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Interactive comment on "Small scale spatial variability of bare-ice albedo at Jamtalferner, Austria" *by* Lea Hartl et al.

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Author responses are below the respective reviewer comments and separated by —- throughout the document.

Reviewer comment:

This study by Hartl et al (2020) compares a detailed field survey of albedo on Jamtalferner with synchronous remote sensing derived albedo from Sentinel and Landsat images. The methods for both approaches to albedo determination are well explained. The comparison of the field albedo and remote sensing derived albedo is the key output of this paper and is well illustrated in Figures 7-9. The study provides a richer data set for understanding how Landsat or Sentinel images could be used and is simply

interesting. The primary comments below are seeking more context: 1) On the value of detailed spatial and temporal albedo observations. 2) For connections with energy balances. I am not suggesting additional data or figures be presented, but instead additional reference to other work and how the data here fits with these.

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Author response:

Thank you for your comments and suggestions. We propose to address the main issues raised above in a revised version of the manuscript primarily by expanding the discussion section to include more depth on points 1 and 2 (value of detailed spatial and temporal observations, connection with energy balance), contextualizing our results in the existing body of work more clearly and exploring in more detail the potential for future work on how small scale reflectance variability may affect energy balance. Additionally, we will rework parts of the introduction and add more comments on existing literature in order to better set the stage for approaching the issues related to points 1 and 2.

We address the specific comments below. We are happy to follow all suggestions within the constraints of the data available to us.

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9: The first sentence reverses the cause and effect. "As Alpine glaciers recede, they are quickly becoming snow free in summer and, accordingly, spatial and temporal variations in ice albedo increasingly affect the melt regime. " Instead I suggest, "As alpine glacier become snow free in summer, recession occurs, and further spatial and temporal variations in ice albedo increasingly accentuate the melt regime."

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Will rephrase as suggested.

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16: Finishing the sentence with fluid is confusing since that could be a surface type, “Spectra can roughly be grouped into dry ice, wet ice, and dirt/rocks, although transitions between types are fluid.” Maybe finish with, “although gradations between these groups occur”. Replace “fluid” with gradations throughout.

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Will rephrase as suggested and check manuscript for use of “fluid”.

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24: Explain that firn cover is lost when persistent loss of snow cover in the accumulation zone exposes the firn (Fischer, 2011).

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Will add note on this and citation.

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59: “. . .relatively recent times”, be more specific.

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Propose to replace with “...throughout the last decade”.

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74: Azzoni et al. (2016) also found a significant impact from rain water.

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Will change “as well as significant effects of melt water” to: “as well as significant effects of melt and rain water”

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76: What is the basis for Brun et al (2015) stating importance of remote sensing in albedo assessment?

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Brun et al (2015) point out that satellite products are critical for glaciological studies in data sparse regions such as the Himalayas, where their study sites are, as in situ data are often not available and glaciers may not be easily accessible. In their study they reconstruct annual mass balance from MODIS albedo data for two glaciers, validating this with in situ data. They suggest that this method can be applied to certain other glaciers in the HKH region from which no in situ mass balance or albedo data is available. This highlights that 1) remote sensing is often the only way of getting albedo data and 2) other important glaciological work can be carried out using remote sensing derived albedo data.

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77: Resolution of Naegeli et al. (2015) aerial albedo observations?

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From Naegeli et al. 2015: “The flying altitude of 4000 m above ground level (a.g.l.) in combination with an instantaneous field of view (FOV) of 0.0025° resulted in a surface projected pixel resolution of $\sim$ 2 m.”

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96: Is it worth observing that for degree day modelling changing albedo with time would alter parameters in the model.

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Propose to add: “In addition, delineating temporal variability of albedo is relevant to degree day modelling, as a changing albedo would alter parameters in the model.”

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117: “Along each profile line spectra are gathered at equal intervals, with 14 profile lines containing 11 spectra spaced at 2(?)m and 2 profiles containing 40 spectra gathered at a higher resolution of 0.5(?) m.” // 132: “Google Earth Engine” // 161: “gradational” instead of “fluid”

Will change as suggested.

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196: Profile 8 seems to have the least agreement in Figure 9 between field are remote sensing data, why?

