I was really pleased to see this paper come up in TCD. I think that generating radar freeboard data from ERS1/2 is one of the most pressing tasks for the sea ice community, and so I agree with Jack Landy's review. Overall I think the paper is well written and addresses what is a very significant gap in our knowledge of the Arctic Ocean. In particular I think the figures are well designed.

I do have a couple of concerns, questions and suggestions over wordings, citations etc. I hope the authors will take these in the spirit of discussion, rather than as negative criticism. I really do think that this research is high-quality and useful.

L25) I would question whether "thin ice is more sensitive to climatic hazards". Bitz and Roe (2004) argued the opposite: that thick ice is thinning faster, because areas of thin ice grow more quickly in winter. Age products also show that thicker, older ice is dissappearing from the Arctic and being replaced by thinner, seasonal ice (e.g. Nghiem et al., 2007). So I'm not sure it makes sense to say that thin ice is more sensitive to climatic hazards, when thin ice is coming to dominate the Arctic and is more robust to temperature perturbations.

L32) I don't agree that it's "commonly accepted" that Ku-band radar waves penetrate the snow layer when it is sufficiently cold. I think that assumption is still up for discussion, and I would argue the opposite. I'm not aware of any in-situ or airborne CryoSat evaluation ever done over sea ice that has produced evidence that Ku-band radar waves consistently return from the snow-ice interface.

For instance, neither of the airborne CryoVex 2006 and 2008 campaigns (Willatt et al. 2011) indicated that this was consistently the case over FYI. Results from a different radar system in Antarctica (Willatt et al. 2010) also showed that radar waves do not always return from the ice surface. Results from a third radar system deployed on MOSAiC (on SYI) indicate that more Ku-band power comes back from the snow surface than from the ice surface (Stroeve et al., 2020 Fig. 7; Nandan et al., 2022 Fig. 8). Garnier et al. (2022; Figure 9) shows results from CryoVex 2017 where the difference between Ka and Ku band ranging is at times negative, further casting doubt on the assumption.

Moving to satellite-based evidence, Armitage and Ridout (2015) calculated CryoSat-2's penetration factor as 82%. Ricker et al. (2015) used buoys to show that snow accumulation caused increases in Rfb, not decreases (implying that the radar waves are not penetrating fully). This agrees with the work of Gregory et al., (2022; Figure 9) that shows that snowfall is correlated (not anti-correlated) with Rfb over both ice types.

I would also argue that the often-cited work of Beaven et al. (1995) was not realistic – it featured snow that was shovelled, sifted through a screen, and then artificially smoothed at the surface by the weight of a metal plate before measurement. It is also striking that what the authors identify as the snow-ice interface appears at 20 cm range when it was 21 cm away in free space. Since it was 21 cm away in free space it should have appeared further away, at something like 25 cm in range due to the wave-propagation delay.

There's no need to mention all this in your paper, but I wanted to briefly state my evidence before making the point that *full Ku-band penetration* is not a settled consensus, even for cold, dry snow. I think it would be fair to say that full penetration is "commonly assumed in satellite-based sea ice thickness products". But just because we're forced to assume it in our products doesn't mean the we should actually believe or accept the assumption.

L381: Year of this citation is 1986.

L65: I think we're not really measuring sea ice thickness, but instead estimating it based on freeboard measurements (or radar-altimetry measurements). This might seem like a semantic point, but I think users of sea ice thickness products do benefit from this distinction. "estimates" rather than "measurements" is more commonly used by convention (e.g. Tilling et al., 2018, Kurtz et al., 2014; Landy et al., 2017).

L75: I think readers like me who aren't expert in roughness would benefit from a citation here. Is LRM definitely more impacted by a given roughness than SARM? I can believe it, but would like to read some evidence.

L103: I think you mean NSIDC 0611? This product gives the maximum of the ice age distribution in a grid cell at each timestep (see quote below). So I'm not sure how you've used these max values to generate an MYI fraction product? I think it could be done if you had access to the Lagrangian data, which is out there. But if you've used this I think you should state that.

(Tschudi et al. (2020) states "This approach does not consider new ice that may form within a grid cell because it retains only the oldest ice in its accounting. Thus, the product is effectively an estimate of the oldest ice in a given grid cell.")

L115: I think at some point you should direct the reader to Kwok and Haas (2015), which discusses some key issues in the product that you've chosen.

L310: "Surface roughness is identified as the largest source of uncertainty" - I didn't really understand how you made it to this conclusion.

