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Interactive comment on "Vulnerable top-of-permafrost ground ice indicated by remotely sensed late-season subsidence" *by* Simon Zwieback and Franz J. Meyer

Anonymous Referee #2

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This manuscript shows an original interpretation of InSAR data by isolating the late-season subsidence of an extremely warm summer. Authors then link the high late-season subsidence, significantly different from the low late-season subsidence of ice-poor permafrost, to the degradation of the ice-rich top of permafrost. Although, there are limitations to this approach (well addressed by the authors), there is also a great value to spread the concept so the same idea can be tested in different permafrost environments, and perhaps in more complex settings. I support having this paper published in The Cryosphere. In general, the paper reads well, however, some suggestions are made for clarifications and additional information that can help improve the understanding and support the conclusion.

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Below, I summarize my main comments, followed by specific comments and comments on Figures.

Main comments:

1. Transient layer versus intermediate layer

From the start (abstract), it would be important to bring the distinction between the transient and the intermediate layers (ice-rich top of permafrost) and to explicitly say to what the late-season subsidence is related to (ice-rich top of permafrost). There is some confusion in the introduction about this (lines 38-45 and line 55) and while you mainly associate the late-season subsidence to melting excess ice at the top of permafrost, you can't exclude the thawing of the transient layer as a contributing factor (as mentioned in your discussion). If possible, you should try to provide a description of the ice content within the transient layer as observed in the cores. In doing so, you can perhaps estimate the subsidence associated to the thawing of the transient layer and compare this estimate with the magnitude of late-season subsidence derived from Sentinel-1. This will give you arguments to support your conclusion.

2. Selection of the beginning of the late-season subsidence

The beginning of the late-season subsidence is mentioned quickly in the text (and too late, in line 123) and it is embedded in the caption of Figure 1. The definition of this late-season (especially the beginning) is central to your results and you should discuss your choice of selecting the second week of August for your study area. Your late-season is quite large (1 month) and likely encompass thawing of the active layer, transient layer and ice-rich top of permafrost. Furthermore, for automated ground ice mapping, selection of the late-season period will likely vary across the North.

3. Resolution of 60 m and detection of subsidence associated to the degradation of ice wedge polygons

At several places in the manuscript, you make the association of ice-rich permafrost to

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Discussion paper

the presence of ice wedge polygons; more precisely, you classify ice-rich permafrost based on visible ice wedges, but what about the ground ice content (excess ice) in the center of the polygons? My concern is about the resolution of 60 m used to derive the subsidence. Your manual classification of the ice-rich class seems to be based on visible ice wedges, but the InSAR result returns a 60 m pixel value where the subsidence is a mixture of various surfaces.

4. Result over the Kivalina study area

I understand that you want to present a simple case (focus area) to illustrate your approach. However, although not available for review, you seem to have, for your study area (Kivalina), the ground ice map in term of ice-rich, ice-poor, and indeterminate classes. Why then you did not provide the assessment for your entire study area?

Specific comments:

Line 3 : Could you define the late-season period?

Line 5 : Make the distinction between the transient layer and the intermediate layer (ice-rich top of permafrost).

Line 6: Please consider rewording “For locations independently determined to be ice rich” which is a little hard to understand at this stage.

Line 7: Is it also the 5th–95th percentile for the range of subsidence of ice-poor areas? Please add if so.

Lines 25-27: “Current approaches for mapping ground ice have significant shortcomings. One approach, palaeogeographic modelling of ground ice aggradation and degradation, is currently limited to coarse-scale assessments (Jorgenson et al., 2008; O’Neill et al., 2019)”. True, but in fact, it is not the approach that is limited, but the input data that limits the result of such approach (in particular, the scale of the surficial geology used. In O’Neill et al. 2019, the surficial geology is at 1:5000000. As stated by O’Neill et al. 2019, the model output could be improved by including updated surficial geology

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mapping). Please consider rewording.

Lines 38-45: It is somehow understood here that you relate the late-season subsidence to thawing of ice-rich top of permafrost (intermediate layer) and not to the thawing of the transient layer. However, you can be clearer by adding the transient layer and intermediate layer in your schematic of Figure 1 and by explicitly say to what the late-season subsidence is related to.

Line 55: In contrast to previous statement (in lines 38-45), you seem here to relate late-season subsidence to both “excess ice at the base of the active layer and top of the permafrost”. Please clarify.

Line 71: Please define the rubble-covered surfaces in term of material or terrain unit type.

