

The authors thank the reviewer for the thorough and constructive review of the manuscript, and for recognizing the value of the CryoSAR dataset and the supporting in situ measurements. The comments helped strengthen the analysis and presentation, and the manuscript has been revised accordingly.

The F/T retrieval is now validated quantitatively against the in situ stations for all ten acquisitions, with a confusion matrix and a per-station breakdown of the results. The figures showing VV backscatter and the Freeman–Durden components have been redesigned so that the in situ soil state at each station appears directly above the SAR response, allowing the two to be compared without switching between figures. The results are now also discussed in relation to previous studies, including a comparison of the classification accuracy with the SMAP radar F/T product.

During the revision, an error was also identified in one of the SAR data processing steps. After it was corrected, all SAR images were reprocessed and every result derived from them was recomputed. Following the reviewer's suggestion, the I2EM section has been removed, and the whole manuscript has been carefully rechecked for dates, figure references and other small details. Responses to each specific comment are provided below.

Line 40-53: C-band is not mentioned at all even when it is one of the most common frequencies used in SAR. Please add it to the frequency considerations.

Response: Thank you for pointing this out. We have added C-band to the frequency discussion in the Introduction and updated Figure 1 to include C-band alongside L-, X-, and Ku-band.

Line 54-66: Please add background information on how soil state transitions influence backscatter and polarimetric scattering mechanisms. No information is now provided about whether there is an increase or decrease of these SAR responses after soil freezing and relative to snow conditions.

Response: Thank you for this comment. We have added background on how soil F/T transitions affect L-band backscatter and polarimetric scattering, including the direction of these changes and the role of snow conditions. The revised text reads:

When soil transitions from thawed to frozen, liquid water converts to ice and the real part of the relative permittivity drops sharply, reducing the dielectric contrast at the soil surface (Long and Ulaby, 2015). This reduction in permittivity lowers L-band backscatter in the frozen state relative to thawed conditions by several decibels and increases the penetration depth (Cohen et al., 2021; Zhou et al., 2021; Crevier et al., 2026). Dry snow is nearly transparent at L-band, whereas wet snow can strongly attenuate the L-band signal, which can complicate the interpretation of F/T transitions during melt periods (Taghavi-Bayat et al., 2024).

Polarimetric SAR decomposition techniques have been used to investigate the F/T state of soils, showing that changes in soil state can be detected through the evolution of polarimetric parameters (Jagdhuber et al., 2014). These methods, grounded in physical scattering models, not only enable the detection of F/T transitions but also provide insight into the underlying scattering mechanisms (Jagdhuber et al., 2014; Park, 2015). The polarimetric response also varies with soil F/T state. At C-band, Khaldoune et al. (2008) reported that volume scattering was the main mechanism over unfrozen soil, while surface scattering became dominant once the soil froze, although the difference between the two states was small. Jagdhuber et al. (2014) applied the H/A/ α decomposition to a C-band time series and found a similar pattern: scattering moved from volume scattering in thawed soil toward surface scattering as the soil froze. Similarly, Zhou et al. (2021) applied the dual-polarized H/ α approach to C-band data across summer and winter seasons, highlighting how seasonal variations correspond to shifts in scattering mechanisms.

Figure 2: Increase text size of legend and scalebar.

Response: Thank you for pointing this out. The font size of the legend and scale bar in Figure 2 has been increased for improved readability.

