

The Cryosphere Discuss., author comment AC3
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Reply on RC3

Julie Z. Miller et al.

Author comment on "An empirical algorithm to map perennial firn aquifers and ice slabs within the Greenland Ice Sheet using satellite L-band microwave radiometry" by Julie Z. Miller et al., The Cryosphere Discuss., <https://doi.org/10.5194/tc-2021-116-AC3>, 2021

Author Response Reviewer #3

I apologize deeply for being "the late reviewer." I hope the tardiness of this review has not harmed the authors significantly.

Note: the editor asked the authors to respond to the reviewers' comments before revising the paper. So, the authors have described the intended revisions.

The authors forgive the tardiness of "the late reviewer". We thank you for the detailed and challenging comments, many of which the authors wrestled with in the process of writing the submitted manuscript.

As usual, I wish to iterate that the authors have engaged in far more work and consideration in writing this paper than I have undertaken while reviewing it. My comments here are meant to be productive and lead to a better manuscript. If, however, any part of my review seems unfair, or if it misunderstands the authors' points (or even misses them entirely), then I fully encourage and welcome the authors to respond accordingly with rebuttals to those points. I hope that the process remains constructive.

Primary comments on scientific merit:

On the whole, this manuscript is a solid (liquid?) contribution to the ice sheet remote sensing community. The recent discoveries of two previously unmapped hydrologic regimes across Greenland's percolation zone, which already cover nearly 25% of the entire ice sheet as mapped by airborne radar, are each widespread hydrologic phenomena that need to be monitored. To my knowledge, this is the first paper that has proposed a repeatable method for monitoring these facies using spaceborne sensors. These methodologies equip the cryospheric community to learn far more as these facies (presumably) are poised to cover an increasingly large fraction of the Greenland (and Antarctic) ice sheet(s). This is an important contribution to science, and one that should absolutely be added to the canon and taken seriously for future studies of ice sheet hydrology.

Thank you for these positive comments. With collaborators, our intention is to do just that.

The idea of "perched firn aquifers" is an interesting one. Miller and co-authors are correct here in noting that interannual variability in melt & accumulation are very large in Greenland's percolation zone. It has been an open question about "what happens in areas where the accumulation thresholds for ice slabs vs firn aquifers fluctuate between these thresholds from year to year, or every few years?"

The hypothesis that aquifers could form occasionally on top of ice slabs, as proposed here in an "intermittent perched aquifers" hypothesis, would rely on a few assumptions about the meteorology at such a firn column.

(1) That enough meltwater was produced in a given year to stay liquid (not fully freeze) in the oncoming winter;

(2) that meltwater would be able to get deep enough (even atop an ice slab) to be insulated by overlying layers winter snow & firn (existing documented firn aquifers have all been at least 5-20+ meters under the surface at their tops); and

(3) that enough winter accumulation would form to adequately insulate that water-saturated firn against the winter cold.

It is worth noting that no accuracy analyses (false-positive and -negative) have been performed on the Icebridge-derived radar maps of aquifers and ice slabs produced by Miega et al and MacFerrin et al, respectively. (This isn't inherently a criticism of their work... having made the first observational maps of each respective facies, it is unclear what "truth" they could have been compared against save for a few individual field cores.). Miega, et al (2016) had no knowledge of the existence of ice slabs identified & mapped in these regions by MacFerrin, et al (2019). MacFerrin, et al (2019) identified more than 100 buried lakes on top of ice slabs that were filtered out in their analysis. These are many of the same buried lakes identified several years earlier by Koenig et al (2015), mapped using the same radar instruments. Miega, et al (2016) identified a number of these regions as "aquifers", even though they do not necessarily meet the definition of permanently soaked porous medium. (Miega would not necessarily have been able to differentiate between buried lakes and aquifers, as the radar signatures alone are essentially identical once the signal hits deep water.).

Koenig, et al., 2015 do document buried perennial supraglacial lakes, but those are a different (and more spatially-limited & localized) phenomenon than what is proposed here as a perched aquifer. An individual buried lake is not inherently an aquifer and doesn't require the same thresholds of surface-mass-balance conditions (high melt, very-high accumulation) to sustain itself, given that water flows horizontally over great distances into localized lake basins and reaches local water depths far greater than possible by vertical percolation alone.

The authors started writing this response by looking for additional data that would support our classification and mappings. We analyzed 'buried lake' locations derived by Koenig et al., (2015) between 2009 and 2012 using OIB data, and by Dunmire et al., (2021) between 2018 and 2019 using Sentinel-1 SAR data, visible satellite imagery, and RACMO2.3 climate simulations together with our results. During our analysis, the authors came to several conclusions and a stronger hypothesis, and will make the following revisions to the manuscript.

