The rapid retreat of two lake-terminating outlet glaciers of the Northern Patagonian Ice Sheet and underestimation of mass loss due to subaqueous ice volume

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① INTRODUCTION

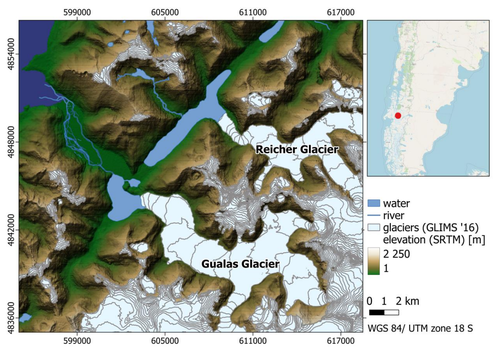


Figure 1 : Gualas Glacier and Reicher Glacier and their proglacial lakes

- The **Northern Patagonian Ice Sheet (NPI)** and the Southern Patagonian Ice Sheet are the largest ice masses on the southern hemisphere outside of Antarctica, with an ice volume of ~4,756 ± 923 km3 (McDonnell et al., 2022).
- **Lake-terminating glaciers at the NPI had the most significant increase in mass loss between the 1976-2000 period and the 2000-2020 period**
- First-ever data collection in Nov. 2023 and in Mar. 2024 at the remote **Gualas** and **Reicher glaciers**: using boat, zodiacs, packrafts and kayaks to study interaction of glacier and proglacial lakes

② RESEARCH QUESTIONS

- **How do lake-terminating glaciers** in Northern Patagonia behave under rapid retreat? What are the governing processes?
- Does ablation measured at stakes and UAV-based ice elevation change for Gualas glacier correspond to estimates from satellite-based analyses?
- **What is the estimated subaqueous ice mass loss** of lake-terminating glaciers Gualas and Reichter since the 1980s?

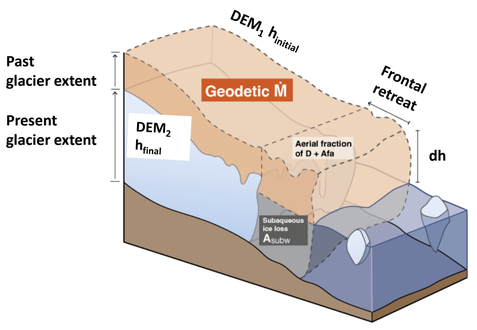


Figure 2 : Geodetic mass balance and underestimation of subaqueous ice mass loss

③ METHODS

- **Historical aerial imagery** for glacier extents
- **Glacier extents** from satellite imagery
- **Photogrammetry**: Processing with Metashape Pro and ImGRAFT
- **Bathymetry**: interpolation of kayak-based sonar surveys to obtain DEMs

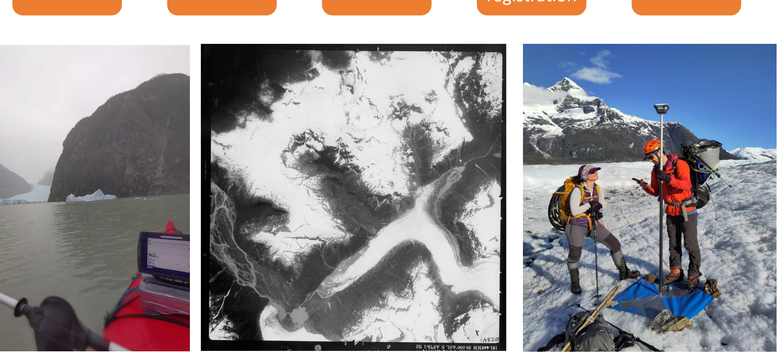


Figure 3 : Bathymetry survey on Reicher glacier, Nov. 2023

Figure 4 : Historical aerial imagery of 1945 showing Reicher Glacier, filling up the 9 km long valley

Figure 5 : Ground target measurements on Gualas Glacier in November 2023

$$\Delta M = \dot{M} + A_{subw}$$

Total mass loss
= Geodetic mass loss + subaqueous mass loss

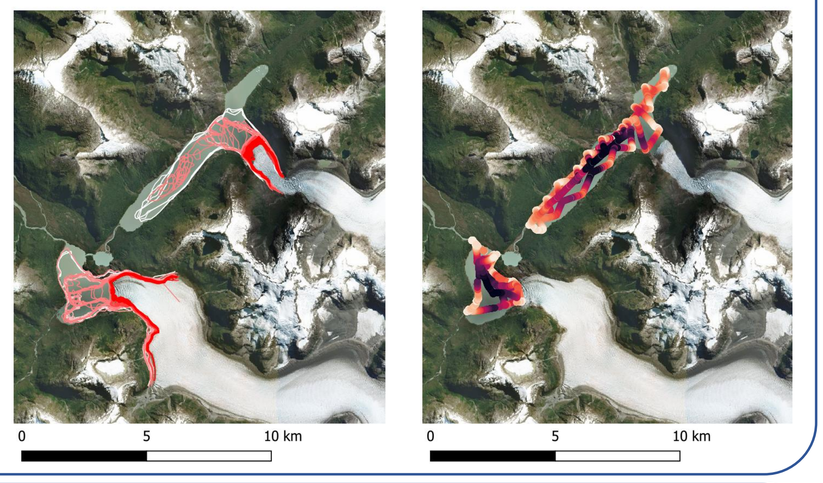
④ FIELD DATA collected in November 2023 and in March 2024

- Repeated **UAV surveys** of both glacier tongues
- **Bathymetry surveys** of Reichter and Gualas lakes
- **Ablation stakes** on Gualas glacier
- **GPR surveys** on Gualas glacier
- **Lake profiling** : temperature, conductivity and depth
- **Water isotope samples** collected on the glacier and in streams

Figure 6: Reicher glacier terminus

Figure 7 : **(a)** Glacier retreat since 1985, manually drawn from satellite data (Google Earth Engine): bright is 1985, red is recent.

