Reviewer 2

The study investigates the spatial variability and characteristic length scales of snow properties on Antarctic sea ice during late summer. This is important because snow significantly affects sea ice thermodynamics, mass balance, and remote sensing. However, knowledge about its variability is limited beyond local scales. Researchers combined manual snow pit observations with more than 900 high-resolution SnowMicroPen (SMP) profiles collected during three expeditions in the Weddell Sea from 2018 to 2021. Using a supervised one-dimensional convolutional neural network (1D-CNN), they classified snow microstructural layers and types from SMP data. The paper focuses on characterizing snow properties for FYI and MYI to improve representation of snow on Antarctic sea ice. I only have specific comments.

We thank Reviewer 2 for the positive and careful review of our manuscript. The comments helped us to improve the clarity of the terminology, better justify the SMP-derived density and SSA retrievals, clarify the snow state during the late-summer measurements, and more carefully frame the implications for remote sensing and upscaling. Below, we provide a point-by-point response. Reviewer comments are shown in black text, our responses in blue text. Manuscript text is quoted and manuscript changes are set in bold. Line numbers refer to the preprint manuscript.

Line 8: which regimes?
We agree that the wording was ambiguous. We have clarified that the statement refers to the two sea-ice regimes considered in this study, first-year ice and multi-year ice.

Line 8 now reads: “Across both **sea-ice** regimes, intrinsic properties of individual snow types, including density and specific surface area, were remarkably similar.”

Line 13: 50% of the variability of what? Snow density…
We agree that the original sentence did not specify which property the variance estimate referred to. We have clarified that this statement refers to snow bulk-density variability. This is consistent with the analysis in Sect. 4.5, where floe-wise and pooled variances are calculated for bulk snow density.

Line 13 now reads: “Individual ice floes capture only about 50 % of the **snow density** variability characteristic of their respective ice regime, underscoring fundamental limits to the representativeness of point measurements.”

Line 60: I would mention SSA here if you are going use it.
We agree and have added SSA to the description of the SMP-derived snow properties, as SSA is an important parameter throughout the manuscript and is later discussed in relation to radiative transfer and remote-sensing applications.

The sentence now reads: “The SMP offers an efficient approach to rapidly characterize snow structural properties, including density **and SSA**, through mechanical resistance profiles in sub-millimeter-scale vertical resolution and independent of the observer.”

Line 73: microstructural
We agree and have changed the wording.

The sentence now reads: “However, snow **microstructural** properties such as grain or snow types are not directly measured by the SMP and must be inferred from characteristic features of the penetration signal.”

Line 107: What is the mean temperature? does that mean that the snow is wet? Can you describe what the effect is on the snowpack if temps are above zero.

We agree that the snow thermal state could be described more clearly, especially because the measurements were conducted during late austral summer. We have added a clarification that the measured snow temperatures were below 0 °C during the campaigns. This indicates that the snowpack was not undergoing active surface melt at the time of measurement. The manuscript already discusses that SMP force signals can be sensitive to temperature, liquid water content, and salinity, which can increase uncertainty in inferred snow properties during melt or flooding events.

We therefore clarify the state of the snow in Section 4, line 295 (see specific comment below).

Line 163: maybe a word on coefficients? King et al. (2020) provided coefficient for density on sea ice but no ssa…

We agree that the choice of SMP parameterization requires further clarification. We selected the Calonne et al. (2020) approach because it provides both density and SSA, which are required for the subsequent analysis, and because it showed the best agreement with the co-located snow-pit density and stratigraphy observations in our dataset. We now also acknowledge that King et al. (2020) provide sea-ice-specific density coefficients, but that no corresponding SSA retrieval is available in that framework. This distinction is important because our study benefits from a consistent retrieval framework for both density and SSA. Your notes already identify this as one of the key points.

The revised paragraph from line 163ff now reads:

"With appropriate assumptions and calibration, penetration resistance data **can be** converted to snow density and SSA following the approach of Calonne et al. (2020). **This parameterization was selected because it yields density profiles consistent with the co-located snow pit density and stratigraphy observations and provides both density and SSA, which are required for the subsequent analysis. Although Arctic sea-ice-specific SMP density coefficients have been proposed by King et al. (2020), no corresponding SSA retrieval is available.**"

Line 189: Is this how it was done in Kaltenborn et al. (2023)?