(1) The term 'perched firn aquifer' is too simple. We will change this terminology to 'other englacial hydrological features'. In the percolation facies during the freezing season, englacial hydrological features likely range from deep, expansive, perennial firn aquifers that form in firn pore space, to small, shallow, supraglacial lakes that form on relatively impermeable ice.

(2) These features form intermittently, often in ice slab areas, likely due to these relatively impermeable layers buried within the firn. However, they can also exist anywhere above, below, or within the snow, firn and ice, regardless of local climate conditions as a result of vertical meltwater percolation combined with lateral meltwater flow.

(3) Meltwater is retained on variable time scales (weeks-months, years) during the freeing season.

(4) The effective resolution of SMAP (~18 km) is too coarse, and the sampling of the airborne radar data too sparse to effectively calibrate our current empirical model and accurately classify and map 'other englacial features', although we hypothesize they exist and can be observed in the L-band microwave signatures. The authors will remove the 'perched firn aquifer' classification from our maps, and simply map firn aquifers and ice slabs.

(5) The authors will add a discussion on the potential controls on the decreasing 2-year elevated-but-declining plateau of L-band TB, which will include 'buried lakes' maps, visible satellite imagery, and RACMOP2.3 climate simulations as supporting lines of evidence. The authors do strongly believe that the signatures represent subsurface meltwater, but we will also present several alternate hypotheses. We will discuss future work using this L-band signature to develop an algorithm that does not require calibration with airborne radar data.

The authors propose that a temporary perched aquifer formed near the upper portion of the K-transect area and then retained some amount of liquid for the next two years before fully freezing up, is at least partially supported by the presence of an anomalously elevated but gradually-decreasing 2-year apparent trend in L-band TB spanning from summer 2016 through 2018, as shown in figure 4b. And indeed, as seen in that same panel, 2016 was a significantly higher melt year than any of the other three years in that record, potentially meeting condition.

(1). But the IceBridge AR radar profiles shown in Figure 3b show the upper horizon of ice slabs very near the surface, within the top 1-2 m of snow & firn (these profiles were collected in April & May, at the end of the winter season when snow is at its deepest of the annual cycle). The bottom of a perched aquifer there would not be anywhere near the closest upper-horizon of deep aquifers seen in any existing documented literature.

(2), the annual accumulation in that region of southwest Greenland, partially rain shadowed by the Maniitsoq ice cap, is typically 0.2 – 0.6 m w.e., or perhaps 0.6-1.5 m of snow. It would require a substantial amount of additional snow to insulate a perched water layer in this region (Kuipers-Munneke, et al, [2014] show this with modeling, low accumulation regions do not physically form aquifers). That alone does not disprove their presence though. One would hope that, perhaps in the way that both aquifers and ice slabs were originally discovered by in-situ cores (Forster, et al, 2014, and Machguth, et al, 2016, respectively), that perhaps some in situ data could be found to document such a phenomenon.

Reviewer #3 is correct in pointing out that there is no perched firn aquifer in the Icebridge echogram (Fig. 3b) where the TB time series (Fig. 4b) is discussed.

The authors agree that modeling does not tell the complete story – as perennial firn aquifers and ice slabs were not explicitly predicted by models prior to their discovery.

It is important to first note the significant difference in the scale of the satellite footprint vs the airborne footprint. The gridding of the TB observations used to derive the maps is

3.125 km; however, the effective resolution is ~ 18 km. The gridding (or trace spacing) of the IceBridge echograms is 15 m x 20 m (Accumulation Radar) or 14 m x 40 m (MCoRDS). For a full 18 km airborne transect across the satellite footprint, the complete IceBridge echogram observes 2-3% of what the satellite observes. In other words, 97-98% of what the satellite observes is unknown. The authors note that there are mapped 'buried lakes' within the satellite footprint of the Icebridge echogram (Fig. 3b), and observable lakes and lateral drainage off ice slabs in visible satellite imagery.

Fortunately, there were multiple field teams in that region of Greenland in 2017, namely the GreenTRACs campaign who collected in situ radar in that immediate vicinity, and the FirnCover campaign who collected at least one core at KAN-U in April 2017, in the immediate vicinity of that cyan dot in Figure 2b (MacFerrin, et al, 2019, Figure S1.b). Neither in situ campaign showed any evidence of liquid water perched shallowly above an ice slab in that region in Spring 2017, nor do they show the anomalously high snow accumulation rates that would be needed to do so. The MacFerrin, et al, 2019 core from KAN_U shows no water at all. The AR profile shown in Figure 3b in this manuscript, also does not indicate an anomalously bright reflector followed by a near-complete signal-extinction to depth as would be characteristic of a liquid water table (seen in Figure 3a in Southeast Greenland), nor the high (2-3 m thick) annual snow layer atop the ice slabs that would be needed to insulate it. If such an aquifer water table existed there at that time, one would expect to see it in that airborne AR transect, right where the cyan circle is placed in Figure 2b, but I simply don't see any evidence of liquid water there.

