



Dynamic response of lake-terminating glaciers to the abrupt drainage of Lago Greve, in the Southern Patagonia Icefield

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Abstract. Abrupt drainage of proglacial lakes has the potential to trigger large changes in lake-terminating glaciers. However, observations of glacier response to lake drainage remain sparse. Here, we report changes seen in three glaciers in
10 the Southern Patagonia Icefield (Glaciar Pío XI, Greve, and Lautaro) terminating in a large proglacial lake, which drained, lowering the lake level by ~18 m in 2020. This event provided a rare opportunity for a natural experiment to compare glacier responses to a common lake-level perturbation. Using satellite data from 2017–2021, we investigated the impact of lake drainage on ice-front position, surface elevation, flow speed, and frontal ablation. Glaciar Pío XI decelerated to <10% of its pre-event speed during the drainage, suggesting the ice-flow influenced by lake level through changes in subglacial water
15 pressure. Glaciar Greve showed speed-up, ice-front advance, and surface lowering, suggesting hydrostatic pressure plays a fundamental role acting on the glacier front. Glaciar Lautaro showed no clear changes attributable to the event. The contrasting responses of these glaciers are likely due to individual settings, i.e., subglacial hydrology, ice thickness, bed geometry, and frontal ablation. Our results provide important implications for glacier and ice sheet response to changes in conditions at glacier fronts.

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1. Introduction

Mountain glaciers and ice caps worldwide lost ice at a rate of $273 \pm 16 \text{ Gt a}^{-1}$ from 2000–2023, contributing to recent global sea-level rise (The GlaMBIE Team, 2025). A substantial fraction of this mass loss is driven not only by atmospheric forcing but also by dynamic processes near the front of calving glaciers (Benn et al., 2007; Carrivick et al., 2020). The front position,
25 surface elevation, flow speed, and frontal ablation near calving glacier termini are strongly modulated by ice-water interactions and by subglacial hydrological conditions (Vielé et al., 2001; Tsutaki et al., 2019; Vijay et al., 2019). As a result, terminus dynamics and the evolution of calving glaciers are partly decoupled from climatic forcing (Nick et al., 2009; Truffer and Motyka, 2016; Minowa et al., 2023). The importance of these processes is increasing as proglacial lakes continue to expand globally and more glaciers transition to lake-terminating settings (Tsutaki et al., 2013; Shugar et al.,



2020; Sato et al., 2022; Zhang et al., 2024; Steiner et al., 2026). To understand and project future glacier mass loss, it is therefore essential to clarify how lake-terminating glaciers respond dynamically to changes in proglacial water conditions.

Near the terminus of a lake-terminating glacier, ice flow is controlled by a force balance that is sensitive to changes in lake level. This is because the driving stress is resisted by the hydrostatic pressure acting on the calving front (O’Neel et al., 2005), whereas the subglacial lubrication is affected by lakewater given its connection to the glacier base (Tsutaki et al., 2013; Minowa et al., 2023). Although in-situ measurements are limited, several studies reported substantial ice speed variations triggered by lake level changes (Laumann and Wold, 1992; Boyce et al., 2007; Sugiyama et al., 2010). Glacier response to a lake level change is likely complex, as is the tidal influence on the dynamics of marine-terminating glaciers (Sugiyama et al., 2025). Complexity arises because lakewater affects several components of the force balance (Minowa et al., 2023), and the geometrical settings of individual glaciers (i.e., ice thickness, bed geometry, and glacier width) play critical roles (Sato et al., 2022; Minowa et al., 2023). Therefore, a lake-level change may cause ice acceleration or deceleration, depending on the conditions of the glacier mentioned above, which makes the prediction of glacier response difficult (Laumann and Wold, 1992). Furthermore, ice speed variations near the glacier front can generate a feedback loop between the glacier geometry and ice dynamics. For example, acceleration towards the calving front results in glacier thinning and steepening due to longitudinal stretching of ice, so-called dynamic thinning (Howat et al., 2008; Nick et al., 2009; Minowa et al., 2023). The process leads to the reduction in the effective pressure at the glacier base (defined as the difference between ice overburden pressure and subglacial water pressure; Iken and Truffer, 1997; Tsutaki et al., 2013) as well as an increase in the driving stress, which are favorable for further acceleration.