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We have attached photos of the profile at the end of this document to provide visual context. Profile 8 crosses a section of ice where the contrast between dark and bright areas is comparatively strong. The profile is roughly at a right angle to the flow direction and there are “stripes” of meltwater channels and/or dirt that cross the profile. The profile has a comparable number of individual spectra with reflectance values above and below the profile mean, i.e. it is not a dark profile with a few bright outliers (compare e.g. to P6 in Fig 8) or vice versa (e.g. P3), but alternates along the profile line. Agreement with the remote sensing data is decent for the darker spectra in P8 but the bright values are not captured.

While we cannot rule out that the lack of agreement between the field and remote sensing data is due to an unusually unfortunate/unrepresentative positioning of the field measurement points in the satellite pixels, this may be an instance where the diurnal melt cycle and the associated presence/absence of water on the surface exacerbates the contrast between the dark and bright sections of the profile. In the bright sections, the porous weathering crust and cryconite hole structures appear to be drained of water, while the depressions of the melt channels are noticeably wet. Cook et al.

2015 (https://doi.org/10.1002/hyp.10602) indicate the occurrence of “sudden drainage events” in the weathering crust on a day-to-day time scale and a diurnal cycle of the hydrology of the weathering crust driven by meteorological conditions (radiation, turbulent fluxes). The time of day of a satellite overpass would determine which stage of this cycle the satellite “sees” and consequently the satellite data would not capture this variability. A more definitive explanation would require further study and dedicated field experiments designed specifically to explore this aspect of reflectance variability – we hope to do this in the future.

We propose adding a version of the above commentary to the manuscript to explain the particularities of profile 8.

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204: Figure 8 has excellent potential for the direct spatial correlation of the Sentinel albedo to the point measurements. I think showing all the profiles prevents being able to visualize the relationship. I suggest focusing on a few of the same profiles that were a focus of Figure 5 and provide a range of conditions ie. P 3, 5, 8, and 11. Anzoni et al (2016) noted a future goal of generating an albedo map. Is that feasible for the area of the glacier shown in Figure 1?

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We are happy to change Figure 8 so that it shows only selected profiles, as suggested.

Based on high resolution, close range digital images of the ice surface at Forni glacier, Anzoni et al (2016) develop a relationship between the area ratio of ice covered by fine debris and clean ice (d) such that albedo can be derived for a given area if d is known. To apply this method to the area of the glacier in Figure 1 would require an estimate of d, for which we would need close range imagery of the ice surface for the entire area. We could perhaps apply the method of Anzoni et al. to the photos we took of the ice surface at our sampling sites, but this would still result in albedo values only at our sampling sites without addressing the question of how representative these locations are for the rest of the glacier area and how albedo might be interpolated between them. We hope that our work may eventually contribute to methods for producing high resolution albedo maps, but do not think making such a map is feasible with our current dataset and the method described by Anzoni et al.

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210: This is a key observation. What have other studies found in terms of the over/under-estimate transition?

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We have not been able to find many other studies with explicit information on this issue specifically over glacier ice surfaces. Hendricks et al. (2004) state for measurements at Hintereisferner: “Except for ice, the glacier reflectances derived from the satellite image are large underestimations when comparing them to the spectrometer measurements. A maximum underestimation of 139 % was found for firn in band 4. New snow, with the highest reflectance of 86 % is predicted most accurately within a confidence interval of 15 - 18 %. The reflectance of ice seems to be highly variable with both under - and overestimations of up to 76 % and 31 % respectively.” This refers to Landsat ETM+ imagery acquired about 2 weeks before the corresponding field measurements. We propose to cite this in the revised manuscript with additional discussion of the effects of changing atmospheric conditions, which make direct comparisons of ground measurements and satellite data challenging if measurements and satellite overpasses do not coincide closely, especially at a comparatively small spatial scale.

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226: The variation in energy balance as albedo/debris cover changes spatially and temporally was a focus of Nicholson and Benn (2006) provided a nice overview of this from Ghiacciaio del Belvedere. They observed for debris cover areas the dominant

energy contribution varied from sensible heat to shortwave radiation due to decreased albedo and higher surface temperatures. They further found that for dry debris cover, sensible heat flux became negative as debris cover thickened, because of higher surface temperatures and that longwave radiation became negative even for thin debris cover.

