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Quantification of ice-breakup events and iceberg dynamics in a highly dynamical proglacial lake in Austria (Pasterze Glacier)

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Glacier recession into glacier bed overdeepenings commonly cause the formation of highly dynamical proglacial lakes. Such a proglacial lake at the terminus area of Pasterze Glacier, Austria's largest glacier (approximately 16km^2), sextupled during the last decade from 0.05 (2010) to 0.3km^2 (2019) as measured during multiannual ground-based differential global positioning surveys and terrestrial laser scanning campaigns.

Sonar measurements in September 2019 revealed a maximum lake depth of 48.2m and detected several depressions at the lake bottom. The calculated mean lake depth was quantified to be 13.4m based on 4276 individual data points (unevenly distributed over the lake) yielding a calculated water volume of 4 million m^3. Five large-scale and rapid ice-breakup and ice-floating events were observed during the period September 2016 to October 2018 based on webcam images with a temporal resolution of (mostly) 5 minutes. Furthermore, three medium-sized and five smaller ice-cracking events or collapses as well as three iceberg-tiltings were observed. These events as well as the dynamics of icebergs for one specific day (16.06.2019) and for one specific iceberg (from September 2017 to its disappearance in September 2019) were quantified. For this, we either applied the Environmental Motion Tracking (EMT) software for feature tracking or we orthorectified (Erdas, Phyton) and analyzed (ArcGIS) webcam images using three comparative orthophotos from the years 2015-2018.

The icebergs at the proglacial lake of Pasterze Glacier probably formed by disintegration of glacier ice at the lake bottom or at the near-shore surface influenced by high water pressure along fractures. The breakup events demonstrate that the originally presumed pure "proglacial lake" seems to be (at least during the period of observation) to some extent a "supraglacial lake" covering glacier ice, which steadily disintegrates forming icebergs. During breakup events, such ice masses show signs of tilting, sudden disintegration and formation of icebergs, which steadily melt accompanied by further tilting events at the lake surface.

The first analytical approach using the EMT software yields meaningful results if icebergs do not modify substantially their geomorphological appearance during the event. If new objects appear

at the lake or icebergs tilt, no trajectories can be calculated by EMT. The second approach yields surface extent and structure data as well as location of the icebergs at different times during for instance the ice-breakup events. With this information, the process of the ice-breakup could be divided into sub-processes partly related to each other. Detailed quantification of for instance crack evolution, tilting of debris-covered ice bodies, lake transgression or lateral ice shift were possible in high detail. Reasons for detected errors in the analyzed orthophoto imagery are changes in the lake level (order of 1m) or offset of the camera (maximum of 5 pixels).

No major ice-floating event was observed during the ablation period 2019. Furthermore, the aerial extent of icebergs in the proglacial lake decreased substantially in 2019. We therefore conclude that the process of lake-bottom ice disintegration has widely ceased and that the glacier ice at the lake bottom has mostly vanished.