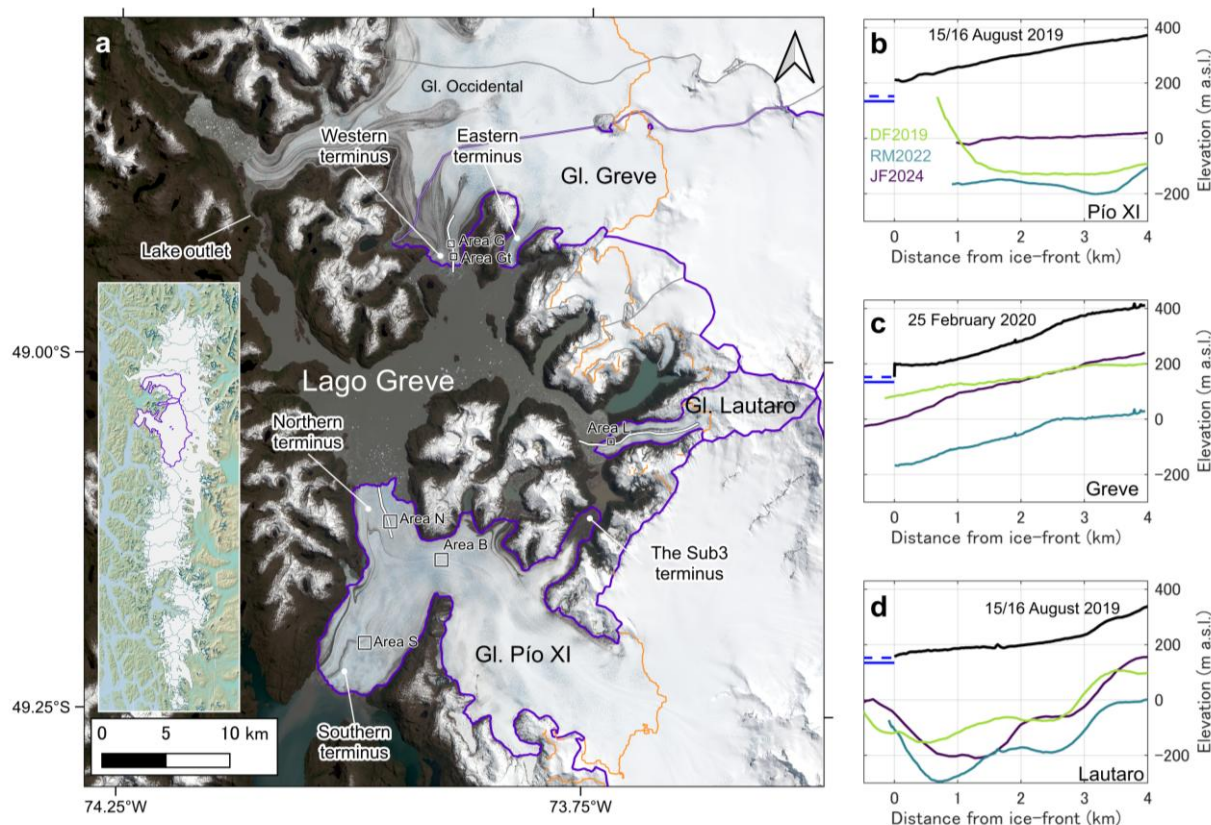
The proglacial lake level affects not only glacier speed but also calving and ice-front variations. Underwater melting controls the geometry of the calving front, which may destabilize ice and facilitate calving (Luckman et al., 2015; Ma and Bassis, 2019). Lakewater also exerts a buoyancy force on the glacier front, leading to subaqueous calving driven by torque (Warren et al., 2001; Dell et al., 2019). These changes in the calving rate, as well as in ice speed, induce variations in the glacier front position. After a glacier retreat or advance, the geometry of the glacier further affects the hydraulic conditions near the calving front (Tsutaki et al., 2013, 2019; Hyde et al., 2025). These processes, i.e. acceleration, steepening, thinning, increased calving, and frontal variations, can form a positive feedback loop that initiates rapid and large-scale retreat of a calving glacier (Howat et al., 2008; Nick et al., 2009; Minowa et al., 2023). Despite the importance of the subject, general understanding is hampered by a lack of observations under changing lake levels, varying magnitudes of lake-level change, and the geometric glacier settings.