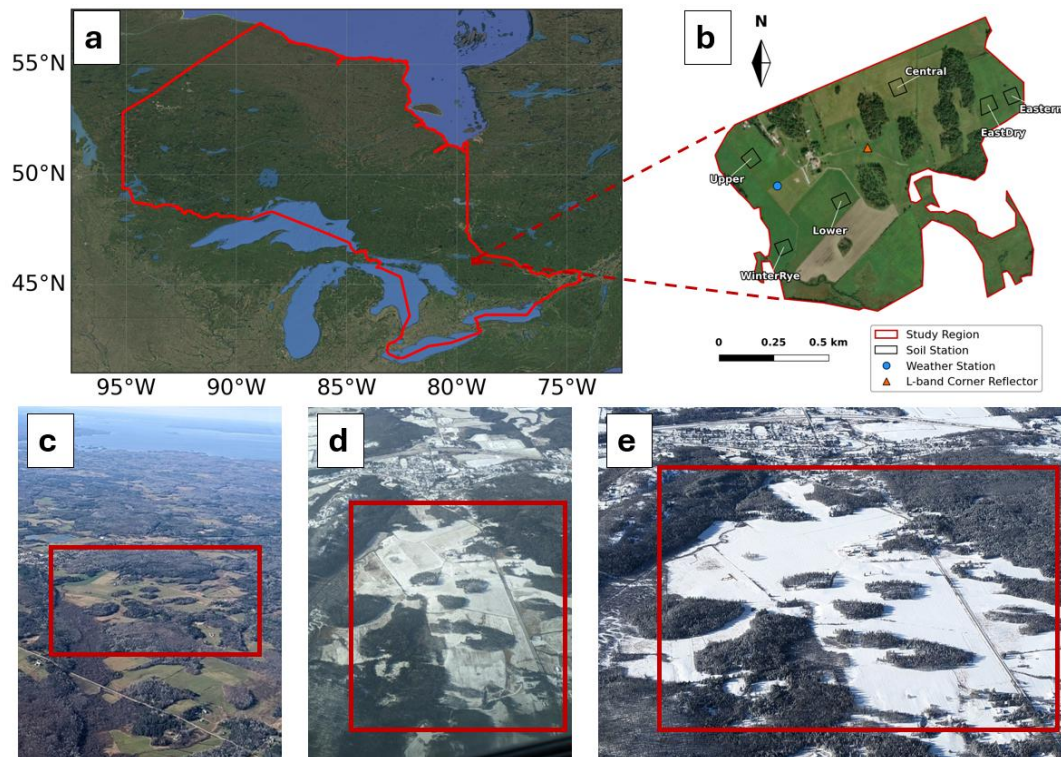


Table 2: What is the imaging angle? How uniform was it?

Response: Thank you. We have added the incidence angle range for each acquisition to Table 2 and noted it in Section 2.2. Across the study area, the incidence angle ranged from about 31° in near range to 65° in far range, with a similar range on all flight dates.

Line 108: Airborne data collection did not start in November 2022, but in January 2023.

Response: Thank you for catching this. The airborne acquisitions started in January 2023, and we have corrected this throughout the manuscript. The revised text in Section 2.2 now reads:

"A total of ten single-look complex (SLC) Level-1 images with full polarimetric channels (HH, HV, VH, VV) were collected over two winters (2022–23 and 2023–24), with SAR acquisitions spanning from January 2023 to January 2024 and the most frequent flights occurring between January and March 2023 (Table 2)."

We have also clarified that the field campaign itself began in October 2022, while the CryoSAR acquisitions used in this study started in January 2023.

Line 144-146: Sentence not clear, please check and rephrase.

Response: We thank the reviewer for pointing this out. The sentence has been revised for clarity as follows:

Precipitation events recorded at the ECCC North Bay airport (YYB) weather station (46.37°N, 79.40°W) were retrieved throughout the field campaign. For dates listed in Table 4, precipitation was expected to fall as rain, as inferred from the daily minimum and maximum temperatures (Environment and Climate Change Canada, 2024).

Line 148: Add figure numbers as references to “time series plots”.

Response: We thank the reviewer for this comment. As part of revising this section to reflect the updated time series starting in early January 2023, the sentence referring to "time series plots" has been removed.

Table 4: Why is 14.2.2023 added here if the precipitation was 0 mm? Also, in case snow depth did not decrease, how do you conclude that the precipitation was rain?

Response: We thank the reviewer for this observation. Upon reflection, we agree that including 2023-02-14 in Table 4 was inconsistent with the table's stated scope, since no precipitation was recorded on this date. We have removed it from the table. For context: air temperature at the field site reached approximately +4°C on 2023-02-14, and the following day (2023-02-15) recorded both precipitation and a decrease in snow depth, consistent with rain-induced melt. We interpret the warm temperatures on the 14th as likely priming the snowpack for the melt event observed on the 15th, though we have kept this as contextual information in the text rather than as a table entry, to maintain a consistent inclusion criterion for the table.

