decided to put only “vegetation height”.

R1-C9: Comment: What DEM did you use for SAR processing. Please provide reference.

The ArcticDEM 2 meters DEM created from ortho-image was used. Porter et al., 2023, “ArcticDEM, Version 4.1”, https://doi.org/10.7910/DVN/3VDC4W, Harvard Dataverse, V1, [Date Accessed]. We also clarified the role of the rational function model (see comment **R3-C4**)

“Finally, to allow the combination of dataset, images were then orthorectified to a fixed grid of 50 m × 50 m using a cubic interpolation method. *The orthorectification was performed with the rational function model and the ArcticDEM digital elevation model at 2 m (Porter et al. 2023)*.”

R1-C10: Comment: Line 233: Remove one of the periods at the end of the sentence.

“done”

R1-C11: Comment: Section 4.2.2 is written as one large paragraph, which makes it difficult to follow the context. I recommend dividing it into two or three smaller paragraphs to improve readability and understanding.

We decided to reduce the paragraph length by removing some unnecessary sentences that complexify the message. We also divide in two paragraphs, one describing the accuracy for each sub-figure, and the other describing the best threshold:

“Figure 5 shows the accuracy of the detection algorithm as a function of the threshold between 0 and 1 (at a 0.01 increment) on HH, HV and HH+HV datasets. The accuracy is calculated for the ten reference sites combined, with T_{soil} (solid line) and T_{air} (dashed line) reference values over a) the entire time series; b) the freezing transition periods for 2018 and 2019 combined; and c) the thawing transitions for

2019. The algorithm applied over the entire time series (Figure 5a) suggests high accuracy (>95%) for threshold values ranging between 0.40 and 0.65 for all polarizations and temperature datasets. ~~This overall classification accuracy provides a good initial assessment of the detection accuracy, but fails to assess the threshold behaviour during the surface F/T transition periods. Since the accuracy for classification values during summer and winter are close to 100% for a threshold close to 1 (i.e., summer) or 0 (i.e., winter). The number of "good" observations is thus increased, which decreases the weight of each individual value in the accuracy calculation (Eq. 5). Therefore, the data from August 11 to October 10, 2018, and August 21 to October 20, 2019, (i.e., freezing seasons) and May 11 to July 10, 2019 (i.e., thawing season) was extracted from the time series to evaluate the behaviour of the algorithm during those key periods of freezing and thawing.~~ Figure 5b and c show the difference in the retrieval accuracy along the increment of thresholds during the freezing (August 11 to October 10 2018) and thawing (May 11 to July 10 2019) periods respectively. Results show that a clear threshold value maximizing the accuracy exists between 0.50 and 0.65 for the classification of the freezing period (Figure 5b) for all datasets. For the thawing transition, multiple threshold values across a larger range yield a high accuracy (Figure 5c).

The signal classification during the thawing transition is largely insensitive to the threshold over a wide range of increments, where the accuracy remains mostly stable (0.2 to 0.6 for HH, 0.3 to 0.7 for HV and 0.2 to 0.7 for HH+HV polarization). A common threshold for both transition periods could then be considered for the surface F/T detection. Figure 5c also suggests that in the classification accuracy, the soil temperature performs better by almost 10% when compared to air temperature over the range of thresholds presented. We therefore chose the optimized threshold from the best accuracy compared to T_{soil} measurements for the combination of both transition seasons. A threshold of 0.56 was defined as maximizing the accuracy of transition seasons for HH polarization and of 0.53 for HV polarization (Table 4)."

R1-C12: Comment: Keep consistent formatting when referring to figures throughout the manuscript (either Fig. X, or Figure X).

The Cryosphere standard is to use (Fig. X) in the text unless it is at the beginning of a sentence. And Figure X in the caption. The format was corrected over the manuscript.

R1-C13: Comment: Line 336: Figure 9b should be changed to Figure 7b.

Done

R1-C14: Comment: Some figures, such as Figure 7, need to be of higher quality.

The quality is related to the word document. The figure in the final submission will be higher quality.

R1-C15: Comment: Line 416: Remove "," after "suggesting".

Done

R1-C16: Comment: Line 436: It should be Figure 7a, not 9a.

Done

R1-C17: Comment: Line 437: change moisture soil to soil moisture.

Done

R1-C18: Comment: Line 456: ...Combines multiple...

Done

Reviewer 2

The paper employs multisensor SAR data for FT mapping, utilizing different polarization modes and a seasonal threshold approach. Given the critical role of FT cycles in hydrological and biological processes, the study addresses an important topic, particularly as FT dynamics are often overlooked in cold-region research.