During glacial lake outburst floods (GLOFs), the lake level drops rapidly by tens of meters over days to months (Lützow et al., 2023; Dømggaard et al., 2024). The change in the lake level promotes a large and sustained reduction in hydrostatic pressure on the ice front, as well as in subglacial water pressure, assuming the bed is hydrologically connected to the lake.



Therefore, GLOFs provide a unique opportunity to investigate the response of lake-terminating glaciers to perturbations in
65 frontal and basal boundary conditions. Unlike ocean tides, which induce only meter-scale cyclic water-level variations, a
GLOF imposes a long-lasting perturbation that affects force balance, basal motion, and frontal ablation. Indeed, at a lake-
terminating glacier in Yukon, Canada, a 1.7 m lowering of proglacial lake level resulted in a 48% decrease in ice speed, due
to the change from a flotation to a grounded condition of the terminus (Main et al., 2023). However, compared to studies on
the drainage of ice-marginal lakes and their impact on glacier dynamics (Anderson et al., 2005; Sugiyama et al., 2010),
70 observations remain sparse for glacier response to a proglacial lake level change.

In this paper, we perform satellite data analysis on the dynamics of three lake-terminating glaciers in Patagonia (Glaciares
Pío XI, Greve, and Lautaro; Fig. 1a) during a period including a rapid lake drainage. In April–July 2020, one of the largest
proglacial lakes in Patagonia, Lago Greve (Fig. 1a), suddenly drained through an outlet stream. The lake level dropped by
75 18.3 ± 1.2 m and the lake lost 3.7 ± 0.2 Gt of water (Hata et al., 2022). This event was one of the largest GLOF events
reported in recent decades (Hata et al., 2022). From satellite observations, the drainage pathway was located at the northern
margin of the lake, where the outlet stream deepened due to erosion. Thus, subglacial drainage was not involved in the event.
This event provided a rare opportunity for a natural experiment with glacier dynamics. By analyzing the three glaciers
terminating in Lago Greve, the impacts of the lake drainage on the glaciers were investigated with attention to ice and bed
80 geometries (Fig. 1). The response of multiple glaciers, each possessing different geometry and thicknesses, to the same
magnitude of perturbation sheds light on the key processes at the calving glacier front, such as basal sliding and frontal
ablation.



85 **Figure 1. (a)** Satellite image (Sentinel-2 true-color composite image acquired on 1 November 2020) showing the region of study.
 The inset map shows the Southern Patagonia Icefield, and the target glaciers are shown with purple polygons using the RGI 6.0
 inventory glacier boundaries (RGI Consortium, 2017). The terminus positions are as present on 1 November 2020. Orange lines
 show the equilibrium line altitude of each glacier as estimated by Schaefer et al. (2015). Glacier flowlines are indicated by the
 white lines. (b) Glacier surface (black) and bed elevation (green, blue, and purple) along the flowlines of Glaciario Pío XI, (c) Glaciario
 Greve, and (d) Glaciario Lautaro. Bed elevations are estimated by models; DF2019: Farinotti et al. (2019), RM2022: Millan et al.
 90 (2022), and JF2024: Fürst et al. (2024). Blue lines in (b–d) show the altitude of the lake surface before (solid) and after (dashed) the
 drainage event of Lago Greve.