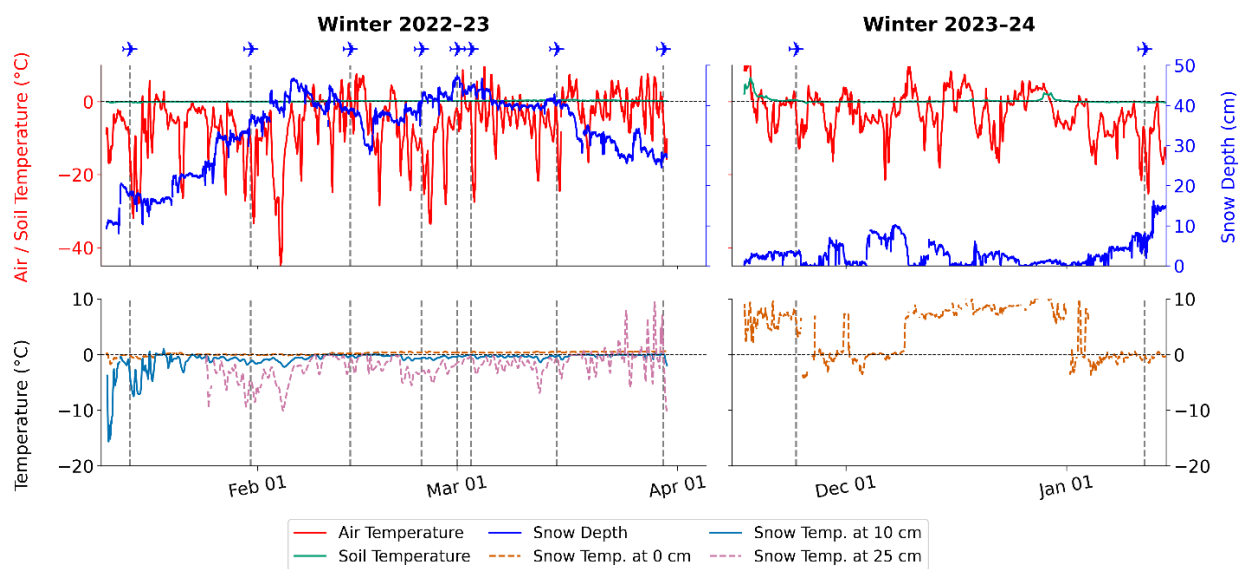
Line 155: The sentence “For our study ... snow layer” sounds to me too trivial to be added here. It is obvious that the main scope of this study is soil F/T beneath the snow.

Response: We agree with the reviewer that this sentence was redundant given the stated scope of the study. It has been removed.

Figure 5: Add the red and blue dotted lines of the top plot to the legend. For a better interpretation of the bottom plot, I would recommend masking out the snow temperature measurements which are during no snow conditions, because they represent air temperature.

Response: Thank you for these suggestions. The dotted lines in the top plot showed gap-filled values. Rather than adding them to the legend, we removed the gap-filling and now plot only the measured weather station data.

For the bottom plot, we masked each probe's temperature whenever the snow depth was lower than the probe height, so the plotted values now represent snow temperature only. We also moved the start of the 2022–23 plot from 1 to 5 January, when all probes were already covered by snow. The 10 cm probe was left out for winter 2023–24 because it had too few valid measurements.



Line 249-252: From Figure 6 I understand that there were two temperature and two permittivity sensors in each station. What is the classification logic? Here you explain the logic as if there were just one temperature and one permittivity measurement.

Response: Thank you for pointing this out. You are right that each station had two sensors. We now state explicitly in Section 2.3 that the two HydraProbe readings were averaged before classification. The revised text reads:

"At each station, the mean of the two HydraProbe sensor readings was computed for both soil temperature and real permittivity prior to classification, yielding a spatially representative station-level estimate. The temperature criterion classified soil as frozen when the mean temperature ≤ 0 °C and thawed when > 0 °C. The permittivity criterion classified soil as frozen when mean $\epsilon' < 10$ and thawed when $\epsilon' \geq 10$. A frozen state was assigned only when both criteria were simultaneously satisfied, and likewise for thawed. Periods where neither condition was jointly fulfilled were classified as transitional."

Figure 6: Add vertical lines marking the CryoSAR flight dates, as in Figure 5. Also, increase image resolution.