(b) bathymetry measured from kayaks / zodiac in November 2023 (dark: deep with max. 260 m for Gualas Glacier and max. 366 m for Reicher Glacier, white: shallow depth).



⑤ PRELIMINARY RESULTS

The geodetic **mass balance** was calculated for the Northern Patagonian glaciers by Dussaillant et al. (2019) based on satellite data. Below, we present a first rough estimate of underestimation of the total mass loss due to the non accounting of the subaqueous mass loss by the geodetic method in glaciers ending in water bodies. We apply it to Reicher Glacier and to Gualas Glacier based on glacier outlines and interpolated bathymetry data from November 2023.

The geodetic mass loss between 2000 and 2018 at Gualas Glacier was -1.3 +/- 0.13 mWE yr^{-1}, while it was -0.9 +/- 0.1 mWE yr^{-1} at Reicher Glacier (Dussaillant et al., 2019).

Subaqueous mass loss	Reicher		Gualas	
Type of measure	% of total	Abs. [m w.e. /a]	% of total	Abs. [m w.e. / a]
2000 - 2023	**14.4 %**	**-0.15**	8.6 %	-0.12
1985 - 2023	36.9 %	-0.40	11.9 %	-0.09

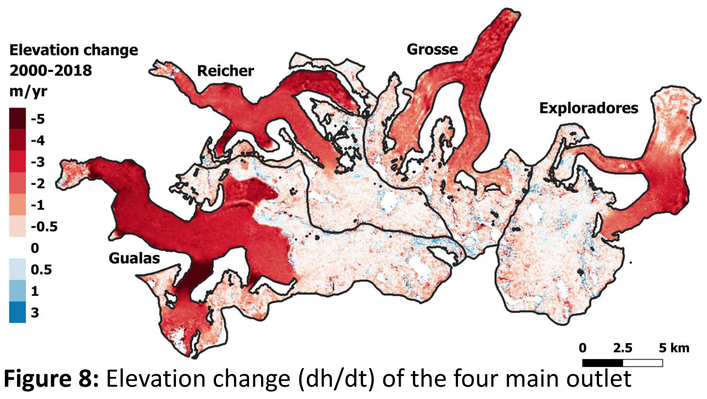


Figure 8: Elevation change (dh/dt) of the four main outlet glaciers on the north-western margin of the NPI.

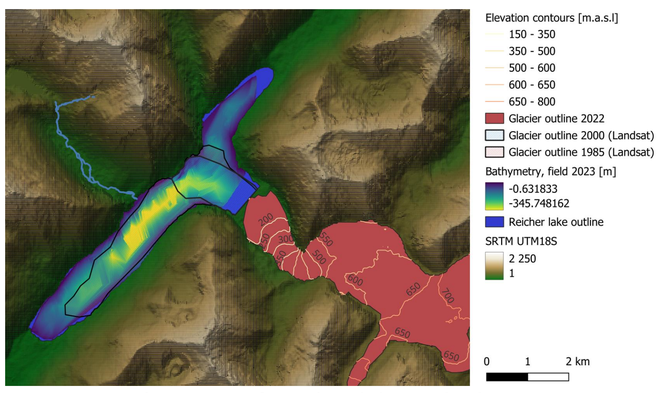


Figure 9: Bathymetry of Reicher lake with glacier extents.

Ice velocities, ablation and dh/dt at Gualas glacier tongue between November 2023 and March 2024

Seasonal ice ablation over 4 months at Gualas glacier was between 5.4 m (at 300 m.a.s.l.) and 6 m (at 250 m.a.s.l). Ice velocities obtained by correlating 1-m resolution drone imagery for an area of 3 km^2 range between 60 and 120 m/a for the frontal part.

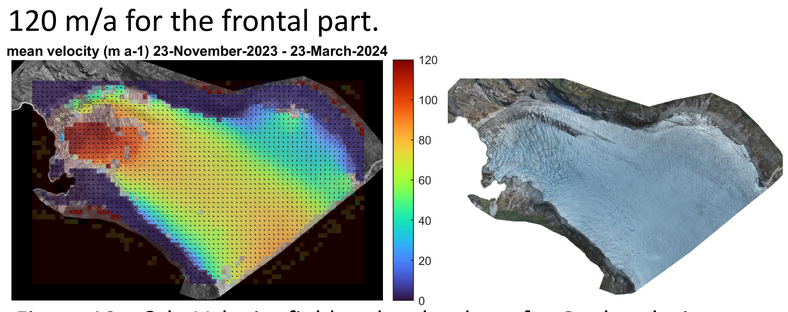


Figure 10 a & b: Velocity field and orthophoto for Gualas glacier

⑥ CONCLUSION

The estimates of subaqueous ice mass loss are only approximations, showing a maximum possible value in the case of grounded ice. The underestimation of ice mass loss by geodetic mass balance seems to be significant, and this merits a region-wide study.

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