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Interactive comment on "Buoyant calving and ice-contact lake evolution at Pasterze Glacier (Austria) in the period 1998–2019" *by* Andreas Kellerer-Pirklbauer et al.

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Comments on the manuscript with the id "tc-2020-227" Entitled "Buoyant calving and ice-contact lake evolution at Pasterze Glacier (Austria) in the period 1998–2019" by Andreas Kellerer-Pirklbauer, Michael Avian, Douglas I. Benn, Felix Bernsteiner, Philipp Krisch, and Christian Ziesler

Reviewer # 2

[1] General comments Reviewer: The paper 'Buoyant calving and ice-contact lake evolution at Pasterze Glacier (Austria) in the period 1998-2019' by Kellerer-Pirklbauer et

al. presents important insights in new type of processes appearing during the present phase of rapid glacier recession in the Alps. The multimethod and long term investigation of the formation of lakes with ice contact, relocation of debris and calving events is key for estimating present and future retreat rates not only in the Alps, but in all mountain regions where the overdeepened glacier tongues disintegrate. The overall presentation is well structured and clear, the language is quite free of spelling and grammar errors and clear. Reply by authors: Thank you very much for these general comments!

[2] Major comments: Reviewer: What actually is missing and would be very helpful, is the quantification of loss by calving during the period to the total ablation at the glacier tongue, showing how large the contribution of this new process actually is. This would be nice to read in the abstract also, just for example the specific mass loss/year at the lake and the mean direct specific surface mass balance at areas in the same elevation without contact to the lake.

Reply by authors: Quantifying the ice loss by buoyant calving and comparing these losses with ablation rates at the nearby glacier tongue of Pasterze Glacier is not trivial with the available data but was attempted as explained below.

First, three of the large-scale ice-breakup events occurred between August and September 2018 (IBE2 to IBE4). For these events we tried to quantify the volume of the newly emerging icebergs as well as the volume of uplifted ice masses detaching from the subaquatic glacier ice. The latter was accomplished by comparing the calculated volume of a given ice-mass (e.g. a debris-covered ice slab) before and after the ice-breakup event. For volumetric calculations we applied the following approach. The horizontal extent of affected (newly emerged or only uplifted) ice masses was transferred back to and drawn into the original webcam images. A maximum iceberg height was also drawn as a line in the original webcam image. The length of this line was then quantified by using the ratio between the quantified horizontal extent and the marked line. The iceberg height then was obtained by applying a correction calculation for the camera distortion produced by an incidence angle of 25° (calculated by a height difference of 310m and a horizontal distance of approx. 650m). One example for such a calculation is shown in Figure 1.

Next, the volume of individual icebergs was approximated by assuming that all ice bodies above the waterline have the form of a truncated pyramid, where A2 is 20% (for dome-shaped iceberg), 50% (for mixed iceberg type) or 80% (for tabular iceberg) of A1. The volume of truncated pyramid (iceberg above the waterline) with irregular base is given by:

$V = h/3 * (A1 + \sqrt{(A1*A2)} + A2)$

With A1 = area at the waterline (larger base), A2 = area of the top face (smaller base; in our cases 20, 50 or 80% of A1 depending on iceberg type), and h = maximum height of iceberg or truncated pyramid.

With this approach we quantified the volume of nine icebergs for IBE2 (09.08.2018), eight for IBE3 (26.09.2018), and two for IBE4 (24.10.2018), respectively. The volume above the waterline was then multiplied by 10 to quantify the total iceberg volume. The sums of movement affected ice masses (without lateral displacement) during the three analysed ice-breakup events was 55,717 m^3 for IBE2, 445,257 m^3 for IBE3, and 537,604 m^3 for IBE summing up to 1,038,578 m^3. We can therefore assume that ice loss by buoyant calving in the glaciological year 2018/19 (01.10.2018-31.10.2019) at Pasterze Glacier was at least in the order of 1 x 106 m^3. However, significant uncertainties in this quantification attempt are the visual and thus subjective estimation of the iceberg height as well as the fact that only large icebergs are considered.