R2-C1: However, despite the significance of the subject, the paper lacks a well-defined research gap and clear scientific questions. Previous studies have already demonstrated the effectiveness of SAR for FT mapping, and while improving the temporal resolution of FT estimates through a multisensor approach can be valuable, the justification for this need within the chosen study area is unclear. Mid-latitude regions, characterized by frequent FT cycles and rapid transitions, require high temporal resolution data to accurately capture FT dynamics. However, the study does not provide sufficient justification for the necessity of near-daily FT products in an Arctic region, where FT status remains largely stable on a daily scale, except during the transitional periods at the beginning and end of the cold season. The analysis and results also do not provide clear evidence of information loss or the limitations of using a single sensor for FT mapping in the study area. The results do not reflect the differences a multisensor approach makes in estimating the transition DOY compared to a single sensor.

High temporal resolution FT product is important in Arctic environment. First, as our results showed there is a small, but significant difference of 2-3 days between the different ecotype in the start and end of the freezing period. Even if these number of days might look small, they are of great importance in Arctic environments. For example, Gehrmann et al (2022) showed that a delayed senescence by 3.5 days can lead to an extension of the growing season end of 10 %for certain species. Hence, in such arid environments, where the growing season length is short, a near-daily product is necessary to provide precise information on inter-annual variation of growing season and the impact on ecological process in these sensitive environments. One of the important ecological processes are the soil carbon emission that are highly related to FT processes (Mavrovic et al, 2023). In spring the zero-curtain can last few weeks even in Arctic environment and having a way to identify these periods precisely is crucial to quantify the impact of zero-curtain effect on the soil emission carbon budget. We acknowledge that these important aspects were not strongly depicted in the introduction. We thus added several sections to strengthen the fact that near-daily FT product is important for Artic environments.

“Furthermore, tundra vegetation, which modulates snow distribution through trapping effects (Barrere et al., 2018; Busseau et al., 2017; Royer et al., 2021), is also changing significantly (Bjorkman et al., 2018; Martin et al., 2017). Royer et al. (2021) suggested that changes in the snowpack microstructure and distribution patterns, linked to the increase of vegetation height and coverage, could further amplify permafrost warming (Callaghan et al., 2011). *These complex soil/vegetation/snow interactions closely tied to FT cycles govern a large part of ecological processes including carbon fluxes in Arctic environments. On one hand, FT processes control* *the growing season length in arctic environments, where the period of productivity and carbon sequestration through photosynthesis for plants is short and critical for the ecosystems. Hence, changes of few days in FT processes could lead to significant change in the growing season length of certain species potentially (Gehrmann et al. 2022). On the other hand, soil FT also govern the soil carbon emission through temperature and the availability of liquid water for microbial activity in the soil (Natali et al. 2019; Mavrovic et al. 2023). Hence, during the zero curtain, which can last from several days to few weeks depending on the soil moisture regime in tundra environments (Davesne et al., 2022), the soil temperature's near-freezing state can sustain microbial activity, which has significant implications for carbon fluxes where can have similar total or probably higher emissions to the rest of the winter (Arndt et al., 2023). Knowing the critical importance of spatio-temporal variation of FT cycles on Arctic ecosystems, it is though essential to improve our capacity to monitor FT processes and high temporal and spatial resolution over Arctic environments."*

We also developed the importance of near-daily FT product based on the analysis made at the ecotypes level:

"That could explain the faster thaw observed for higher vegetation ecotypes. We could then hypothesize that the difference observed in the thawing DOY is linked to vegetation *thermal effect*.

The small but significant differences of 2-3 days in Freeze DOY and Thaw DOY shows the importance to get high spatial near-daily FT maps to monitor the impact of FT cycles on ecosystems processes in Arctic environments. Indeed, because the growing seasons is short in these environments, few days in FT timing can have important impact on ecosystems processes. For example, Gehrmann et al (2022) showed that a delayed senescence by 3.5 days can lead to an extension of the growing season end of 10 % for certain species in Arctic environments. The precise detection of the soil freezing and thawing is also important for accurate monitoring of soil carbon emissions (Arndt et al. 2024; Mavrovic et al., 2023)."

