The Cryosphere Discussions

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Comment on tc-2022-127

Anonymous Referee #3

Referee comment on "Sentinel-1 detection of seasonal and perennial firn aquifers in the Antarctic Peninsula" by Lena G. Buth et al., The Cryosphere Discuss., https://doi.org/10.5194/tc-2022-127-RC3, 2022

The manuscript decribes the development of new algorithm that uses an arbitrary set of thresholds and fixed dates to map ‘seasonal and perennial firn aquifers’ on the Antarctic Peninsula, and then comapres these results to IMAU-FDM. The manuscript further details the simulation of backscatter time series using IMAU-FDM and the SMRT radiative transfer model to ‘validate’ the comparison. ‘Seasonal firn aquifers’ are mapped if meltwater is detected in one year. ‘Perennial firn aquifers’ are detected ‘by proxy’ if meltwater is detected for one or more years. The authors acknowledge that they cannot tell the difference between the signals. Although the comparison between the S1 detection algorithm and IMAU-FDM appear to be in broad agreement when combined over the three-year time series, no year-by-year comparison is provided. Recent field measurements and OIB observations of an expansive perennial firn aquifer on the Wilkins Ice Shelf – which neither the S1 detection algorithm or IMAU-FDM are in agreement with – are not discussed. Alternatively, the authors suggest that coincident field observations are required for validation, which implies that perennial firn aquifer form and refreeze on a regular basis. The manuscript concludes with statements on perennial firn aquifers and ice shelf collapse that are not supported by the study.

Major Comments –

There are significant technical and theoretical issues throughout this manuscript detailed in the minor comments. Assumptions and conclusions are made that are simply not supported by the analysis. In particular, it is unclear how and why the thresholds were chosen other than to simply reproduce the IMAU-FDM simulations. Given that the study uses a radiative transfer model, it would be reasonable to expect that the threshold for subsurface meltwater would be chosen based on a series of simulations. However, that is not the case. The assumption that these thresholds remain stable temporally and spatially is not plausible. There is nearly a 10 C difference in the mean annual temperature between the northernmost islands and the southernmost George VI Ice Shelf. Many of the northern locations have a mean annual temperature near 0 C. This results in a significant difference in the melting seasons between locations. This is reflected in the final mappings which show the north and northwestern Antarctic Peninsula as primarily ‘perennial firn aquifers’, when what the algorithm is actually detecting is surface meltwater during longduration melting seasons. This is further complicated by the shallow penetration depth of S1, which cannot detect meltwater beyond a few meters' depth in the percolation zone. The lack of a detection can simply imply that meltwater is present, and has simply descended below the penetration depth prior to the fixed April 14th date. Overall, my conclusion is that the S1 detection algorithm is mapping both surface and subsurface meltwater within a fixed time interval and limited penetration depth. Unfortunately, I am unable to recommend publication of this manuscript.

Minor Comments:

Line 36-38 – Both the Wilkins (Montgomery et al., 2020) and Muller ice shelves (MacDonell, 2021) have perennial firn aquifers confirmed via fieldwork. The perennial firn aquifer on the Wilkins Ice Shelf is confirmed throughout the winter of 2017-2018, again throughout the winter of 2018-2019, and 2019-2020. Firn cores confirmed ~20 meters of meltwater at depths of ~15 m below the surface. The perennial firn aquifer was also confirmed within a ~15 km radius by GPR surveys in December 2018.

Line 56-57 – Why is horizontal transmit/receive polarization used? Were both channels analyzed?

Line 58 – The gridding is 1 km x 1km. The spatial resolution of the measurements is 20 m x 40 m.

Line 58 – What is the temporal resolution of the combined S1-A and S1-B? 12 days?

Line 60 – What is the incidence angle range of the measurements before averaging? How does averaging measurements with different orbital geometries (i.e., incidence and azimuthal angles) over the complex topography of the Antarctic Peninsula bias the measurements? Can the authors please cite or justify the averaging method?

Line 62-63 – What is the maximum and minimum number of data points 'eliminated' from each time series used in the algorithm? How does that influence the targeted signal spatially and temporally in terms of the algorithm performance, particularly in 2017-2018?