2. Study sites

95 2.1. Glaciario Pío XI

Glaciario Pío XI (49.15°S, 73.90°W) is the largest glacier in South America with a surface area of 1255 km² in 2018 (Fig. 1; Hata and Sugiyama, 2021). The ice covers the elevation range of 0–3300 m a.s.l. and flows west from a plateau in the accumulation area to two main termini (the northern and southern termini) and other smaller termini. The northern terminus flows into a lake (Lago Greve), while the southern terminus, the largest terminus of the glacier, terminates in the ocean (Eyre



100 Fjord). One of the subsidiary termini (Sub3 in Fig. 1) branches northward from the main trunk of the glacier and its debris-
 covered terminus flows into Lago Greve. Other smaller termini terminate in ice-marginal lakes. The equilibrium line altitude
 (ELA) was estimated as 1055 m a.s.l. by modelling of surface mass balance in 1975–2011 (Fig. 1a; Schaefer et al., 2015).
 The ice thickness near the northern terminus was estimated as 285–386 m (Fig. 1b) by models for 2000 (Farinotti et al.,
 2019; Fürst et al., 2024) and for 2017–2018 (Millan et al., 2022): although no thickness observation has been reported in the
 105 ablation area. In contrast to other glaciers in the region, this glacier thickened and advanced by approximately 2 km in the
 21st century (Hata and Sugiyama, 2021; Piret et al., 2024).

The glacier surface velocity below the bifurcation area has shown complex variations in the last three decades. The southern
 terminus gradually decelerated from $\sim 4000 \text{ m a}^{-1}$ in 2000 to $\sim 500 \text{ m a}^{-1}$ after 2010 (Muto and Furuya, 2013; Sakakibara and
 110 Sugiyama, 2014; Minowa et al., 2021). Seasonal speed variations have been observed at both termini, with peak speeds in
 spring to early summer (Sakakibara and Sugiyama, 2014; Mouginit and Rignot, 2015; Minowa et al., 2021). Observations in
 1986 and 2000 showed that the southern terminus flowed more than twice as fast as the northern terminus. In contrast to
 these observations, ice speed at the northern terminus exceeded that in the south in 2015–2017 (Wilson et al., 2016; Abdel
 Jaber et al., 2019; Hata and Sugiyama, 2021). This recent change has been attributed to the formation of a moraine in front of
 115 the southern terminus, which exerts buttressing force and suppresses frontal ablation (Abdel Jaber et al., 2019; Hata and
 Sugiyama, 2021; Minowa et al., 2021). Glaciar Pío XI is likely underlain by a sediment layer, because aerial photographs
 taken in 1945 show sediment occupying the area near the current northern terminus position (Rivera et al., 1997; Fürst et al.,
 2024). This assumption is supported by abundant sediment discharge into Eyre Fjord (Piret et al., 2024; Hata et al., 2026).

120 2.2. Glaciar Greve

Glaciar Greve (48.93°S, 73.90°W) is a lake-terminating outlet glacier of the SPI. Glaciar Greve has two calving fronts
 terminating in Lago Greve, a 3.5-km-wide western terminus and a 1.7-km-wide eastern terminus (Fig. 1). Similar to other
 glaciers in the SPI, the glacier has shown a retreating trend since the 1970s (Minowa et al., 2021). The flow speed at the
 western terminus gradually decreased from $\sim 1.8 \text{ km a}^{-1}$ in 2000 to $\sim 1.3 \text{ km a}^{-1}$ in 2011 (Sakakibara and Sugiyama, 2014).
 125 Although model estimates of ice thickness show a large variation near the glacier front ($\sim 40\text{--}400 \text{ m}$), they suggest the bed
 generally slopes downglacier (Carrivick et al., 2016; Farinotti et al., 2019; Millan et al., 2022; Fürst et al., 2024; Fig. 1c).