Response: Thank you. We have added vertical lines marking the CryoSAR flight dates to Figure 6, in the same style as Figure 5, and increased the image resolution.

Line 256-261: Please use same names or numbers in text and figures. Now in the text only the names of the stations are mentioned while in the figures only numbers (Fig 6) or nothing (A1). Also, add a reference to Table 1 when listing the stations in the text.

Response: Thank you. Station names are now used consistently in the text and figures, and the station numbers have been removed from the figures. We have also added a reference to Table 1 where the stations are listed in Section 3.1. The former Fig. A1, a close-up of the soil temperature records, has been removed. The current Fig. A1 shows weather station data from mid-October 2022 to January 2023, before the SAR observation period.

Line 287: I understand that in theory VV-pol is optimal for F/T detection of soil. However, analyzing the HH-pol and cross-pol is still interesting for finding possible differences, speculating the reasons for them, and for validating the theoretical assumption that VV-pol is optimal.

Response: Thank you for this suggestion. We agree that comparing HH and the cross-polarized channels with VV would be useful, both to understand their differences and to test whether VV is indeed the best choice for F/T detection. In this study, however, we focused on the VV response to soil F/T beneath snow cover as a first step. A full comparison of the polarizations, including a physical explanation of how and why they differ, would considerably widen the scope of the paper. We see this as the next step in our work and plan to carry out a systematic comparison of HH and the cross-polarized channels using this dataset and approach.

Line 291-295: The comparison of scattering properties for the different polarizations is interesting and useful, however, there are a few things that should be further clarified. 1) Is it that VV and HH can similarly penetrate the snow layer. If yes, begin the section by saying that co-pol penetrates the snow better than cross-pol (not VV penetrates better than cross-pol). 2) The reduced sensitivity of co-pol to vegetation is well known, but is co-pol (or specifically VV-pol) less sensitive to terrain roughness than cross-pol? If yes, add a reference justifying this claim. 3) Complete “Zeng and Chen” references.

Response: Thank you for these detailed and helpful comments.

1. The text has been revised to generalize the penetration comparison to co-polarization rather than VV alone: "Co-polarized backscatter (VV and HH) penetrates the snow layer with minimal attenuation at L-band and is less affected by vegetation than cross-polarized backscatter, with vegetation height remaining low (≤ 20 cm) and stable throughout the campaign (Shi and Dozier, 2000)."
2. A reference has been added to support the claim that VV polarization is less sensitive to surface roughness than HH and HV polarizations: Holah et al. (2005) showed that HH and HV backscatter are more sensitive to surface roughness than VV over bare agricultural fields.

Source: Holah, N., Baghdadi, N., Zribi, M., Bruand, A., and King, C. (2005). Potential of ASAR/ENVISAT for the characterization of soil surface parameters over bare agricultural fields. *Remote Sensing of Environment*, 96(1), 78–86.

3. The incomplete "Zeng and Chen" reference has been corrected to Zeng et al. (2018).

Line 296-299: The combination of these two sentences is not clear. The first sentence "As expected, frozen ... content" as itself does not justify what is said in the following sentence "This confirms ... channel". Nevertheless, the first sentence can be moved to the introduction (see comment regarding Lines 54-66).

Response: Thank you for this comment. We agree that the first sentence did not support the second. The first sentence, on the lower backscatter of frozen soil, has been moved to the Introduction, where it now forms part of the new background on how soil F/T transitions affect L-band backscatter (see our response to the comment on Lines 54–66, please). The second sentence has been removed, as our analysis did not compare VV with the cross-polarized channels. The reasons for choosing VV are now given, with supporting references, at the end of Section 2.2, and Section 3.2 reports the measured difference in VV backscatter between frozen and thawed soil.

Line 300-306: There seems to be errors in some of the CryoSAR flight dates. Please correct.

Response: Thank you for catching this. We have carefully checked all CryoSAR flight dates in this section, and throughout the manuscript, against the acquisition table and corrected them where needed.

Line 303: "even under dry snow cover" is an odd expression here. Dry snow is almost invisible for L-band and therefore should not be a problem.

