> Review of “Vulnerable top-of-permafrost ground ice indicated by remotely sensed lateseason subsidence” by Simon Zwieback and Franz Meyer
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> This work proposed the use of late-thaw-season subsidence occurring in an extremely warm year to indicate the presence of ground ice at the top of permafrost. The study builds on a simple idea that if ice-rich ground thaws at the end of a warm summer, the resulted surface subsidence should be larger than in other normal or cooler summers. The authors presented InSAR observations in their study area that soundly support this idea and further backed up using independent ground ice mapping as obtained based on borehole data and manual interpretation from optical imagery. Overall, this is an innovative way to utilize InSAR data for studying permafrost. Despite that the current work only provides a new indicator for the presence of excess ground ice at near surface, it may lead to more quantitative estimates of ice content or even temporal changes of ice content using observations alike.
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> I would like to raise a few points, hoping to improve the clarity and rigor of the paper.

We are grateful to the reviewer for their helpful suggestions and comments, which we address below.

> 1. Excess ground ice
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> For TC readership, it would be better to first define what excess ground ice is, e.g., referring to the Glossary of permafrost and related ground-ice terms as ‘the volume of ice in the ground which exceeds the total pore volume that the ground would have under natural unfrozen conditions’. A clear definition would help to interpret the schematics as shown in Figure 1 and equation 1. Since the excess is relative to pore volume, it is more rigorous to include the contribution of pore ice. The authors’ strategy is clever as the use of late-thaw-season subsidence in a warm summer implicitly removes the contribution from melting of pore ice (which happen in all summers, manifesting in the ‘early-mid-season’ results shown in Figs 6 and 10). The validity of equation 1 also builds on the fact that subsidence due to the melting of pore ice is negligible in late summer.
> Figure 1 is confusing at first sight. The ice content profiles imply excess ice in the active layer, even in the ice poor case (or the authors mean pore ice instead of excess ice in the active layer?). And a minor note is that the label ‘heave - subsidence’ unnecessarily implies heave. The figure caption is already clear.

We are not sure whether we have entirely understood the comments about the pore ice contribution. In our study area, the coring data show that massive ice, segregated ice and pore ice are abundant, but their relative contribution to the excess ice contents at scales relevant to the remote sensing observation is poorly constrained. In ice-rich permafrost, pore ice is commonly a minor contribution (we believe the referee is referring to the ~10% volume decrease upon thawing, which has the biggest impact when the entire pore space is occupied by ice). Note that in that case, the relevant fraction of the pore ice volume would be part of the excess ice. In light of our lack of ground observations, we will remain agnostic to the cryostratigraphic details of the excess ice.

We will make the following changes:

- We have added the definition from the glossary in the first paragraph of the introduction.
- To clarify Fig. 1., we have reduced the excess ice content in the active layer in the figure. We additionally added the following sentence to the caption:

> Early-season subsidence reflects excess ice at the top of the active layer, which may also be present in units with ice-poor permafrost (top row), such as young floodplains.

The purpose of the heave/subsidence labels is to clarify our sign convention in which downward movement corresponds to positive values. We intend to retain it.

2. Top of permafrost

> The classic two-layer model, active layer on top of permafrost, is adopted and well suits the nature of this work. In the discussion section, the authors did introduce the more complete four-layer structure: active layer, transient layer, intermediate layer, and permafrost. As the time scale of concern is an extremely warm summer within a fewyears (three, in this case), it is very likely that the excess subsidence is due to melting of ice-rich intermediate layer or transient layer (later of which is possibly ice rich, yet the authors claimed to be ice poor, L248), instead of the permafrost below. Then, is it justifiable to claim that excess ground ice is present at the top of permafrost (part of permafrost)? I would be more comfortable to use 'near permafrost table' or alike to allow some leeway. Quantitively, excess subsidence of 5 cm may correspond to an ice-rich layer of 5-10 cm, roughly the same order of magnitude as the thickness of transition zone (transient layer + intermediate layer).

In response to these concerns, we have strengthened the discussion of the transition zone. We continue to refer to "the top of permafrost" for simplicity, but we try to account for the definitional issues that arise when one considers longer time scales.

To this end, we have added a separate paragraph in the introduction.

> The stratigraphy of permafrost-affected soils adds complexity to the link between upper-permafrost ice content and remotely sensed late-season subsidence. To describe the cryostratigraphy in ice-rich terrain, divide the long-term permafrost into three layers. The uppermost layer, the transient layer, generally has a low to moderate excess ice content, as a result of occasional deep thaw. Disappearance of the transient layer is frequently triggered by sustained warming or disturbance. The subjacent ice-rich intermediate layer is then exposed, increasing the susceptibility to enhanced subsidence. The risk of sustained thaw consolidation is amplified where the intermediate layer overlies massive ice such as ice wedges. Once the protection afforded by the transient and intermediate layer has been lost, further thaw will lead to ice wedge degradation. Ice wedge polygons also illustrate the large lateral variability in ground ice conditions, which need to be considered when interpreting late-season subsidence as an indicator of ice-rich upper permafrost.