In addition, we added the fact that the developed method shows the concordance of Sentinel-1 and Radarsat-2 observations for high temporal resolution FT and could potentially apply in other biome where high temporal resolution FT product could also be of use. The study also opens a path to merge Sentinel-1 and RCM constellation observations to improve temporal resolution of SAR product, but also mitigate the impact of possible lost of satellite such as Sentinel-B in December 2021. Additional text was added in the conclusion:

“Overall, this study demonstrated the capacity of C-band SAR backscatter intensity to detect surface F/T in the tundra environment. *The multisensor approach allowed to create high spatial resolution near-daily FT product based on SAR observations allowing to better monitor ecosystem processes in Arctic environments, but could also help mitigate potential satellite failure and increase our capacity to produce long-term SAR FT products. Note that the signal of wet snow limits accurate thawing transition detection.”*

Other comments:

R2-C2: Please consider including more recent literature on the application of SAR for FT mapping.

More recent literature on application of SAR for FT mapping were added in the introduction section.

“SAR backscatter information can thus help to detect changes in the dielectric constant of the soil surface during F/T cycles for different ecosystems such as agriculture (Baghdadi et al., 2018; Fayad et al, 2020; Taghipourjavi et al., 2024), forested (Jagdhuber et al., 2014; Cohen et al., 2021; Cohen et al. 2024; Moradi et al., 2024) and permafrost covered (Park et al., 2011; Chen et al., 2019; Chen et al. 2022; Zhou et al. 2022; Taghavi-Bayat et al, 2024; Bartsch et al 2025) environments.”

We also used that new literature to improve the discussion and compare our results to existing studies:

“The seasonal threshold algorithm was effective in classifying SAR backscatter observation into frozen or thawed states*, with obtained overall detection accuracy of over 96% for the whole time series, and over 91% for every transition period. These results are similar, or even superior to other studies using SAR observations for FT monitoring in permafrost regions (Bartsch et al., 2025; Wang et al., 2022; Taghavi-Bayat et al., 2024)*. The influence of the snow cover on the freezing transition and the differences between the freezing and thawing detection ability are now discussed, along with the impact of the low arctic environment ecotypes on the transition onset for the case study region.”

"Even though the C-band signal is affected by the presence of wet snow on the ground *(Cohen et al., 2024)*, the fact that the wet snow signal and the thawed soil seem to happen almost at the same time, could indicate that the detection of soil surface thawing during the spring using C-band SAR observations is possible considering the strong agreements obtained with the soil surface temperature in the Arctic's tundra environment."

R2-C3: Please include information on snow depth, snow cover, and potential liquid precipitation in the study area.

We agree with the reviewer that further analysis with in situ could be interesting to understand the different signal seen in the study. However, reliable meteorological information is limited in the region. Hence, we added several discussion aspects related to snow depth and precipitation. See R1-C1 for more details.

R2-C4: Please include the band and frequency details for both Sentinel-1 and RADARSAT-2 SAR

The information was provided at line 122-123. However, we agree that it might not be clear that Sentinel-1 and Radarsat-2 operates at the same frequency (5.405 GHz). Hence, we adjusted the text to clarify:

"In this study, we used the C-band SAR backscatter obtained from the sensors of two satellite missions, namely the Sentinel-1A-1B constellation (available since 2016), and RADARSAT-2 (made available for this study between August 2018 to December 2019). *Both SAR operates at a center frequency of 5.405 GHz. This* study focuses on the period spanning from August 2018 to December 2019, where the overlap between both data source allows for quasi-daily revisit time in the transition seasons of Fall 2018 (F-2018), Spring 2019 (S-2019) and Fall 2019 (F-2019)."

R2-C5: How does the use of both descending and ascending SAR acquisitions impact FT mapping performance during the transition period, especially considering that daily average soil temperature was used? While soil FT status remains stable during the peak of the cold season regardless of daily soil temperature variations, does the diurnal variability of soil temperature during the transition period affect performance, especially considering that both descending and ascending acquisitions were incorporated?

For Sentinel-1 images (A and B), only observations taken around 13:00 were available. For RADARSAR-2 dataset, most of data were also available during the ≈13:00 UTC pass. Hence, overall, only 14% of SAR observations were taken around 0:00 UTC, limiting the impact of orbits on our overall results. In order to evaluate the impact of the consideration of the average soil temperature on the results, we calculated the annual difference in freezing or thawing conditions in term of soil temperature depending on the time chosen to calculate the soil status (daily FT soil status based on average daily soil temperature vs FT soil status based on 13:00 UTC soil temperature or 0:00 UTC). Our results show that comparing FT status based on average daily soil temperature vs 13:00 UTC and 0:00 UTC soil temperature led to 98,6% accuracy and 98,2% respectively. The results show the limiting impact of using daily average soil temperature on our overall results. Indeed, the change in the soil temperature considered change the FT status of 2-3 days during transitions periods.