I think this is specifically a reference to Fig. 8 of Landy et al. (2020). The error in the sea ice roughness over FYI is 4cm, and the error from the snow basal salinity (just part of the "penetration bias") is 7 cm, and the uncertainty due to snow depth is 6 cm. So over FYI the roughness uncertainty is smaller than either the snow depth or the snow salinity. As such I don't think roughness can be reasonably characterised as "the largest source of uncertainty" over FYI based on Landy et al. 2020 Fig. 8. Over MYI the sea ice roughness uncertainty is equal to the snow depth uncertainty, and admittedly larger than "partial snow penetration" uncertainty. So the statement is narrowly true if you only consider MYI and don't factor in the (highly related) uncertainty in snow depth in the comparison.

But I think that only considering the largest source of uncertainty and ignoring the other uncertainties is a pretty risky strategy, given the other sources are comparable and perhaps actually larger in magnitude? If you are wedded to this approach, I think you should state that this will induce a pretty serious underestimate in your uncertainty values (which is important info for product end-users).

Fig. 6: I see in the top panel that you've "summed the squares", which has the implicit assumption that uncertainties that you have considered are un-correlated. It may be that you have good evidence to support this that I'm ignorant of, but it seems, for instance, that speckle noise may well be (anti?)correlated with surface roughness? Just as an example. I think that the omitted snow uncertainties involving penetration & depth are more likely than not to be correlated in some way. I think you should state that you've assumed the uncertainties are uncorrelated in your analysis, and give the reader some information as to what the results of that assumption may be.

Figs. 7 & 8: These are really well designed and presented

L381: 4) Why take snow density as constant? SnowModel-LG outputs depth and density, and includes some physics of densification/settling over time. So I think it's odd to use one of its variables and not the other, since they're so linked in the model. Snow impacts thickness retrievals by weighing the floe down and slowing radar waves: both of these effects are proportional to the mass of overlying snow – not the depth (see Mallett et al., 2021). So I think it makes a lot more sense to use both the depth and density (the SWE) in your thickness retrievals rather than just the depth. Here's a plot of the seasonal densification of SnowModel-LG snow north of 88N for the period 1995-2018. You'll see that as well as being more dense than your assumption, it also evolves over the season.

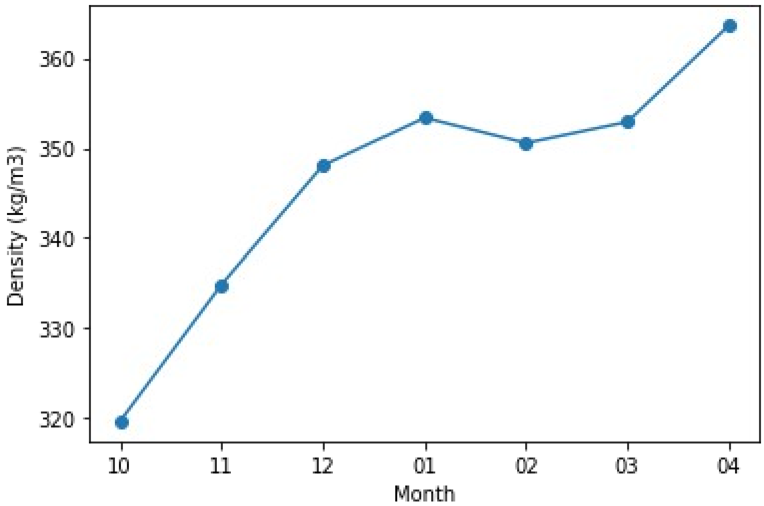

Fig 13: I'm a little unclear what the radar freeboard timeseries is supposed to represent. I imagine it mostly reflects the trend and variability in sea ice extent, and I think you should point this out to the reader. A simple correlation with SIE would quantify this relationship and reveal if the quantity is useful. For the part of it that doesn't represent SIE, would decreasing volume reflect a thinning of sea ice? Thinning snow (Webster et al., 2014) will mask the effect of thinning ice on the Rfb. In areas where the snow is really thinning quickly, the Rfb could potentially even increase even if the ice is thinning. I guess I would like to see a little interpretation of this quantity & figure 13 rather than being left to do it as the reader.

L450: I think you should state the limitations in your uncertainties here. In particular (and I think this is key), do the "observed" thicknesses fall within your uncertainty bounds? If not, then either your uncertainty bounds are wrong or the validation data is wrong. I think uncertainty bounds on retrievals are not useful unless you can show that observed data fall within them.

Data availability: I was disappointed to see that the data were not made available given the community-focus of The Cryosphere. Also, because the code is not available, the work is not reproducable or checkable by the nominated reviewers. The data policy of TC is clear that:

"If the data are not publicly accessible, a detailed explanation of why this is the case is required".