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We will add comments discussing the results of Nicholson and Benn (2006) in this section, with notes on how they relate to our findings.

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231: How significant is the time of day variation in albedo? How consistent would this variation be from day to day? Moller and Moller (2017) provide one measure of this in an examination of spatiotemporal variations of albedo across Svalbard glaciers, recognizing this is a larger scale model albedo product. Nicholson and Benn (2012) examining Ngozumpa Glacier identify surface albedo variation across an area of varied debris cover, as well as the changing diffusivity through the melt season. The surface temperature variation of this glacier in the Himalaya would be much different than in the Alps, yet the continuous record compiled does provide context to the degree of variation and the potential importance of ongoing point measurments. They observe the importance of distinguishing wet vs dry surfaces. Azzoni et al (2016) note the increased albedo due meltwater presence during the middle of the day to albedo, while rain led to increased albedo for several days.

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We will expand this section with a discussion of the above points. We will discuss our thoughts on the potential magnitude of day to day variations, the regularity of the diurnal cycle, and meteorological factors affecting the cycle in the context of our study as well as the relevant literature (citations by the reviewer, as above, and others, e.g.

Cook et al., 2015).

In order to quantitatively answer the questions posed at the beginning of this comment, we very much hope to expand our data collection at Jamtalferner and install instrumentation that would allow continuous point measurements.

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249: Similarly, the question of how well the albedo variations need to be resolved to model or understand surface processes need to be acknowledged/discussed. One reason a relatively sparse ablation stake network can represent ablation during a melt season is that despite significant surface changes the spatial distribution of energy balance over time tends to balance. Your Figure 5 illustrates this that though albedo varies considerably along the Profile 3 and 11, and the profiles have been exposed ablation ice for some period, the ice surface is relatively even. Energy balance distribution across an ice surface in a small area responds to the variations in surface level, albedo and debris cover.

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"Similarly, the question of how well the albedo variations need to be resolved to model or understand surface processes need to be acknowledged/discussed." - This is a valid and interesting point of discussion. We suggest that the answer to this question depends on the processes one is trying to understand and the scale at which they occur. In the context of glacier wide ablation monitoring via the direct glaciological method, resolving sub daily and sub meter variations is perhaps not exactly a very pressing need, but, in our opinion, still interesting. The area of the glacier shown in Figure 1 contains 9 ablation stakes, which we maintain as part of our mass balance monitoring program at Jamtalferner. We observe significant differences in the amount of melt that occurs at these stakes. Aspect, shading, and slope angle of course play a strong role in this, as does locally increasing debris cover. We hypothesize that darkening due to water on the glacier surface is more of a factor at some of our stakes than at others, depending

e.g. on their position in relation to seasonally shifting meltwater channels. We would like to eventually achieve a clearer separation of the influence of these factors (especially the influence of water), their relative magnitudes, and possible changes over time. We think that small scale reflectance monitoring can contribute valuable insights in this context.

Additionally, data with high spatial and temporal resolution seems essential to improve understanding of micro-hydrological processes in the weathering crust and how these may affect a possible larger scale darkening of increasingly snow free glaciers, e.g. by favoring or impeding the growth of ice algae, or the collection/washing out of cryoconite.

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260: A significant source of uncertainty for what?

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Surface reflectance and parameters that might be derived from it are key variables in glaciological modelling and uncertainty therein accordingly contributes to overall model uncertainty. This has implications for applications such as modelling runoff and catchment hydrology. We will clarify the phrasing in a revised version of the manuscript.

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271: Need a reference from a different region to emphasize this point.

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Propose to rephrase this sentence slightly to focus on changing debris cover as a source of uncertainty for future glacier change and to additionally cite Bolch et al., 2012, for the Himalayan region and Stokes et al., 2017, for the Caucasus.

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280: Did you sample spectra at any location over a period of time? If so, this helps relate the logistical challenge of temporal albedo monitoring.

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We have not had opportunity to do that but hope we will in the future.

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Fig. 1. Profile 8, looking east.

Fig. 2. Profile 8, looking west.