We now state that the transient layer has low to moderate excess ice contents.

We also made changes to the discussion section. Most importantly, we strengthened discussion of how we suspect the transient layer contributed to the difference between 2018 and 2019:

> Inter-annual variability in late-season subsidence of ice-rich areas poses challenges for ground ice mapping. Potential sources of inter-annual variability and trends include surface changes (e.g., soil moisture, disturbance, snow) and variable meteorological conditions such as precipitation. Memory effects could also be relevant. Taking the ice-rich area in Figure 8a) as an example, we speculate that thaw of materials with moderate excess ice contents (transient layer) at the end of the warm summer of 2018 (limited late-season subsidence of ~ 2 cm) could have promoted larger subsidence in 2019 by weakening the protection given to the subjacent materials richer in excess ice (intermediate layer, massive ice). Equally, the summer of 2018 may not have been warm (and wet) enough to allow for reliable identification of the vulnerable ground ice at this location. That the identification strategy presupposes an initial degradation of ground ice constitutes its biggest limitation.

3. Extremely warm summer

> I have no doubt that 2019 was an extremely warm summer in Kivalina (it was the warmest according to Fig. 2b). Without a statistical or meteorological perspective, I would also regard 2018 as very warm (2nd warmest in the Fig 2b time series); yet the late-summer subsidence in 2018 was normal. Then I was wondering how 'exceptional' the warming must be to cause the excess subsidence. Is it ever possible that the excess subsidence in 2019 resulted from the decadal warming in the region, esp. considering that it typically takes decades or longer to thaw permafrost in continuous permafrost zones?

We agree that the inter-annual variability raises important questions. In addition to temperature, we mention complicating factors such as winter conditions (e.g., snow) and soil moisture. We agree that legacy effects such as the general warming trend and the warm preceding summer of 2018 are relevant. We have added a specific example:

> Inter-annual variability in late-season subsidence of ice-rich areas poses challenges for ground ice mapping. Potential sources of inter-annual variability and trends include surface changes (e.g., soil moisture, disturbance, snow) and variable meteorological conditions such as precipitation. Memory effects could also be relevant. Taking the ice-rich area in Figure 8a) as an example, we speculate that thaw of materials with moderate excess ice contents (transient layer) at the end of the warm summer of 2018 (limited late-season subsidence of ~ 2 cm) could have promoted larger subsidence in 2019 by weakening the protection given to the subjacent materials richer in excess ice (intermediate layer, massive ice). Equally, the summer of 2018 may not have been warm (and wet) enough to allow for reliable identification of the vulnerable ground ice at this location. That the identification strategy presupposes an initial degradation of ground ice constitutes its biggest limitation.

In addition, we will include precipitation data (despite concerns about gaps)

> 4. Timings of late thaw season
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> The choices of the beginning and end of late season (namely, t1 and t2) make sense. I was just wondering if these are backed up by temperature data and do you need to adjust them when applying this method in different areas (I suppose you need). The authored mentioned 'diurnal frost heave', were there any signs of heave in September? Then how about late-summer heave (Mackay 1983 10.1139/e83-012)?

We agree that these choices are of practical relevance. We thus plan to add sensitivity analyses, i.e. we plan to see how the results in Fig. 8 change when the beginning and duration are altered.

Late-season frost heave is a particular concern, especially in areas or years with freezing in late August/early September. We did not notice any clear signs of frost heave in this data set, but they are well documented in the literature.

We agree that we did not give sufficient attention to summer heave. We have added that we "neglect summer heave due to water movement into frozen materials", and we cite R. Mackay's classic paper.

> 5. Overall, I think larger-than-usual late-season subsidence is an indirect, instead of direct, indicator of "vulnerable excess ground ice" near the permafrost table.

We have decided not to refer to late-season subsidence as a direct indicator in the abstract any more. Arguably, directness is a matter of degree rather than of kind.

> Minor comments
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> 3.1.4 The authors may provide more details of the spline fitting and help us to understand
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> Fig 3b.

L167: $ should be &

L209: Delete the extra for

L228: indicate should be indicates

L251: Its should be It

L312: an should be and

L316: includes should be include

Thank you. We have fixed these errors. We have expanded the description of the spline fitting process, now describing how we used ordinary least squares to estimate the coefficients of the spline expansion.