The context of this is also given by the data policy:

"The output of research is not only journal articles but also data sets, model code, samples, etc. Only the entire network of interconnected information can guarantee integrity, transparency, reuse, and reproducibility of scientific findings. Moreover, all of these resources provide great additional value in their own right. Hence, it is particularly important that data and other information underpinning the research findings are "findable, accessible, interoperable, and reusable" (FAIR) not only for humans but also for machines.”

I really would encourage the authors to follow the data policy, especially as it is likely to significantly increase the impact of their work.

References

Landy, Jack C., et al. "Sea ice roughness overlooked as a key source of uncertainty in CryoSat 2 ice freeboard retrievals." Journal of Geophysical Research: Oceans 125.5 (2020): e2019JC015820.

Tilling, Rachel L., Andy Ridout, and Andrew Shepherd. "Estimating Arctic sea ice thickness and volume using CryoSat-2 radar altimeter data." Advances in Space Research 62.6 (2018): 1203-1225.

Kwok, Ron, et al. "Intercomparison of snow depth retrievals over Arctic sea ice from radar data acquired by Operation IceBridge." The Cryosphere 11.6 (2017): 2571-2593.

Kwok, R., and C. Haas. "Effects of radar side-lobes on snow depth retrievals from Operation IceBridge." Journal of Glaciology 61.227 (2015): 576-584.

Landy, Jack C., et al. "Sea ice thickness in the Eastern Canadian Arctic: Hudson Bay Complex & Baffin Bay." Remote Sensing of Environment 200 (2017): 281-294.

Webster, Melinda A., et al. "Interdecadal changes in snow depth on Arctic sea ice." Journal of Geophysical Research: Oceans 119.8 (2014): 5395-5406.

Mallett, Robbie DC, et al. "Faster decline and higher variability in the sea ice thickness of the marginal Arctic seas when accounting for dynamic snow cover." The Cryosphere 15.5 (2021): 2429-2450.

Tschudi, Mark A., Walter N. Meier, and J. Scott Stewart. "An enhancement to sea ice motion and age products at the National Snow and Ice Data Center (NSIDC)." The Cryosphere 14.5 (2020): 1519-1536.

Armitage, Thomas WK, and Andy L. Ridout. "Arctic sea ice freeboard from AltiKa and comparison with CryoSat 2 and Operation IceBridge." Geophysical Research Letters 42.16 (2015): 6724-6731.

Willatt, Rosemary C., et al. "Field investigations of Ku-band radar penetration into snow cover on Antarctic sea ice." IEEE Transactions on Geoscience and remote sensing 48.1 (2009): 365-372.

Willatt, Rosemary, et al. "Ku-band radar penetration into snow cover on Arctic sea ice using airborne data." Annals of Glaciology 52.57 (2011): 197-205.

Ricker, Robert, et al. "Impact of snow accumulation on CryoSat 2 range retrievals over Arctic sea ice: An observational approach with buoy data." Geophysical Research Letters 42.11 (2015): 4447-4455.

Gregory, William, Isobel R. Lawrence, and Michel Tsamados. "A Bayesian approach towards daily pan-Arctic sea ice freeboard estimates from combined CryoSat-2 and Sentinel-3 satellite observations." The Cryosphere 15.6 (2021): 2857-2871.

Beaven, S. G., et al. "Laboratory measurements of radar backscatter from bare and snow-covered saline ice sheets." Remote Sensing 16.5 (1995): 851-876.

Garnier, Florent, et al. "Advances in altimetric snow depth estimates using bi-frequency SARAL and CryoSat-2 Ka–Ku measurements." The Cryosphere 15.12 (2021): 5483-5512.

Bitz, C. M., and G. H. Roe. "A mechanism for the high rate of sea ice thinning in the Arctic Ocean." Journal of Climate 17.18 (2004): 3623-3632.

Nghiem, S. V., et al. "Rapid reduction of Arctic perennial sea ice." Geophysical Research Letters 34.19 (2007).

Stroeve, Julienne, et al. "Surface-based Ku-and Ka-band polarimetric radar for sea ice studies." The Cryosphere 14.12 (2020): 4405-4426.

Nandan, Vishnu, et al. "Wind Transport of Snow Impacts Ka-and Ku-band Radar Signatures on Arctic Sea Ice." The Cryosphere Discussions (2022): 1-38.

Kurtz, Nathan T., N. Galin, and M. Studinger. "An improved CryoSat-2 sea ice freeboard retrieval algorithm through the use of waveform fitting." The Cryosphere 8.4 (2014): 1217-1237.