We added some lines in the methodology to clarify some aspects related to satellite orbits.

"*Note that all Sentinel-1A-1B and most RADARSAT-2 observations were taken around 13:00 UTC. Hence, only 14% of SAR observations were taken around 0:00 UTC (all RADARSAT-2 observations).*"

R2-C6: How does the presence of shrubs and fen with a height of 30 cm impact performance of FT mapping? Were there any differences in performance across the ecotype classes?

The transmissivity of vegetation in tundra region remains low (Liu et al, 2023) which confirm that the soil is the main contributor to the signal. In addition, in this study, we chose to use the Total H power for the creation of the F/T maps to decrease the impact of the target orientation and reduce the possible impact of vegetation. Sentences were added in the discussion (see **R1-C5** for the new material added in the manuscript and additional explanation about vegetation).

RC3: 'Comment on egusphere-2024-3580', Anonymous Referee #3, 21 Feb 2025 reply

The detection of soil F/T transitions in the lower arctic tundra environment with C-band SAR was studied. Sentinel-1 and Radarsat-2 observations were normalized for incidence angle and calibrated to Sigma_0 backscatter coefficient, in order to combine them and create a temporally dense timeseries. The study focused on two freezing seasons and one thawing season during 2018-2019. The reference freeze and thaw backscatter values used in the seasonal threshold-based detection algorithm were derived by iterating through possible values and finding the ones that provide the best agreement with the air and soil temperature observations. The influence of ecotype classes and snow cover on the F/T results were analyzed and discussed.

The paper is clearly written, interesting, and contributes to the general understanding of the C-band signatures in the lower arctic. The capability of C-band SAR to detect soil F/T states in the arctic tundra is demonstrated. The results are well analyzed and discussed, with insight on the influence of soil type, vegetation and snow cover on the timing and length of the freezing and thawing transitions. However, there are some new published research articles concerning soil F/T detection with C-band SAR in general, but also specifically from arctic tundra environments, that are not mentioned or addressed in this manuscript.

In my view, the paper can be published after addressing the following issues.

R3-C1: Introduction/Discussion: Please check more recent studies (since 2022) and assess how your work relates to them.

Recent literature was added accordingly to reviewer comments. Please see comment **R2-C2** for detail on changes brough to the manuscript.

R3-C2: Section 3.1: What software was used in the preprocessing of the SAR data?

The information was added in the method:

“Both SAR datasets were preprocessed independently using a common chain (Fig. 3), which includes radiometric calibration, speckle filtering, orthorectification and incidence angle normalization. *PCI Geomatica functionality with python scripts were used in the study.* First, we applied a radiometric calibration to the backscatter coefficient (σ^0).”

R3-C3: Figure 3: What is the “Rational function model”? Please explain in text or figure caption.

The Rational function model is one of the input used for the orthorectification of the SAR images. It is a math model that establish relationships between image coordinates and objects coordinates. Clarification was brought in the method (see also comment **R1-C9** for clarification on the DEM used):

“The calibration removed the dependency of the observation to the sensor characteristics; allowing us to combine the datasets from both sensors. To decrease spatial noise in each image, we then applied a Lee speckle filter with a window of 7 × 7 pixels. Finally, to allow the combination of dataset, images were then orthorectified to a fixed grid of 50 m × 50 m using a cubic interpolation method.

The orthorectification was performed with the rational function model and the ArcticDEM digital elevation model at 2 m (Porter et al. 2023)."

R3-C4: Section 4.1: Why only one pixel was chosen for the analysis of the incidence angle normalization? It would be more reliable to choose a larger window of many pixels and average them.

The analysis of the impact of incidence angle on the standard deviation was made on all the 10 sites studied. However, the figure present one pixel. We hence clarified that point in the method section:

"For winter months, we found that the normalization, on average *over the 10 studied sites*, decreased the signal standard deviation by 39%, 46% and 33% for HH, HV and HH+HV polarizations for Sentinel-1 respectively, and by 37%, 84% and 37% for RADARSAT-2 at the ten reference sites. For summer months, that decrease was 48%, 88% and 46% for Sentinel-1, and 37%, 69% and 36% for RADARSAT-2."

R3-C5 : Line 420: used -> use

Done

R3-C6 : Line 455: combines multiple -> combines multiple

Done