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The Cryosphere Discussions

Interactive comment on "The response of supraglacial debris to elevated, high frequencyGPR: Volumetric scatter and interfacial dielectric contrastsinterpreted from field and experimental studies" *by* Alexandra Giese et al.

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Big changes: (1) The dielectric constant that was used to estimate debris thickness in the field was determined through laboratory experiments. Even though the laboratory debris was chosen to have broadly similar mineralogy, grain size etc. to the field debris, the two will inevitably have had slightly different dielectric properties. This is an important point because the choice of dielectric constant will have affected the threshold derived in the volumetric backscatter method, and therefore the estimated debris thicknesses. I don't think the analysis needs to be done again, because optimising the

threshold against the pit measurements will have compensated for such a difference, but this should be stated more clearly in section 3.3.

We have incorporated the suggestion to make this explicit in Section 3.3 ("Thickness retrieval: Changri Nup") and additionally discussed it in Section 4.5 ("Uncertainty.")

(2) I am not convinced that the pine shavings used in the lab are a good analogue for ice. The dielectric contrast is considerably greater between the debris and the pine than between the debris and the ice. I suppose the point is that if there is no clear reflection at the interface between the debris and the pine, where there is a relatively strong dielectric contrast, it should be expected that there is no clear reflection between debris and ice, where there is a relatively weak contrast? If this is the case, I think this could be explained more clearly.

Indeed, reflectivity for debris-ice = 0.015 is an order of magnitude less than reflectivity for debris-pine = 0.11 (given in Sections 2.3, along with added justification for choosing the set-up). The calculation of and explanation for reflectivity is given in the Methods, and the relative magnitude is discussed subsequently. The intention was to construct an interface whose reflectivity (0.11) was on the order of (i.e. very low) but greater than that on the glacier to investigate wave behavior at an interface; although the magnitudes differ, they are both far below a reflectivity that would be detected under the debris medium we studied. A greater reflectivity in our constructed setup allowed us to observe processes that occurred during data collection on Changri Nup but which were not detected (in a way, enhancing them for the purpose of our investigation). We also improved the Discussion section description of this.

(3) On p18, in Table 3, the standard deviations are larger than the mean, suggesting a non- normal distribution if debris thickness is always positive. Median debris thicknesses and interquartile range might be more appropriate here.

Median debris thicknesses and interquartile ranges have been added to the table and the observation that standard deviations are larger than the mean added to the Dis-

cussion text.

Specific comments:
P1, L2. The first paragraph of the introduction could do with restructuring. The first sentence is about water supply, the second, third and fourth about debris-covered glaciers, the fifth back to water supply, then the sixth to climate change. Maybe the water supply and climate change sentences could go together instead.

We rewrote and restructured the Introduction; now, the initial sentence is no longer about water supply, and the introduction does not jump between topics.

Small changes (line numbers refer to TCD version):
P2, L26. Technical corrections: Sentence beginning 'Because debris thickness. . .' needs to be rearranged, otherwise 'its thickness' – 'it' meaning 'debris thickness' – reads 'debris thickness thickness'.

This sentence was eliminated in the revised manuscript.

P3, L10. I don't see why the frequency affects the area that can be covered using GPR.

We removed this to avoid confusion. The thought behind this statement was that a lower frequency GPR system could not, practically, be run from a drone (which would have vast areal coverage).

P3, L12. Remove 'implying a layer of solid granite or very dense debris'. Any number of sediment or debris layers with a dielectric constant of 6.46 are possible. Therefore a dielectric constant of 6.46 does not imply a layer of solid granite or very dense debris.

Removed.

P3, L21. Remove 'yet'.

Removed.

P3, L31. Suggest 'to the southeast'. 'Southeasterly' suggests flow from the southeast,

as e.g. westerlies are winds blowing from the west.

Fixed.

P4, Figure 1. Would be good to have the transects labelled and the caption updated accordingly.

Both have been done.

P4, L9. Suggest 'longitudinal to ice-flow direction'.

Language changed to across- and along-glacier in response to Reviewer 3.

P4, L12. By 'collecting more thickness data', do you mean making pit measurements? Please clarify.

By this statement, we meant collecting transect A. The language has been revised to clarify/specify.

P5, Table 1 caption. Why did you add 1 cm? This seems quite arbitrary. Please explain and include the explanation in section 2.2 main text, rather than in table caption.

We added 1 cm when calculating the hypotenuse distance of a triangle with geometry established by the antenna manufacturer. As this detail is not important to our methods or results and seemed to confuse the reader, we removed it.

P7, L26. Sentence beginning 'We collected. . .' seems like it would fit better in section 2.2 as it is more about data collection than results.

This sentence was, indeed, more about data collection than results. We removed it from the Results section.

P7, L29. 'Spectra' is plural, yet we have 'is shown in Figure 7'.

Fixed, and this material is now in the Supplementary Materials.

P9, Figure 5. Needs axis labels and clearer numbers.

This figure was completely remade and has axis labels and clearer numbers.

P10, Figure 6. Needs axis labels and clearer numbers.

This figure was updated in the Supplementary Material P10, Figure 6. Text on figure suggests volume scatter and direct coupling both begin at 1.9 ns, yet these two lines are separated by at least a nanosecond in time. Possibly one is a typo?

This was, indeed, a mistake in the original manuscript and has been updated in the new figure.

P11, Figure 7. Needs axis labels and clearer numbers.

This figure was updated in the Supplementary Material

P11, L3. 'compared the scatter behaviour'.

This sentence in the original submission is not in the revised manuscript.

P16, L3. This is the first mention of the porosity measurements. Should be mentioned in section 2.2 as well.

The porosity measurements that we collected (to inform a constant in a moisture diffusion model) are not relevant to the porosity in the Complex Refractive Index Method calculation for GPR and have been removed from the manuscript.

P17, L5. McCarthy et al (2017) discussed the possibility that the strength of the ice surface reflection in their GPR data was variable due to variable dielectric contrast. It seems likely that they could often see an ice surface reflection in their GPR data because the ice was often melting during their study period. I would suggest that this is the key difference between the two studies.

We expanded the Discussion to include season, reflecting reviewer comments, in the "Absence of interface" section.

P16, L5. Remove 'personal'.

Fixed.

P17, L25. Suggest 'Assuming the small reflections in the profiles are englacial debris, englacial debris is more concentrated. . .'. There is no proof that these reflections are englacial debris, so some caution is required.

Fixed; the suggested text is included in the new manuscript.

P18, L1. There must be a thickness limitation unless the debris cover is completely lossless. Possibly it is better to say there is no thickness limitation within the range of debris thicknesses that is likely to be encountered in a supraglacial setting.

Fixed; the suggested text is included in the new manuscript.

P19, L12. I am not sure of the meaning of the sentence beginning 'Future work. . .'. This should be clarified.

This has been rewritten and clarified.

P29, Figure B1. Y-axis limits are too wide to see any detail near the debris-ice interface. Suggest 0 – 4 m would be sufficient.

P30, Figure B2. Y-axis limits are too wide to see any detail near the debris-ice interface. Suggest 0 – 4 m would be sufficient.

The point of these figures was to illustrate the entire time range of our data. Although these figures have not been changed, the point of showing all collected data has been made more clear in the text: we wanted to show, by including data from the entire time range used, that most of the energy is returned from the near-surface.

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