The authors use three (not four) years of data 2017-2018, 2018-2019, and 2019-2020. However, none of the provided plots or maps show 2017-2018, which is odd for such a short time series. Can the authors please provide a reason for this omission? If the data isn't suitable to show, is it suitable to use in the S1 detection algorithm? Are the results viable?

Please cite the ice masked used in the detection algorithm.

Line 120-121 ‘IMAU-FDM does not simulate standing water or lateral water flow, so only a qualitative comparison can be made with S1 detected aquifers on the basis of the presence of irreducible liquid water content’.

If these processes were included in IMAU-FDM, can the authors please describe how a quantitative comparison could be made? The S1 detection algorithm is binary.

Line 124-128 – The S1 detections are 20 m x 40. The IMAU-FDM is 5.5 km x 5.5 km. Can the authors please describe how the time series and map comparisons were made?

Line 133-135 – An observational technique (S1 detection algorithm) can’t be ‘validated’ using a model simulation (SMRT) parametrized with a model simulation (IMAU-FDM). The simulations are simply not real.

Line 188-190 – ‘The South Shetland Islands show almost complete firn aquifer cover, confirmed by local observations (Jiahong et al., 1998; Travassos and Simoes, 2004; Macheret et al., 2009).’

These studies do not describe a ‘complete firn aquifer cover’. These results describe a ~1 m water table above the firn ice transition at ~ 30 - 50 m depth in a temperate glacier at field sites. These studies were conducted in 1985-1992, 1997-1998, and 2000-2006 – as much as 30 years prior to this study, and not coincident in time with S1. No comparisons between the S1 detections and these fields sites are provided.

Noting that the penetration depth of S1 is several meters – can the authors please justify using these field sites to ‘validate’ the detection algorithm?

Can the authors also please justify using these field sites to ‘validate’ the detection algorithm, when the field sites on the Wilkins Ice Shelf and the Muller Ice Shelf - which are coincident in time and do not appear to be consistent with the results of the S1 detection algorithm - are simply disregarded as ‘complex’, citing ‘dissimilar quantities in different time scopes’?

Line 202-203 – ‘The increase of backscatter over time after the peak melt season can be caused by the wet layer getting buried under fresh snow accumulation’

Backscatter from snow accumulation at C-band wavelengths is negligible.

Line 235-236 This issue will become less relevant in the coming years as the amount of data is increasing, although a complication is that Sentinel-1B has failed since December 2021 with no guarantee of operating again’.

Sentinel 1-B has failed. Only Sentinel 1-A is operational. The authors stated in the methods section that ‘sufficiently dense data coverage for our purpose was only reached after the launch of Sentinel-1B in April 2016’. If Sentinel-1B failed, and both satellites are required for ‘sufficiently dense data coverage’, can the authors please describe how is the amount of data increasing?

Line 253-254 - ‘Comparing the satellite detection results with in-situ measurements on the Wilkins and Müller ice shelves (Montgomery et al., 2020; MacDonell et al., 2021) is complex as dissimilar quantities in different time scopes are measured.’

This is an overly complicated sentence, when the comparison is simple. The authors are using S1 data with a resolution of 20 m x 40 m - comparable to a firn core. The authors claim to be ‘confidently’ mapping ‘seasonal and perennial firn aquifers’ over the Antarctic Peninsula. There is a field confirmed perennial firn aquifer on the Wilkins Ice Shelf in 2017-2018, in 2018-2019, and 2019-2020. Not simulated. Confirmed. At some point near the end of the austral meting season in 2017, 2018, and 2019, the seasonally recharged upper layers of the perennial firn aquifer were within the penetration depth of S1 and detectable. The authors appear to detect a ‘seasonal firn aquifer’ on the Wilkins Ice Shelf in 2018, however - as previously noted – the data is oddly not shown. The algorithm fails to detect even a ‘seasonal firn aquifer’ in 2019 or 2020.

Can the authors please justify the lack of a S1 detection?