Line 71: Please give the mean annual ground temperature of this warm permafrost and the range of active layer thicknesses with the approximate date of the maximum thaw front (see comment of line 108).

Lines 78-79: “Ice-rich layers of segregated ice are also ubiquitous in fine-grained sediments (Shannon & Wilson, Inc., 2006)” Do you mean in marine sediments? Please clarify.

Line 82 and Fig 2b: Please add the climatic normal (TDD) in Fig. 2b, so that the decade and summer 2019 will be put into a longer perspective.

Lines 80-85: Could you also define the climate of the three years (or summers) in term of precipitations? That may help understand the soil moisture content at the end of the summers and support some discussion points (e.g. soil moisture used to aggrade ice at the base of the active layer, line 298). In addition, Douglas et al. (2020) recently shown the relationships between anomalously wet summers and thaw depth in discontinuous permafrost (Alaska). Therefore, not only extremely warm summers can lead to degradation of vulnerable excess ice in the upper permafrost, but extremely wet

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summers as well.

Lines 89-92: Please add the resolution of Sentinel-1 interferometric wide mode. The resolution of 60 m is obtained by multi-looking (lines 98-99). This might be obvious to remote sensing experts, but not necessarily to permafrost experts. Please explain your choice for the resolution of 60 m.

Lines 89-92: Could you add the looking direction of the satellite?

Lines 98-99: Perhaps, briefly explain the purpose of multi-looking or link the multi-looking to the 60-m resolution.

Line 106: Can you show that there is no aspect-dependent trends that are associated with downslope movements in the supplementary file?

Line 108: Could you define and discuss your choice for the beginning of the late-season subsidence in the text. In Fig 1, you mention second week of August. When is the maximum thaw front generally reached? Please add this information in the study area section (see comment of line 71).

Lines 113-115: Please refer to Fig.3b

Line 123: If not done previously, please explain why you choose August 10 as the starting point of your late-season. Your late-season is quite large (1 month) and likely encompass thawing of the active layer, transient layer and ice-rich top of permafrost. Please explain.

Line 132: Please add a reference to your ground ice map. However, and unfortunately, the independently derived ground ice map (Zwieback, 2020a) is not available for review (see comment of lines 515-516).

Line 155: Alluvial deposit seems to be classify as ice-rich based on visible ice wedge polygons, what about the ground ice content in the center of the polygons, can you add this information?

Line 168: Can you specify the surficial geology of all sites in Shannon & Wilson, Inc., 2006 since the readers don't have access to this reference? Perhaps add the information in Table S1.

Lines 168-170: Again, does ice-rich permafrost associated to ice wedge polygons only?

Line 175: Even if you acknowledge that the cores were taken in 2005 compared with Sentinel-1 over summers 2017-2019, you should try to provide a description about the ice content of the transient layer as observed in 2005.

Line 182: Please correct Table S1, it should be Cores from 2005, not 2015.

Lines 179-181: Could you specify if ground ice contents represent the first meter below top of permafrost? Perhaps add the depth interval corresponding to the ground ice description in Table S1.

Line 187: Not sure if the use of the word "peak" to describe spatial variability is appropriate since it can be confused with a temporal peak. Please consider rewording.

Line 189: For negative late-season subsidence, do you mean in 2017 or 2019 or both?

Line 189: Do you mean uplift displacement and/or displacement toward the satellite? Please clarify. Did you add this sentence to support lines 105-106 about downslope movement? Please clarify.

Line 200: Again, it looks like the ice-rich deposits are only associated to the presence of ice wedge, and therefore, associating the subsidence to ice wedge degradation, however, at a resolution of 60 m, subsidence will rather reflect the one in the polygon center or at least be an average of polygon center and trough.

Line 207: In your manuscript, you chose to shown only the results over the limited focus area. However, your manual classification into ice-rich and ice-poor terrain (and indeterminate category) was done for the study area of Kivalina (Zwieback, 2020a –

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unfortunately unavailable). It would have been interesting (perhaps at the end of your result section) to provide the distribution of the late-season subsidence over the Kivalina study area, such that someone can appreciate the performance of the approach compared to a small, almost ideal case study.

Line 207: Even if the difference in 2017 between ice-rich and ice-poor areas is smaller than 2019, is it statistically different?

Line 209: Is it also the 5th–95th percentile for the range of subsidence of ice-poor areas? Please add if so.