Response: Thank you, we agree. We have removed the phrase "even under dry snow cover." The point that dry snow is nearly transparent at L-band, so that the backscatter changes mainly reflect the dielectric state of the soil, is now made in the Discussion.

Figure 7: The legend ranges between -20 dB and 10 dB. Is this true? If yes, can there be a problem in data calibration? 10 dB is very high for SAR. It seems like the forests show very high backscatter compared to fields. The forests are anyway not relevant in this study, so should they be masked off? Narrower color scale would then allow better separation between pixel values around the different soil stations. Currently it is very hard to observe any backscatter differences between the sites based on the colors of the images. This comment applies to Figures 9, 10 and A2 as well.

Response: Thank you for this careful observation. We investigated this carefully and found an error in one of the data processing steps. We then went through the full processing chain again, and the backscatter values and color scales shown in the revised figures are the corrected version. All results derived from the SAR, including the polarimetric decomposition and the soil F/T maps, were recomputed, and the related text has been revised accordingly.

We also agree that the forests are not relevant to this study. Forest pixels are now masked in Figures 7, 9, 10 and 11, and the color scales have been narrowed so that differences between the soil stations are easier to see. Figure A2 has been removed, as it did not add information beyond what is shown in these figures.

Line 316: Add station numbers (see comment regarding Lines 256-261).

Response: Thank you. Following your earlier comment, we now use station names consistently instead of numbers in both the text and figures. The stations discussed here are labeled by name in the figures, so they can be identified directly.

Line 322-327: For winter 2023-2024 no in situ observations are shown. At least the evolution of air temperature and snow depth should be available for this time period, I guess. If not, it is hard to draw any strong conclusions.

Response: Thank you for raising this point. Observations for winter 2023–24 are now included. Air temperature, soil temperature, and snow depth from the local weather station for 15 November 2023 to 15 January 2024 have been added to Figure 5 (right panel), together with the snowpack temperatures. Soil permittivity and temperature for the three stations with records in this season (WinterRye, Upper and Lower) are shown in Figure 6 (right panels), with F/T states based on the same criteria as in winter 2022–23. These conditions are described in Section 3.1 and summarized in Tables 5 and 6. The VV backscatter at these

stations for the two 2023–24 acquisitions (24 November 2023 and 12 January 2024) is shown in Figure 8.

Figure 8: The plot is not clear, too many lines on top of each other, some with similar colors. There seems to be a mismatch between values of this figure and Figure 7. The plot shows stronger backscatter than the colors in Figure 7, at least for stations 4, 5 and 6. But as said in the comment regarding Figure 7, it is hard to estimate the backscatter values from the images.

Response: Thank you for this comment. We have redesigned Figure 8. Each station now has its own panel, in which the soil permittivity and temperature, with the F/T state shading, are shown directly above boxplots of the VV backscatter within the station area for each acquisition. This removes the overlapping lines and lets the reader compare the SAR response with the in situ soil state at each station without switching between figures. The backscatter values in Figure 8 were updated after the SAR data were reprocessed, and they are now consistent with Figure 7.

Line 333: Should it say Figure 9?

Response: We thank the reviewer for catching this. Following the renumbering of figures elsewhere in the manuscript, this reference has been corrected to Figure 10.

Line 340-341: This sentence seems to be contradictory. If higher soil moisture levels cause more surface-like scattering, then how can the surface-like scattering be more originating from the snow surface? Please check the sentence but also confirm the physical interaction with the layers. Is it that wet snow causes high surface scattering from the air-snow interface, more than the snow-soil interface? See comment regarding Line 54-66 about adding more theoretical information on SAR responses over snow-soil combinations in variable conditions.

Response: Thank you for pointing this out. We agree that the original sentence was contradictory, and it has been removed. In the revised Section 3.4, the surface and volume scattering results are reported for each acquisition date together with the in situ soil conditions, without attributing the surface scattering to a specific interface.

On the physical interaction, we agree with your interpretation: wet snow has a much higher permittivity than dry snow, so it can increase backscattered signal at the air–snow interface and attenuate the signal reaching the snow–soil interface, whereas dry snow is nearly transparent at L-band. We have added background on how soil freezing and snow conditions affect L-band backscatter to the Introduction. Because snow wetness was not measured during the campaign, we could not separate the contributions of the two interfaces, and we now state this as a limitation in the Discussion.