Yes. We have clarified this in the manuscript by explicitly stating that the initial identification of characteristic SMP signal patterns from co-located snow pit observations follows the approach suggested by Kaltenborn et al. (2023).

The sentence now reads: "In an initial step, all SMP profiles co-located with the 50 snow pit sites were analysed to identify characteristic signal patterns associated with snow types determined from the corresponding snow pit observations**, as suggested in Kaltenborn et al. (2023).**

Line 202: Maybe mention these parameters are also used to derive density and SSA.

We agree that this connection can be made explicit. We have added a sentence explaining that the Poisson shot-noise parameters are also the parameters used to derive density and SSA from the raw SMP force signal.

The revised text reads:

"Furthermore, the parameters deflection at rupture in mm (δ), mean rupture force (f_0), element size (L), intensity of point process (λ), as well as the median force (F_m), calculated within a 4 mm context window, were derived using the Poisson shot-noise model of Löwe and Van Herwijnen (2012). **These are the same parameters used to derive density and SSA from the raw force signal**."

Line 210: Switch the order to match "Rare or weak". New snow is not rare…
We agree and have revised the wording so that the order of examples matches the description of "rare or weakly expressed layers."

The sentence has been changed to:
"Rare or weakly expressed layers, such as **surface hoar or new snow** were excluded."

Line 295: everything is still frozen? Clarify the snow state with respect to melting.
We agree that the snow state during the late-summer measurements could be stated explicitly. We have added a sentence clarifying that observed snowpack temperatures were below 0 °C throughout the campaigns, indicating that the snowpack was not undergoing active surface melt at the time of measurement.

Line 295 now reads:
"**Although sampling took place during the austral summer, observed snowpack temperatures ranged from -7°C to 0°C with a mean temperature of -3.3°C throughout all campaigns, indicating that the snowpack was not undergoing active surface melt at the time of measurement.**"

Table 3: SSA values are key for remote sensing. I think it should be emphasized more in the conclusion or abstract.
We agree that SSA can be emphasized more strongly, because it is a key microstructural parameter for radiative transfer and microwave remote-sensing applications. We have therefore added a sentence to the abstract highlighting that the consistency of SSA within snow types across sea-ice regimes may help constrain snow-type-specific inputs to microwave emission and radiative transfer models. This addition is consistent with the manuscript's finding that snow-type-specific SSA differences between FYI and MYI are generally small, while snowpack structure and snow-type fractions differ more strongly.

Line 19 in the abstract now includes: **"In particular, the relative consistency of specific surface area within snow types across ice regimes provides observational constraints that can be evaluated for future microwave-emission and radiative-transfer modeling studies."**

Line 550 in the conclusion now reads:
"… particularly on multi-year ice. **This consistency suggests that snow-type-specific SSA values may be transferable across ice regimes, offering a basis for parameterizing snow-type-dependent inputs to microwave emission and radiative transfer models, even as bulk snowpack properties diverge structurally between FYI and MYI.** "

Line 324: Probably because of more developed facet on MYI or melted Facet which will have a small SSA.
We thank the reviewer for this helpful interpretation. We have revised the discussion of the bimodal SSA and density distributions in rounded and faceted layers on MYI to explicitly mention more developed or melted facets. This provides a more physically specific explanation for the observed lower-SSA and density mode in MYI snow.

Line 425 in Section 5.1 now reads:
"For rounded and faceted layers in this study, both density and SSA distributions transitioned from unimodal on FYI to bimodal on MYI, likely reflecting the coexistence of decomposing precipitation and older, **more developed or melted facets**."

Line 344: 35% of MF… is this even with accounting for the basal layer that couldn't be measured by the SMP on MYI?
Yes, the reported melt-freeze fraction is based only on the part of the snowpack that was penetrable by the SMP and could therefore be classified. We agree that this should be stated more clearly, especially because hard basal melt-freeze or ice layers can prevent full SMP penetration, particularly on MYI. We have clarified this in the results and expanded the methodological limitations to state that melt-freeze fractions and density estimates are biased toward the penetrable part of the snowpack. The manuscript already notes that the SMP reached its force threshold primarily on MYI floes with extensive basal melt-freeze layers.