We note that a firn core is on the centimeter-scale as compared to the ~ 18 km effective resolution of the satellite, which significantly less than meter-scale of the airborne transect. It is possible that a single core could 'miss' a diffuse liquid layer especially if that layer is intermittent in time.

Comment: since conclusions are being made about specific points on the ice sheet in Figure 2, the exact locations (lat/lon) of the icons shown in Figure 2 need to be provided, especially since a new firn hydrology regime is being proposed at one of those specific points. (If they are, I did not see them and apologize for the oversight.)

Thank you. Very good suggestion. The authors will add these lat/lon points to the text/figure or in a related table depending on the number of points and their relevant metadata.

I cannot (and won't) completely rule out that "intermittent perched aquifers" could possibly exist under the right firn conditions, but I don't see the multiple lines of evidence necessary to make such a conclusion yet, nor a piece of irrefutable evidence (such as discovery of such a hydrologic regime in a set of firn cores or snow pits). To be fully clear, I am not wholly sure what else would cause a 2-year elevated-but-declining plateau of L-band TB values seen in Figure 4b. In fact, I am not entirely sure it truly is a "2 year" trend as hinted by the drawn arrow, it could just as likely be two non-related seasonal one-year declines (nearly identical to every other year at that location) but with 2016 in particular seeing higher values than other years for some reason. Given that the IceBridge AR data presented do not support the existence of an aquifer there, and adjacent cores by other campaigns/papers in that region in that Spring don't as well, and anomalously high accumulation rates necessary for such an aquifer to be properly insulated don't seem to be present there either, I cannot really support a claim of the discovery of "intermittent perched aquifers" in this manuscript based upon L-band TB signatures alone. More evidence, or more concrete and non-conflicting evidence, would be needed to make that claim. I do welcome the authors to broaden the discussion about what could have caused such a jump in annual TB values at that location in 2016-17, such as winter snow accumulation differences, the refreezing of anomalously-high amounts of water there, or other possible causes. Perhaps even include an adjacent discussion of a possible "perched

firn aquifer” (although again, they would need to explain why it isn’t seen in Spring 2017 airborne radar data), and suggest it as a possible explanation. But going straight to the conclusion that intermittent perched aquifers have now been discovered, and subsequently mapped, I do not believe is strongly enough supported solely by an interpretation of L-band TB microwave signals with no other supporting evidence (and multiple lines of contradictory evidence).

We agree with the reviewer and will add qualification to the text to more clearly state that this is a difficult hydrologic regime (perhaps multiple hydrological regimes based on location and climate), and that while we strongly feel it likely based on the observed L-band signatures, it cannot be mapped without significant uncertainty on the basis of the available remote sensing to date. We plan to add similar language to the discussion to encourage further work in the field.

The authors note that they don’t consider a satellite mapping a discovery per se, but rather a prediction of what may be hiding underneath the surface. Brightness temperature signatures are too complex (and often non-unique) to definitively define a new hydrologic regime without multiple lines of evidence.

A satellite prediction map might be the first step in the discovery of such phenomenon. Indeed, it was the authors prediction maps that led to the discovery of an expansive perennial firn aquifer on the Wilkins Ice Shelf, Antarctic Peninsula via firn cores, GPR, and airborne radar surveys during a 2020 expedition (Miller et al., 2019; <https://ui.adsabs.harvard.edu/abs/2019AGUFM.C33A..07M/abstract>). Once the phenomenon was identified, multiple lines of evidence indicated that these features had likely been present, yet undetected, for decades (since at least the early 1960s).

(Final note: my conclusion about the perched aquifers is not irrefutable. As I noted at the start, if I have missed important aspects of the analysis, or there is more evidence to support the claims made of a new “perched aquifer” ice sheet regime that I do not see, such as firn model data that may suggest an alternating regime between ice slabs and aquifers, and the evidence contradicting it can be refuted or explained, then I would love to stand corrected. It would be an exciting new development in ice sheet firn hydrology.)

Game on. ;)

Again, it may be possible that some form of “perched aquifer” exists in Greenland, but the map provided here does not inherently lead to that conclusion without further evidence. However, none of this detracts from the fact that using a single L-band sensor to reliably map both aquifers and ice slabs across the Greenland ice sheet is a significant scientific advancement, and more than worthy of publication. I suspect, if revised, accepted, & published, this work is likely to become a seminal contribution to future methodologies for the remote sensing of polar ice sheets. For that reason alone, I truly hope the authors can adjust their interpretations noted above, and get the manuscript accepted and published.