Line 344: Please be precise, do you mean from the snow-air interface or from the snow medium. I assume the first is true.

Response: Thank you for this comment. In the original text, we meant the air–snow interface, as you assumed. However, since snow wetness was not measured during the campaign, we could not confirm which interface dominated the surface scattering on a given date. We have therefore removed this attribution in the revised manuscript. Section 3.4 now reports the surface scattering values at each station together with the in situ soil conditions, without assigning the scattering to a specific interface.

Line 351: Are you still referring to Mid-January 2023? 16.9 mm rain happened in mid-February. Be precise about the time periods you are explaining in the text.

Response: Thank you for this observation. We have rewritten this section so that it follows the acquisitions in chronological order, and each date is described with the air temperature, snow depth and soil conditions recorded on that date. The time periods are therefore stated explicitly throughout. The mid-February rain event is no longer discussed in this section; it is described at its correct date in Section 3.1.

Line 352-353: Is it still in mid-January? The snow was dry and thus did not have much influence on the variability of surface scattering. Or was the snow wet here? On what date did this happen?

Response: Thank you for this comment. This sentence referred to 14 January 2023, the first acquisition date, when snow depth at the weather station was 17.7 cm. Since snow wetness was not measured, we could not confirm whether the snow was dry or wet on this date, or how much it contributed to the variability in surface scattering. We have therefore removed this sentence. The revised section now states the date explicitly and reports the surface scattering at each station together with the snow depth and soil conditions on that date, without attributing the differences between stations to the snow cover.

Line 355: What about surface scattering in dry snow conditions? Is it weak as well?

Response: Thank you for this question. Yes, dry snow also produces very little surface scattering at L-band. Its permittivity is low and close to that of air, so the reflection at the air–snow interface is weak, and under dry snow the surface scattering comes mainly from the snow–soil interface. We have removed this sentence in the revised manuscript, and "dry snow" is now used only in general statements from the literature. The revised section reports the surface and volume scattering on each date together with the in situ conditions, without attributing them to a particular snow state.

Line 359: What about the presence of ice layers during other dates? Are you sure that the high volume scattering in the beginning of March is due to these ice layers? What happened to the ice layers later in spring when volume scattering decreased? For example in March 15 the temperatures were negative (most likely dry snow), but volume scattering was much lower than in March 1 and 3.

Response: Thank you for this important question. After reprocessing the SAR data, the elevated volume scattering is no longer limited to 1 and 3 March. It persisted through mid-March, with the campaign maximum on 15 March 2023, during a period when air temperatures repeatedly fluctuated around 0 °C. However, the ice layers were only reported qualitatively by the field crews in early March, and their presence, extent and evolution on other dates were not measured. We therefore cannot confirm that the ice layers caused the high volume scattering. We have removed this attribution from the Results, which now report the ice layer observation and the volume scattering separately. In the Discussion, the ice layers are presented as one possible contribution from the snowpack, together with the known tendency of the Freeman–Durden model to overestimate volume scattering, and we note that separating these effects would require detailed snowpack observations.

Line 362: On March 1 temperatures seem to be negative.

Response: Thank you for this comment. On 1 March 2023, the daily mean air temperature was indeed below freezing (around -1 °C), which is likely what the figure suggests. However, temperatures varied strongly during the day, from -8.2 °C to a maximum of $+8.7$ °C, and the temperature at the base of the snowpack remained close to 0 °C (about 0.3 °C).

Line 364: On March 1 the snow depth was at its peak. Was the snow cover still heterogeneous?

Response: Thank you for this question. Yes, the snow cover remained heterogeneous on 1 March 2023. Although the snowpack was at its deepest and covered the whole field, its depth still varied between different parts of the field.

Figure 10: Change surface scattering to volume scattering in the figure caption.

Response: We thank the reviewer for catching this. The caption has been corrected accordingly.

Figure 11: Please add one plot showing at least air temperature and snow depth as in Figure 6. This would make it much easier for the reader to analyze the results with respect to the in situ conditions. Note one of my general comments about presenting

the results in a better format that would help to directly evaluate the capability of the SAR responses to detect soil F/T.