In line 339, Sect. 4.3 we added:
"The relative fraction of each snow type within individual snow profiles is calculated, **based on the classification of the penetrable snowpack.**

In line 498 in Sect. 5.3 we revised the limitations: "As a result, density **and snowtype fraction** estimates for melt-freeze layers are biased toward the penetrable fraction, and bulk snow density may be underestimated where thick, hard layers occur, predominantly on MYI (Arndt, 2022a).

Line 372: "indicating that bulk density is the most spatially homogeneous property." That is good for remote sensing retrieval.
We agree that the comparatively low variability of bulk density is relevant for large-scale applications. We have added a short pointer in the results and expanded the discussion in Sect. 5.2 to distinguish between applications that rely mainly on bulk-integrated properties, such as first-order snow-load or SWE estimates, and applications that are sensitive to internal stratigraphy.

Line 372 now reads: "In contrast, lowest RSD values are found for bulk snow density, indicating that bulk density is the most spatially homogeneous property, **a favourable characteristic for large-scale snow-load estimates, as discussed further in Sect. 5.2.** However, individual layer densities exhibit RSD values approximately twice as high as those of bulk density."

Line 430: King et al. (2020) measured data in winter.... this study in the summer. How do you think this affect the comparison.
We agree that the comparison with King et al. (2020) is affected not only by hemisphere but also by season. King et al. (2020) measured Arctic snow under winter conditions, whereas our dataset represents late austral summer conditions in the Antarctic. Therefore, the observed contrast may reflect both hemispheric differences in sea-ice surface processes and seasonal differences in snow metamorphism. In particular, late-summer Antarctic snow is more likely to preserve signatures of melt-refreeze modification, flooding, snow-ice formation, and superimposed-ice processes, whereas winter Arctic snow is more strongly shaped by cold-season accumulation and temperature-gradient metamorphism. We have therefore revised the discussion.

The paragraph now reads:

"Finally, we note a hemispheric contrast, though a direct quantitative comparison is limited by the fact that King et al. (2020) sampled Arctic winter snow, whereas our dataset represents Antarctic late summer. In their study, Arctic winter FYI showed higher bulk density than MYI, linked to a larger fraction of low-density depth hoar on MYI and pronounced surface heterogeneity. Our Antarctic snowpacks, by contrast, were sampled at the opposite end of the seasonal cycle: by late summer, depth hoar is comparatively minor and MYI bulk density instead exceeds FYI, driven by the greater prevalence of dense melt-freeze layers near the base of the snowpack. Because the two datasets capture different stages of seasonal snowpack evolution, the contrasting patterns reflect a combination of seasonal and hemispheric

differences in snowpack processes rather than ice-age effects alone. We therefore highlight that snowpack evolution and bulk properties are strongly shaped by both regional (climate) regime and season, underscoring that density-stratigraphy relationships established for one hemisphere and season cannot be directly transferred to another without accounting for these differences."

Line 431: Do you also see the same thing for SSA?
As King et al do not report any SSA values, we cannot directly compare to their datasaet. However, within our dataset we observe a related but slightly weaker pattern: snow-type-specific SSA values are generally similar between FYI and MYI, with slightly lower mean SSA values on MYI for most snow classes. This is consistent with more metamorphosed snow grains in snowpacks affected by repeated melt-refreeze cycling.

The revised sentence in line 419 in Section 5.1 now reads:
"In particular, **lower mean SSA and** higher snow bulk density on MYI is not caused by denser individual layers, but by the nearly three-times greater prevalence and two-times higher thickness of **low-SSA,** dense melt-freeze layers (for details see Table 3)"

Line 486: What if you want to retrieve bulk properties like SWE?
We agree that bulk applications such as snow load or first-order SWE estimates should be distinguished from stratigraphy-sensitive retrievals. We have revised the discussion accordingly. Our results suggest that bulk density may be more robustly upscaled than layer thickness, snow-type fractions, or SSA because it is the most spatially homogeneous property in our dataset. However, SWE also depends directly on snow depth, which remains spatially variable, and therefore robust SWE estimates still require spatially representative snow-depth information. Moreover, the comparatively low variability of bulk density does not imply that bulk snow representations are sufficient for retrievals that depend on vertical snow structure, such as microwave emission, microwave scattering, or snow-ice interface detection.