2.3. Glaciar Lautaro

Glaciar Lautaro (49.05°S, 73.72°W), also known as Glaciar HPS-9, is a lake-terminating glacier, feeding ice into the eastern
 130 part of Lago Greve from a 2.2-km wide terminus (Abdel Jaber et al., 2019; Fig. 1). Ice thickness near the front is $\sim 200 \text{ m}$ and



the bed slopes upglacier, according to inversion models (Carrivick et al., 2016; Farinotti et al., 2019; Millan et al., 2022; Fürst et al., 2024; Fig. 1d).

2.4. Lago Greve

135 Lago Greve is the fourth-largest glacial lake in the world with an area of 187 km² in November 2020 (Fig. 1; Shugar et al., 2020; Hata et al., 2022). The lake formed when Glaciar Pío XI advanced and blocked Eyre Fjord in 1945–1962; before that, the area was occupied by the terminus of Glaciar Greve and its proglacial outwash plain (Rivera, 1992). Although no bathymetric measurements have been reported, the lake depth at the calving front of Glaciar Pío XI before the 2020 drainage was estimated to be up to 150 m (Warren et al., 1997). The lake receives ice and meltwater from eight outlet glaciers of the
 140 SPI, including Glaciares Pío XI, Greve, Lautaro, and HPS-8 (Fig. 1).

Lago Greve abruptly drained in 2020. The lake level dropped by 18.3 ± 1.2 m and 3.7 ± 0.2 Gt of water drained over a four-month period, making it one of the largest GLOF events reported (Hata et al., 2022). Satellite data show that the water drained through an outlet near the northern edge of the lake towards Glaciar Occidental (Lake outlet in Fig. 1). The drained
 145 water therefore did not pass beneath the glaciers flowing into Lago Greve.

3. Methods

3.1. Ice-front position

Ice-front positions of the glaciers were delineated manually on optical satellite imagery using the QGIS software. For the
 150 period from 2017–2021, we used false color composite images from Sentinel-2 MSI and panchromatic images from Landsat 8 OLI with spatial resolutions of 10 and 15 m, respectively. For the period from 2020–2021, we used PlanetScope imagery with a resolution of 3–4 m. The mean displacement of the glacier front (L) and the displacement rate ($\frac{dL}{dt}$) were calculated from the areal change near the ice front divided by the glacier-width. The uncertainty in L was estimated as <10 m from repeated delineation (Hata and Sugiyama, 2021).

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3.2. Surface elevation change

To investigate surface elevation change, we analyzed digital elevation models (DEMs) generated from stereo-pair satellite images. Five DEMs (Table 1) were generated in this study from SPOT-6/7 and WorldView-1 satellite images by using Ames Stereo Pipeline software (Shean et al., 2016) version 2.7.2. A standard workflow with the RPC (rational polynomial



160 coefficient) model of the images was employed to obtain DEMs in 5-m resolution (Hata et al., 2022). We also analyzed
 ASTER-VA DEMs (Fujisada et al., 2005) distributed by AIST (National Institute of Advanced Industrial Science and
 Technology, Japan). Spatial resolution of the ASTER-VA DEM was 30 m.

Table 1. Satellite data or mission derived DEMs used for glacier surface elevation analysis

Date	Satellite	Resolution/vertical uncertainty (m)	Source
Pío XI			
2017-02-26	ASTER-VA	30/20.3	Hata and Sugiyama (2021)
2019-08-15/16	SPOT-6/7	5/5.9	This study
2021-03-02	ASTER-VA	30/13.4	AIST (Fujisada et al., 2005)
Greve			
2017-04-01	ASTER-VA	30/12.3	AIST (Fujisada et al., 2005)
2020-02-05/06	SPOT-6/7	5/10.5	This study
2020-07-15	WorldView-1	5/9.8	This study
2021-03-02	ASTER-VA	30/10.5	AIST (Fujisada et al., 2005)
Lautaro			
2000-02-11–22	SRTM	30/7.0	USGS (2014)
2019-08-15/16	SPOT-6/7	5/8.8	This study
2021-02-25/26	SPOT-6/7	5/10.0	This study