Response: Thank you for this suggestion. We have added a panel with air temperature and snow depth to Figure 12, which now shows the Freeman–Durden surface and volume scattering together with the HydraProbe observations and the F/T state shading at each station. This lets the reader compare the decomposition results directly with both the weather and soil conditions in a single figure, without switching between figures.

Line 377-383: More information is needed for winter 2023-2024. It is not clear what the conditions were in Nov and Jan. According to Figure 8 the soil state was thaw in Nov and freeze in Jan. However, in the polarimetric analysis it sounds like the soil state in Jan was thaw. There is no in situ data to support the study, and there seems to be a contradiction between the VV-pol soil state interpretation and the polarimetric one.

Response: Thank you for this observation. In situ permittivity and soil temperature from the three stations with records in winter 2023–24 (WinterRye, Upper and Lower) are now included, and the paragraph has been rewritten. On 24 November 2023, all three stations were thawed. By 12 January 2024, WinterRye had frozen, while Upper and Lower were in a transitional state. Between these two dates, VV backscatter and both surface and volume scattering decreased, so the VV and polarimetric results now agree with each other and with the change in soil state. On 12 January 2024, VV backscatter response and volume scattering was the lowest of all acquisitions.

Chapter 3.5: This chapter should in my opinion be located straight after Chapter 3.2, because the soil F/T state retrieval is based on the VV-pol backscatter as explained in Chapter 2.6. Generally, the soil state retrieval results should be analyzed and presented more thoroughly. Quantitative validation of all flights against in situ sensors is also important, and I don't see a reason why this cannot be done. The current Figure 11 only shows four flights and is anyway not really helpful when evaluating the capability of VV-pol to detect F/T. Please see general comments concerning better presentation of results.

Response: Thank you for this comment. Following your suggestion, the F/T retrieval section has been moved directly after the VV backscatter results and is now Section 3.3, with the following sections renumbered. The previous figure showing four flights has been replaced by a figure with F/T maps for all ten acquisitions across both winters. We have also added a quantitative validation of all flights against the in situ stations, including a confusion matrix and a per-station breakdown of correct and false retrievals. Of the 40 station-date pairs with a clear frozen or thawed in situ state, 22 (55%) were classified correctly.

Line 470: January which year?

Response: Thank you. This sentence was removed when the Discussion was restructured. Throughout the revised manuscript, months are now given with the year, or are placed within a clearly identified winter season.

Chapter 4.5: This chapter is currently more suitable to be merged with the results. Instead, a discussion concerning the F/T state estimation accuracy with respect to previous research should be added.

Response: Thank you for this comment. The content of Section 4.5 has been moved to the Results, which now include a quantitative validation of all ten acquisitions with a confusion matrix and a per-station breakdown. In its place, the Discussion now compares our classification accuracy with that reported by Derksen et al. (2017) for the SMAP radar F/T algorithm, and explains the main reasons for the difference: the small number of acquisitions available to define the frozen and thawed reference values, the possible influence of wet snow in spring, and the uncertainty of the interpolated ground truth at EastDry after its sensor failed.

Line 544: The freezing mechanism of tree canopy and its contribution to SAR response is quite complex. I would just omit this sentence and say that forests were neglected in this study.

Response: Thank you for this suggestion. We have removed the sentence on tree canopy freezing. Forested areas were masked in all maps and excluded from the analysis, and this is now stated in the text and figure captions.

Line 553: Wasn't it the VV-pol backscatter that was employed for mapping the soil state?

Response: Thank you for pointing this out. Yes, the F/T maps were derived from VV backscatter.

Line 557-559: As said in the general comments, the reader is currently not fully convinced that this statement is true. How well do the VV-pol backscatter and polarimetric scattering components capture the soil F/T conditions?

Response: Thank you for this comment. We agree that the original statement was not sufficiently supported, and it has been removed. The revised manuscript now evaluates the SAR responses directly against the in situ stations. VV backscatter was on average 3.4 dB lower under frozen than under thawed soil, although changes at individual stations did not always coincide with changes in soil state. Surface scattering was highest during the spring thaw, whereas volume scattering peaked when ice layers were reported in the snowpack,

which limits its use as an F/T indicator. The Conclusions have been rewritten to reflect these results and their limitations.