Lines 211-213: Should you also discuss 2017 and 2018? You can perhaps quickly say that the suitability of cooler years will be address in section 4.2.2

Line 234: What the distribution overlap in 2017? Even with large overlap, is it statistically different?

Lines 220-224: See comments for Figure 10.

Line 248: It is true that the transient layer contains less ice than the underlying intermediate layer (Shur et al., 2005) commonly known as the ice-rich top of permafrost. However, the transient layer could contain excess ice that will lead to late-season subsidence (you refer to this in lines 297-298). From the coring done in 2005, is there any indication of the thickness of the transient layer and its ice content? If yes, you can perhaps estimate the subsidence of the transient layer and compare with the magnitude of late-season subsidence derived from Sentinel-1.

Line 274: Please specify the magnitude of this spurious heave signal?

Lines 282-283: Do you infer than the warm summer of 2018 was enough to thaw the transient layer? Please clarify.

Lines 297-298: See comment of line 248 about the ice content of the transient layer from the 2005 cores.

Line 310: This automated ground ice mapping presuppose the selection of a starting date for the late-season subsidence; this starting date (and the end) will vary across the North. As mentioned previously, you should consider adding a discussion on the choice, for your study area, of the starting date for the late-season subsidence.

Line 312: However, frozen cores will be needed for the interpretation of ground ice content (e.g., in the transient layer, not only to estimate excess ice at depth – line 321) as well as other ground truthing to reduce observational uncertainties. Please consider nuancing your sentence and moving lines 319-322 after the first paragraph.

Line 316: How, with the resolution of Sentinel-1, the results can show subsidence of ice wedges?

Lines 515-516: These two products are unavailable to review:

Zwieback, S.: Kivalina ground ice map (Version 1.0), https://doi.org/10.5281/zenodo.4072407, 2020a. Zwieback, S.: Kivalina subsidence observations (Version 1.0), https://doi.org/10.5281/zenodo.4072257, 2020b.

Is it possible to consider adding them in the supplementary file?

Figures:

General: I suggest changing the color of your late-season subsidence scale; the blueish color is not the best to see the contrast, everything looks the same. You can maybe try the brown to blue, you used at Figure 5a-b, but only for subsidence (positive values). This scale will also be consistent with the colors chosen at Figure 7c, and choose another scale of colors for any heave displacement (negative values in Figure 5 a-b).

Figure 1: Please consider adding the transient layer and intermediate layer in your schematic of Figure 1.

Figure 2: Please add a horizontal line corresponding to the climatic normal; 30-year

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average in term of TDD.

Figure 3: Not sure if Fig. 3a and 3b go together. The figure title does not really represent Fig. 3b? Could they be separate figures?

Figure 4: Please locate these two sub-regions within Figure 4 or Figure 2 and add an arrow for the North. Also, please define Catena.

Figure 5: Please add the reference of Figure 2 for the study area shown in Figure 5 “Regional variability of remotely sensed late-season subsidence dI within the study area (see Figure 2 for location)” Figure 6: Move this Figure after its first mention in the text, after line 199.

Figure 7: Please add the reference of Figure 5 for the focus area shown in Figure 7 “. . .determined by manual mapping in the focus area (see Figure 5 for location)”

Figure 7: Please consider rewording “a) Versus independent ground ice map and cores” (it took me some time to understand the meaning of that sentence). Suggestion: For example, “a) Distributions of late-season subsidence in 2019 according to the three ground ice classes manually/independently mapped”

Figure 7: I like Fig. 7a, but I don’t understand why the distribution has to be in both direction, can it just be a “positive” distribution? I was trying to understand the “lense” effect.

Figure 7: “The diamonds indicate points mentioned in the text” this is rather vague, could you say “for points mentioned in Figure 10”?

Figure 8: I like this figure!

Figure 9: Please refer to Figure 5 for site location (after the mention of Tatchim Isua site).

Figure 10: Why points 4 to 19 while in Fig 7b-d it is points 1 to 17 with points 11, 18, and 19 missing? Please explain.

Figure 10: point 4, independently determined as indeterminate not ice rich, please explain or correct.

Figure 10: point 17, looks more ice poor than indeterminate according to manual mapping, please explain or correct.

Reference:

Douglas, T.A., Turetsky, M.R. and Koven, C.D. 2020. Increased rainfall stimulates permafrost thaw across a variety of Interior Alaskan boreal ecosystems. Climate and Atmospheric Science (2020) 3:28, https://doi.org/10.1038/s41612-020-0130-4

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