We revised the discussion from line 482 on:
"… snow-type composition and stratigraphy requires substantially higher spatial sampling density. **This distinction is also relevant for remote-sensing applications: for first-order estimates of snow load or snow water equivalent, bulk density may be more robustly upscaled than layer thickness, snow-type fractions, or SSA. However, the comparatively low variability of bulk density does not imply that bulk representations are sufficient for all retrieval applications. Microwave emission and scattering are sensitive to the vertical distribution of density, SSA, and melt-freeze layers, so retrieval approaches that depend on radiative transfer or snow-ice interface detection still require information on stratigraphic structure (Durand et al., 2011; Royer et al., 2017; Tonboe et al., 2022).** More fundamentally, representing Antarctic snow processes …"

and in line 486:
"Consequently, Antarctic snow variability is governed by meter-scale structural heterogeneity and ice-regime dependence rather than by bulk properties alone. This implies that observational strategies, remote-sensing retrievals, and model parameterizations **that depend on internal stratigraphy, as opposed to bulk-integrated quantities such as snow load,** should move beyond uniform bulk representations toward approaches that explicitly account for ice-regime-dependent snow stratigraphy and its scale-dependent variability."

Line 507: Different parametrizations also exist…

We agree and have expanded the methodological limitations to acknowledge that different SMP parameterizations exist and may yield different absolute values. We selected the Calonne et al. (2020) approach because it provides both density and SSA and showed the best agreement with the co-located snow-pit stratigraphy in our dataset. We now state explicitly that alternative parameterizations, including Proksch et al. (2015) and King et al. (2020), were calibrated on different snow populations and could shift absolute density or SSA magnitudes. However, because the same retrieval framework is applied consistently across all profiles, we expect the relative contrasts between ice regimes and snow classes to be more robust than the absolute values. This is consistent with the methodological limitations already discussed in Sect. 5.3.

Revised text from line 509 on: **"Alternative parameterizations for retrieving density and/or SSA from SMP signals also exist (e.g., Proksch et al., 2015; King et al., 2020), calibrated on different snow populations, and these can yield systematically different absolute values. We selected the Calonne et al. (2020) approach based on its agreement with our co-located snow pit stratigraphy. Using an alternative parameterization would likely shift absolute density and SSA magnitudes, though relative contrasts between ice regimes and snow types, as well as spatial variability patterns, are expected to be less sensitive than the absolute values."**

Line 550: Yes but is there an impact of a bulk representation for remote sensing retrieval? This wasn’t shown here.
We agree that our study does not directly quantify the impact of bulk versus stratigraphic snow representations on individual remote-sensing retrieval algorithms. We have therefore revised the conclusion to distinguish between findings demonstrated by our observations and implications that require dedicated forward-modeling studies, which go beyond the scope of this manuscript. The revised wording now states that uniform bulk representations are insufficient for applications that depend on internal stratigraphy, while acknowledging that direct retrieval impacts remain to be tested.

Together with the changes pointed out in the comment above on Table 3 and SSA values as a key variable for remote sensing, the revised conclusion from line 550 onward now reads:
“This consistency suggests that snow-type-specific SSA values may be transferable across ice regimes, offering a basis for parameterizing snow-type-dependent inputs to microwave emission and radiative transfer models, even as bulk snowpack properties diverge structurally between FYI and MYI. **At the same time, this transferability applies at the level of snow types rather than snowpacks as a whole.** This highlights that Antarctic snow cannot be adequately represented by uniform bulk properties or sparse point observations. Instead, snow on Antarctic sea ice should be treated as a stratigraphically structured, ice-regime-dependent medium, with implications for sampling strategies **and, pending dedicated forward-modeling studies for remote-sensing retrievals,** and the representation of snow processes in sea ice models.”