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The ASTER-DEMs were corrected for horizontal shift, elevation dependent bias, and along-/across-track dependent bias,
 based on a method proposed by Nuth and Kääb (2011). For the SPOT- and WV-DEMs, horizontal-shift, elevation dependent
 bias, and vertical shift were removed. Along-/across-track bias was not corrected because only a small part of the satellite
 imagery scenes was used in the study. The corrections were performed in off-ice areas adjacent to the glaciers. The
 170 uncertainties in the DEMs over Glaciar Pío XI were evaluated in a gently sloping off-ice area (<30 degrees) by comparing
 the elevation data with those from satellite altimetry (ICESat-2). DEMs over Glaciar Greve and Lautaro were evaluated by
 comparing with the DEM from the shuttle radar topography mission (SRTM-DEM; USGS, 2014) acquired in 11–22
 February 2000. The uncertainties of the DEMs are summarized in Table1. Elevation accuracy of the ICESat-2 ATL06
 product (Smith et al., 2021) was reported as <0.1 m (Zhang et al., 2021), and the accuracy of SRTM-DEM is < 7 m (Rignot
 175 et al., 2003). Elevation change was analyzed in three regions (the northern terminus: Area N, the southern terminus: Area S,

the bifurcating area: Area B) for Pio XI, two regions for the western terminus of Glaciar Greve (Areas G and Gt), and one region for Glaciar Lautaro (Area L) (Fig. 1a).

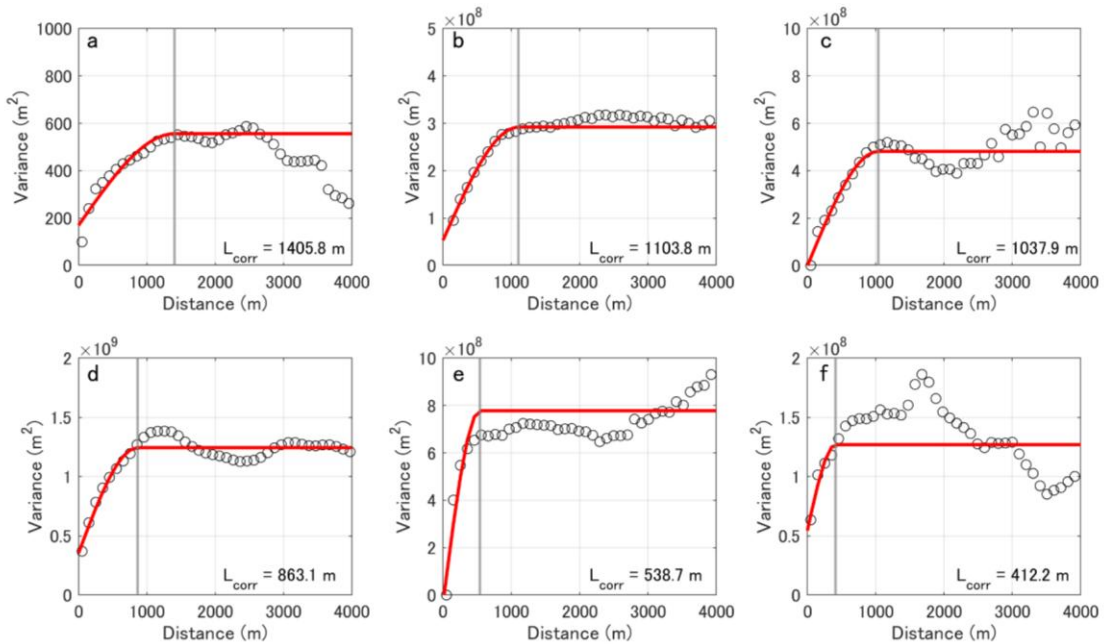
The uncertainty in the mean elevation change over a certain area (σ_{dh}) was estimated as:

