

Response to reviewer comments (RC1)

All reviews have been very helpful in significantly improving the manuscript and we agree with all the major changes that were suggested. The following changes were made in response to comments from Reviewer RC1 (B. Etzelmüller) and are detailed in blue text. All page and line numbers refer to the updated revised manuscript while a second document is also provided with track changes marked.

The study by Reinardy et al investigates the thermal regime of an outlet glacier (Midtdalsbreen) emerging from the northern part of Hardangerjøkulen in southern Norway. The authors used a dense GPR network to map cold-ice patches on Midtdalsbreen. They identify cold zones at the glacier margin, often in connection with long-lasting snow patches, but also in the accumulation area in association to nunataks. The authors discuss these findings in relation to glacial geology and glacier dynamics. The paper builds on the observations of marginal moraine systems published in 2013 (Boreas) where the main author relates the moraine architecture to cold-based marginal conditions. This manuscript focuses on the mapping of cold ice. The interpretations of the GPR survey are the main part of the study, and seems sound with reproducible results. In general, the paper is mostly well-written and certainly of interest for the community. However, there are several topics, which should be addressed:

1. Structure: The paragraph "Study area" should be divided from the introduction and should have an own number (2). The "Interpretation" chapter is a Discussion, and should be merged into the "Discussion" chapter. The "Conclusions" appear now more as a summary or a discussion part, I would suggest you give clear conclusions from your study.

We have followed all the above recommendations regarding the structure of the paper and reordered the sections accordingly. In addition we have totally rewritten the conclusion (P14 L18-P15 L2)

2. General contents: I am not always happy with the use of references. The core of the study is the mapping of the cold ice patches in the marginal area of Midtdalsbreen, in which the authors claim it is the "first direct observations" (see abstract). First of all, GPR surveying is not a direct observation. Second, this study is probably the first systematic mapping of cold ice on this glacier, however, direct measurements of glacier temperatures exists from earlier studies, unfortunately not published in international literature, but only as a thesis (in Norwegian) or "gray literature" in the form of excursion guides etc. E.g. Jon Ove Hagen has done his thesis in 1978 and measured directly the cold marginal area of Midtdalsbreen (Hagen, J. O. 1978. Brefrontprosesser ved Hardangerjøkulen [Glacier front processes at Hardangerjøkulen]. Cand. real. Thesis, University of Oslo, Norway, Oslo), and attributed the marginal morphology to freezing processes etc. This information was later included in several publications, such as excursion guides (e.g. Liestøl, O. & Sollid, J. L. 1980. Glacier erosion and sedimentation at Hardangerjøkulen and Omnsbreen. In: Orheim, O. (ed.), Symposium on Processes of Glacier Erosion and Sedimentation, Field Guide to Excursion. Norsk Polarinstitutt, Oslo, Geilo, Norway, 1-22.) or subsequent publications discussing the interaction between glaciers and permafrost in high mountain and arctic settings (e.g. Etzelmüller and Hagen 2005, Glacier-permafrost interaction in Arctic and alpine mountain environments with examples from southern Norway and Svalbard, Geological Society, London, Special Publications 2005; v. 242; p. 11-27, doi:10.1144/GSL.SP.2005.242.01.02, see e.g. Fig. 1e). Most of these publications are cited in Reinardy et al 2013, and used as indications that the observed moraine pattern in the Boreas study was related to basal on-freezing (Fig. 9). I totally understand that literature in Norwegian is not necessarily known and certainly not understandable for international colleagues, however, some of the co-authors in this study might help. Concerning the

important process of subglacial material entrainment, and also the possibility of material transport along shear planes, maybe you can also have a look on Weertman, J. 1961 (Mechanism for the formation of inner moraines found near the edge of cold ice caps and ice sheets. *Journal of Glaciology*, 3, 965 -978).

We follow the above recommendations and have now incorporated all suggested literature highlighting the results of earlier studies into the thermal regime and permafrost distribution at Midtdalsbreen (P4 L3-7; P9 L9-10; P10 L6-8, P10 L31-32). We also now indicate what we believe to be the base permafrost in GPR profile 2 in our new Figure 5b which fits the thermal regime model suggested by Etzelmüller and Hagen (2005, their Fig. 1e) (P10 L6-11). We also now include discussion of debris entrainment (P9 L31-P10 L14) with reference to Weertman (1961) and sediment elevation (P11 L4-25).

3. Glacier-permafrost interaction: The study in general generates very nice results and discussions, which are interesting in a glacier-permafrost interaction context. E.g., cold ice patches in connection to nunataks in the accumulation area is not surprising for the Finse area as these nunataks probably have permafrost (lower regional permafrost limit is c. 1400-1600 m a.s.l., depending on snow cover). Permafrost in mountain settings is of course a 3-dimensional problem (e.g. Nötzli et al 2007, JGR), and cold non-glaciated and maybe even snow-free areas influence adjacent glacier bodies thermally. If this is of interest, you may find relevant literature in e.g. Myhra, K. S., et al . ("Modelled Distribution and temporal Evolution of Permafrost in Steep Rock" PPP 28.1 (2017): 172-182). Another interesting topic is the influence of long-lasting snow patches as reason for cold ice development and persistence. I think the reasoning in the paper is fine. In the mountain-permafrost community, longlasting and relatively stable snow patches have been used as permafrost indicators. Maybe some relevant literature is available within this topic also for the present study. There are also some recent activities about snow and permafrost in the Finse area you may find useful in your discussion.

We have followed all the above recommendations and have now included far more discussion on the distribution of permafrost (including the suggested references), the potential influence of permafrost on glacier thermal regime (P11 L31-P12 L11) and the interaction of the cold-temperate surface (CTS) with the base of the permafrost at the glacier snout (P10 L6-12). We also include literature discussing the influence of variable snow cover/depth on ground thermal regime (P9 L8-15) as well as basal motion.

4. Implications: The authors discuss implications of the cold-based areas for different topics. One is of course the sedimentology and moraine architecture. Here the authors rely much on the Boreas paper, which is fine, but avoid redundancies (also between introduction and discussion in this manuscript). Concerning the discussion on the influence on glacier dynamics, I wonder if a model sensitivity test could justify some of the proposed implications. Some of the co-authors certainly have modelling experience from Hardangerjøkul, and may help or indicate if such tests are difficult to perform. Another implication in the manuscript is related to the lake (Demmevatnet) dammed by Rembedalskåka. I wonder if this discussion is a bit out of scope of the paper and speculative. Probably you cannot compare thermal conditions at Rembedalskåka with Midtdalsbreen, where the first outlet glacier incl. Demmevatnet ends much lower than Midtdalsbreen (c. 1200 m a.s.l. or below, Midtdalsbreen c. 1400+ m a.s.l.). At this elevation, permanent frozen conditions can only be expected in extremely shaded conditions, based on our experience on permafrost distribution both in steep snow-free rock walls and in more gentle, snow-covered terrains.

We try now to focus more on the controlled moraines and other landforms within the south-eastern glacier foreland (P6 L32-P7 L33) that have not been previously described in Reinardy et al. (2013). We

have also removed or toned down references to glacier dynamics including changing the title of the paper (P1 L1-2). We have removed the discussion relating to Nedre Demmevatnet.

Some minor comments: P1, l 20: Consider avoiding term “. . . the first observation . . .”. P3, Study area: See comment above P6, l. 14: Delete this sentence, no need to know your plans for upcoming papers. P 8/9: Interpretation section – see comment above. Again, you have a 4.1. chapter without 4.2 etc, should be avoided and can included into a discussion.

All suggested minor comments have been applied.