Second, we quantified the ice-surface elevation changes of Pasterze Glacier where the glacier is directly attached to the proglacial lake. For this, we used two sets of TLS-Data from the 13.09.2018 and 03.08.2019. Although with this data set we do not cover the entire glaciological year 2018/19, we get an idea about direct ice mass losses at the shores of Lake Pasterze. The emergence velocity as well as the general glacier

motion at the glacier terminus is close to zero (Kellerer-Pirklbauer et al. 2008; Kellerer-Pirklbauer and Kulmer 2019) apart from ice movement related to crevasses or steeper sloping areas (Seier et al. 2017). Therefore, we can assume that surface elevation changes at the glacier terminus between the two stages equals basically glacier ablation rates. Figure 2 visualizes a quantification of surface elevation differences for a section of the lake-proximal part of Pasterze Glacier. As shown in Figure 2c, surface elevation changes and thus more or less glacier ice ablation was up to 5 m between the two stages. It was not the scope of this paper to analyze ablation rates at the terminus of Pasterze Glacier in detail. However, for a rough estimate we can calculate for the lowest part of the glacier tongue next to the proglacial lake (for extent see Figure 2d, c.0.35 km^2) the total ice loss for the glaciological year 2018/19. Mean ablation rates of 2.5 m or 3.0 m for this area would yield total ice losses for this area of 870,000 m^3 and 1,050,000 m^3, respectively.

To sum up, approximations of the ice volume lost by buoyant calving as well as by ablation by subaerial melting at Pasterze Glacier as shown here, seem to have been in the same order of magnitude in the glaciological year 2018/19. However, as the glaciological year 2018/19 was very unusual in terms of larger ice-breakup events (three of the four larger events occurred in this year), we can clearly conclude that glacier ice losses by buoyant calving are substantial smaller compared to subaerial ablation rates.

A condensed version of this description should be considered in the revised version of the manuscript (depending on the editor).

Mentioned references: Kellerer-Pirklbauer, A. and Kulmer, B.: The evolution of brittle and ductile structures at the surface of a partly debris-covered, rapidly thinning and slowly moving glacier in 1998–2012 (Pasterze Glacier, Austria), Earth Surf Processes, 44, 1034–1049. https://doi.org/10.1002/esp.4552, 2019.

Kellerer-Pirklbauer, A., Lieb, G. K., Avian, M., and Gspurning, J.: The response of partially debris-covered valley glaciers to climate change: The Example of the

Pasterze Glacier (Austria) in the period 1964 to 2006, Geogr Ann A, 90 A/4, 269-285, https://doi.org/10.1111/j.1468-0459.2008.00345.x, 2008.

Seier, G., Kellerer-Pirklbauer, A., Wecht, W., Hirschmann, S., Kaufmann, V., Lieb, G. K., and Sulzer, W.: UAS-based change detection of the glacial and proglacial transition zone at Pasterze Glacier, Austria, Remote Sens-Basel, 9, 549, 1-19, https://doi.org/10.3390/rs9060549, 2017.

[3] Specific comments: Reviewer: 145: are you referring to a calendar year or a mass balance year? Reply by authors: We refer here to calendar years. This is now indicated accordingly in the text.

Reviewer: What exactly would be the implication of the temperatures during the winter? Reply by authors: We are not quite sure if we understand the question as it was intended. The main idea about depicting the MAAT evolution in the study area during the rather recent past was to show general climatic changes in the study area not differentiating between summer and winter temperatures.

[4] Technical corrections Reviewer: 233: pixels? Reply by authors: Changed from "(maximum of 5 px)" to "(maximum of 5 pixels)"

Reviewer: 235: 0.95 m Reply by authors: Changed to 0.95 m,

Reviewer: 236: .Thus, : : :? Reply by authors: Modified as suggested

Reviewer: 266: 0.1 m? Reply by authors: Changed to 0.1 m as suggested.

Reviewer: 283: of about 1.4 km Reply by authors: Modified as suggested,

Reviewer: 362: MEZ?, pm missing at the end of the line Reply by authors: "pm" was added where it was missing before. We did not add the information that we speak here about the Middle European Time / MET because this addendum would then be necessary at many places in the manuscript. Furthermore, we assume that the location of the glacier makes it evident which time zone is relevant here.