Overall the manuscript is well-written and readable, and the figures and maps are generally helpful and understandable.

Thank you again for these positive comments. They are sincerely appreciated by the authors.

Minor comments and grammar edits:

Lines 48-53: “As Greenland’s climate continues to warm... ..and stability of the Greenland ice sheet.” This is a very long sentence. Consider breaking into two.

Thank you. The authors will break this into two sentences in the revised manuscript.

Line 63: "Recent launch of ... has provided..." --> "The recent launches of ... have provided..."

Thank you. This will be corrected.

Line 131: McFerrin, et al., 2019) --> MacFerrin, et al., 2019) (also correct in other locations where this reference is used).

Will be corrected.

Lines 135-137: "Particularly in areas that experience intense seasonal surface melting (>600 mm yr⁻¹) during the melting season, and lower snow accumulation (<600 mm yr⁻¹) during the freezing season as compared to perennial firn aquifer areas (McFerrin et al., 2019)." It's unclear if the units being used here are millimeters water-equivalent, millimeters snow-equivalent, or ice-equivalent (which differ by up to a factor of 3). Please clarify. If mm w.e. are used, MacFerrin et al used somewhat different numbers than this in their empirical analysis (266-573 mm w.e. yr⁻¹ for melt, not >600 mm yr⁻¹). The estimate of snow accumulation (572 +/- 32 mm w.e.) used by MacFerrin, et al., does overlap with what is cited here (<600 mm yr⁻¹).

Also, the sentence quoted above is a fragment; fix grammar to complete the sentence.

Thank you. The units and grammar will be corrected.

Line 144: "This results in a lower observed TB at the ice sheet surface during the freezing season." It is unclear what "lower observed TB at the ice sheet surface" in this sentence is compared to, as the previous statement compares ice slabs both to aquifers and other non-ice-slab facies. Please clarify.

Will be corrected.

Lines 212-214: "Critically, the majority of meltwater is stored at depths that only L-band satellite microwave sensors (i.e., radiometers, radar scatterometers, and synthetic aperture radars) are capable of detecting."

Should specify: L-band microwave sensors are the only known category of space-borne instruments that are presently known to be able to detect water at these depths. We do not want to infer that no other instrument could ever exist that would do this. (For instance, we also know in situ active seismic sensors can detect aquifer depth quite well, but of course none of us know what a spaceborne seismic sensor would even look like, I shudder at the thought.) But for now just stating that L-band is the only category of sensors currently proven to detect these features, suffices.

This is a great, thoughtful comment, and I agree, and would have made a stronger comment to that effect but moderated in order to let the data speak for itself.

Lines 286-296: I am glad to see the acknowledgement of sources of uncertainty given the slight temporal mis-matches of datasets here. I do not propose a method to eliminate these biases, as I am not sure that is possible given the data available. I am just commenting that this section appears well written and considered, and I am glad the authors included it here.

Thank you for the positive comment. The authors do not believe these biases can be eliminated either. The temporal mis-matches as well as the spatial mis-matches between

the airborne and satellite data are impossible to overcome from the available data, especially given IceBridge has ceased its regular operations.

Line 371: Culberg et al., 2021) □ Culberg et al. (2021) (fix parentheses)

Thank you. Will be corrected.

Line 374 (Figure 3): The color-bars (along the right axes) in panels (a) and (b) lack units/labels. Please add.

Will be corrected.

Lines 452-455 (Table 1): "Coverage (km²)" is used as an identical header on two columns here. It is identified in the caption that one is the coverage of detections in rSIR grid cells, and the second is the detections that overlapped AR-derived detections, but this should be made more clear in the column titles somehow.

Will be corrected.

Line 467:"and more recent studies using L-band microwave radiometry" ... two lines above, you define the frequency ranges used for Ku-band and P-band, but I don't see anywhere you define the frequency ranged referred to as "L-band" here. I saw you define the wavelength further above in the paper [21 cm] but not the frequency bands. (I may have just missed it, apologies if I did.) Listing the L-band frequency would be helpful to non-microwave experts, just for comparison.

As suggested by Reviewer #1, this text will be removed to shorten the manuscript.

Line 477:"Tedesco and Fettweis, 2020" is listed twice. Remove one.

Thank you, this will be corrected.

Line 942:"Overlapping perennial firn aquifer and ice slab detections are interpreted as perched firn aquifer areas."

This is, perhaps, the source of some of the disagreement in the lengthy commentary I gave above

The authors will remove the perched firn aquifer classification from the empirical model description as well as the mapping. We will instead include only perennial firn aquifers and ice slabs.