Line 254-258 ‘On Wilkins Ice Shelf, the reported aquifer water tables were typically located at 6 to 22 meter the surface in 2014, and IMAU-FDM does not provide indications that the very deep aquifers have been recharged in recent years…'

The OIB-derived detections reported in Montgomery et al., (2020) extend over nearly the entire Wilkins Ice Shelf. Again, not simulated. These are observations. Furthermore, to attenuate the low-frequency MCoRDS signal, the detection implies that a relatively thick perennial firn aquifer with significant volumes of meltwater is present at depth. The assumption that the authors seem to make throughout the manuscript - that perennial firn aquifers form and refreeze regularly on the Wilkins Ice Shelf (and everywhere else) - is simply not plausible. Can the authors please justify this assumption?

IMAU-FDM does not appear to simulate the extent of the perennial firn aquifer confirmed by observations over the Wilkins Ice Sheet in 2014 (van Wessem et al., 2020). Nor does it simulate the perennial firn aquifer 2017, in 2018, and 2019. Can the authors explain the relevance of the fact that IMAU-FDM does 'not provide indications that the very deep aquifers have been recharged in recent years' to the S1 detection algorithm results? If IMAU-FDM is not capable of simulating the field confirmed firn aquifer on the Wilkins Ice Shelf, can the authors justify the comparison between the S1 detection algorithm and IMAU-FDM over the entire Antarctic Peninsula?

Line 259-261 – 'further analysis of OIB flight measurements would be useful for comparison as they provide information on the firn aquifer water table on a larger scale. Especially collecting measurements before the peak melt season would be valuable as they allow detection of perennial firn aquifers which are more robustly defined than seasonal aquifers'

There are almost 20 years of OIB data, including OIB-derived perennial firn aquifer detections (Montgomery et al., 2020) publicly available and not used in this study.

Line 264 – 268 - 'Finally, it is noteworthy that the existence of perennial firn aquifers at the grounding line and the presence of extensive floating ice shelves appear to be mutually exclusive on both sides of the AP (Fig. 7). This suggests that perennial firn aquifers play an important role in ice shelf viability and demise: if a perennial firn aquifer develops around the grounding line or on the ice shelf, it is a precursor for collapse.

Big conclusion that is not supported by the results of this study.

Line 264 – 268 – 'An exception is Wilkins ice shelf, but it is well known that this ice shelf has partly disintegrated in recent years (Braun et al., 2009).'

How exactly did the formation of perennial firn aquifers at the grounding line of the Wilkins Ice Shelf contribute to the collapse and disintegration of the ice front?

Figure 2.
SMRT is a snow model. It is not appropriate for modeling deeper subsurface meltwater within the complex stratigraphy of the percolation facies. During refreezing, the dominant backscattering response is via volume scattering from ice pipes and lenses – which significantly reduces penetration depth. This is well-documented in the literature. Additionally, in perennial firn aquifer areas, SMRT does not include latent heat release from refreezing meltwater.

The SMRT simulated 'dry' and 'wet' layers are inconsistent with the actual backscatter data shown in Figure 4.

The 'dry layer' is simulated with backscatter values of between ~ -25 dB to -15 dB.

These values are consistent with volume scattering from dry snow in the interior of the ice sheet – not the percolation zone where volume scattering from ice pipes and lenses dominates the response. A realistic 'dry layer' in the percolation zone that included ice pipes and lenses would plausibly have backscatter values between ~ -5 dB and 0 dB, which is consistent with the plots shown in Figure 4, except for the Muller.

The 'wet layer' is simulated with backscatter values between ~ -15 dB and almost -40 dB.

However, in the percolation zone, it is uncommon for the backscatter value to drop below ~ -25 dB at C-band. This value is consistent with significant surface melting, not subsurface meltwater. So, in terms of observations, the minimum value (not simulated or the 'radiometric accuracy') should reasonably be set at ~ -25 dB. This is also consistent with peak melt on any of the plots shown in Figure 4.

Setting the lower threshold at -25 dB would decrease the 'detection limit' to ~1 m.

Can the authors justify a reasonable detection of 'seasonal and perennial firn aquifers' at these shallow depths?

Alternatively, can the authors justify their modeling approach? Specifically, why are uniform density, grain size, and LWC values used to depths of 7 m, rather than depth-dependent parameters? Is the 5% LWC value consistent with field measurements? How does the detection limit change with increasing and decreasing LWC values?