Reviewer: 441: 4 106 m3? Reply by authors: 4 x 106 m^3 is correct

Reviewer: Figure 4: please check again the legend, you use a thin black line outlining the hillshade, and at the same time for the outflow Reply by authors: Figure 4 was slightly modified. The outline of the hillshade was deleted and only one black line remained.

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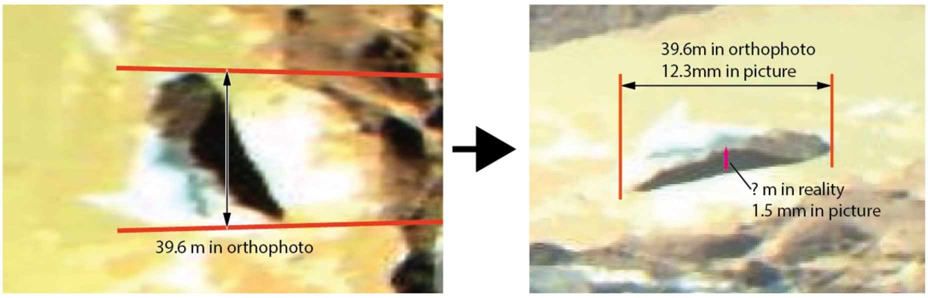

Fig. 1: Approach for iceberg height calculation exemplified for one iceberg in the ice-breakup event 3 (IBE3). Left – detail of the orthorectified webcam image with horizontal extent of iceberg, right – detail of the original webcam image with calculated horizontal extent and estimated height of iceberg. The latter data gives the ratio between the quantified horizontal extent and height. In this case the 1.5 mm in the picture correspond to 4.8 m. Finally, a correction calculation was applied accounting for the camera distortion (see text).

Fig. 1. Approach for iceberg height calculation exemplified for one iceberg in the ice-breakup event 3 (IBE3). Left – detail of the orthorectified webcam ....

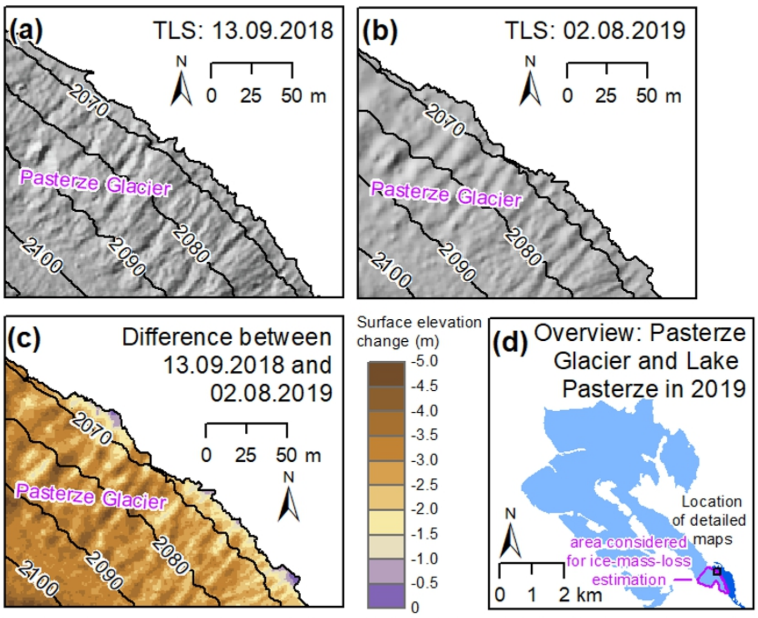

Fig. 2: Surface elevation changes between 13.09.2018 and 03.08.2019 in a lake-proximal section of Pasterze Glacier based on TLS-data. (a) hillshade with contour lines at stage 13.09.2018, (b) hillshade with contour lines at stage 03.08.2019, (c) elevation differences between 13.09.2018 and 03.08.2019, (d) overview map of Pasterze Glacier and Lake Pasterze in 2019 also indicating the area considered in the ice-mass-loss estimation at the terminus area.

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