Figure 3

The authors state that this plot represents an 'idea case' – why was this plot chosen? What are the dates? What are the lat/lon coordinates? Is it a 'seasonal' or perennial' firn aquifer? If you can't tell the difference – why is it ideal?

Can the authors explain the significant differences between the 'ideal case' and the Muller

Ice Shelf site shown in Figure 4, which obviously shows extended, possibly year-round surface melting? How does that influence the detection algorithm?

Can the authors show that the 'ideal case' characterizes the majority of the 'perennial firn aquifers' in the northern Antarctic Peninsula + islands? Or do those sites look more like the Muller Ice Shelf site?

Figure 4

The authors need to provide lat/lons for each of these sites. The Wilkins Ice Shelf and the Muller Ice Shelf sites appear to be field locations from other studies (Montgomery et al., 2020; MacDonell et al., 2021) The authors need to acknowledge this work, and describe what was found at these sites.

Note: There are issues with using a 15 -day smoothing filter on the S1 backscatter and distinguishing surface melting from subsurface meltwater, particularly at the end of the melting season. The smoothed signal with 'mimic' the subsurface meltwater signal if there is late season surface melting. Similarly, the IMAU-FDM is simulated on 10-day intervals, which makes time series comparisons difficult to interpret.

Note: The authors state that the peak melting season is between 1 and 15 January – yet many of the time series, suggest this data is much later, with significant variability between years. As an example, in 2020, the peak melting season appear to be in March, with similar shifts on the George VI in both 2019, and 2020.

The authors state that 'Line 143-145 - there is a clear correspondence between the presence of liquid water in IMAU-FDM and the corresponding forward modelled SMRT S1 backscatter time series on the one hand, and the observed S1 backscatter time series on the other hand'.

Given that the IMAU-FDM is the primary input into the SMRT – it is expected that there would be a 'clear correspondence' between the two.

However, there is no obvious correspondence between the SMRT and S1 backscatter on the Larsen C, George VI, or Wilkins. The SMRT does not simulate the identified subsurface meltwater signal at the end of the melting season – which suggests that the dominant backscattering responses are not simulated in SMRT, or that the IMAU-FDM is not adequate simulating the actual firn conditions at the surface. In 2019 – there are several months where the there is clearly significant subsurface meltwater detected by SI.

The Wilkins Ice Shelf, in particular, is a field validated perennial firn aquifer site that the IMAU-FDM is not simulating and the SI algorithm is not detecting in either year. This is a strong indication that the IMAU-FDM will not simulate accurate results. Furthermore, the 2019 Wilkins Ice Sheff site and 2020 Larsen C Ice Shelf site (Line 135-136 - 'a location with rapid meltwater refreezing and therefore small amounts of retained liquid water ') appear to be near identical in terms of the S1 detection – shifting a threshold would identify aquifers on both sites in different years. This is a strong indication that the S1 detection algorithm is not viable.

On the Muller Ice Shelf in 2019 – the backscatter values appear to be near -15 dB at the start of the time series, and experience a limited drop in backscatter values during the melting season. This suggests that the firn is initially wet at or very near the surface and gets wetter throughout the melting season. It would be difficult to justify these backscatter values from subsurface meltwater underlying ice pipes and lenses. Once surface meltwater began the refreezing process, strong scattering would increase backscatter values very quickly. The authors potentially attribute this to supraglacial lakes (Line 149-150 - The S1 backscatter signal could represent persistent or slowly buried supraglacial lakes'), however, this appears to be the field confirmed perennial firn aquifer site described in MacDonell et al., 2021, where supraglacial lakes are not observed. In 2020, there is obviously surface melting throughout the entire year. Even smoothed, the backscatter time series show significant variability. Backscatter values appear to be below -15 dB prior to the start of the 2020-2021 melting season. The detection thresholds are chosen during active surface melting at this site. The algorithm is detecting active surface melting, not subsurface meltwater. Even know this is a field confirmed perennial firn aquifer site, subsurface meltwater is masked. It is simply not possible to detect 'seasonal and perennial firn aquifers' during active surface melting. This is a second strong indication that the S1 detection algorithm is not viable.

Unfortunately, the backscatter time series on the Muller Ice Shelf are characteristic of the entire north and northwestern Antarctic Peninsula.