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$$\sigma_{dh} = \frac{\sigma_{dh}}{\sqrt{\frac{N_{tot} \cdot \Delta x}{2L_{corr}}}} \quad (1)$$

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where σ_{dh} is the standard deviation of the elevation change, N_{tot} is the total number of pixels, and Δx is the pixel spacing of the DEMs (Gardelle et al., 2013). L_{corr} is the autocorrelation length, which is a parameter of the valid length of the autocorrelation. We estimated L_{corr} for each DEM pair by fitting a spherical variogram model to empirical variograms obtained from the elevation changes over off-glacier areas (Dehecq et al., 2020; Sunako et al., 2023). The estimated L_{corr} was 412–1406 m (Fig. 2).



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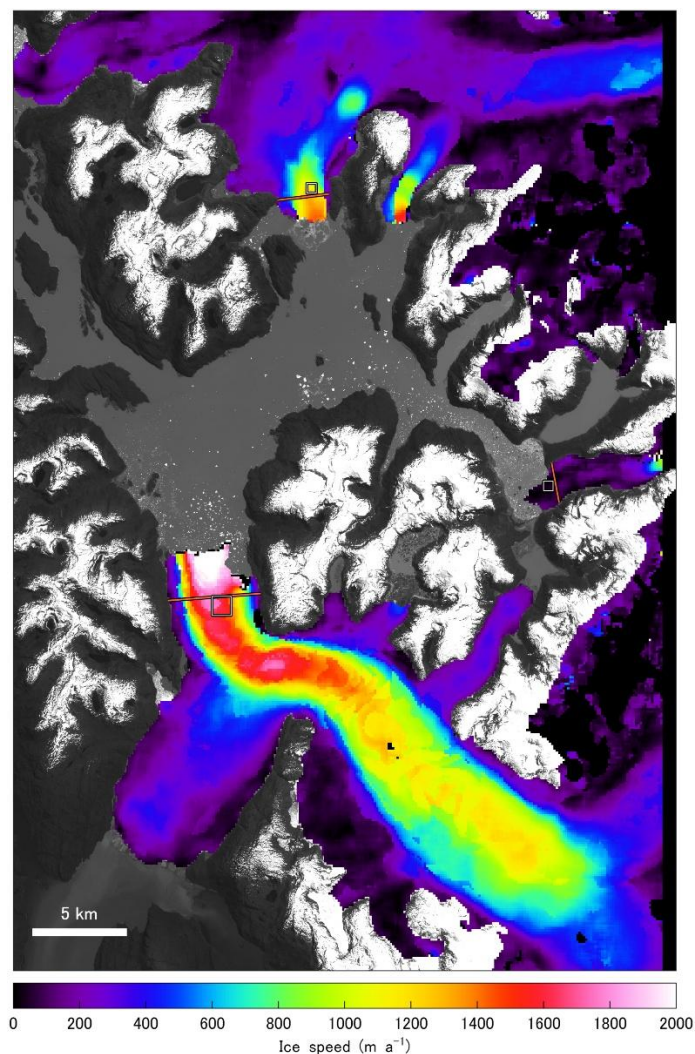
Figure 2. Semi-variogram for the DEM pairs of (a) 2017–2019 of Pio XI, (b) 2019–2021 of Pio XI, (c) February–July in 2020 of Greve, (d) the pair of July in 2020 and March 2021 of Greve, (e) 2017–2020 of Greve, and (f) 2019–2021 of Lautaro. Circles indicate the variance for the corresponding distance, and red curves indicate the spherical variogram model estimated from the empirical variance. Vertical grey lines indicate estimated autocorrelation length L_{corr} for each DEM pair.

3.3. Ice-flow velocity

Glacier surface velocities were measured by applying a feature tracking technique to optical satellite imagery (Landsat 8 OLI and Sentinel-2 MSI) acquired in 2017–2021. We used ImGRAFT (Image GeoRectification and Feature Tracking; Messerli



195 and Grinsted, 2015) implemented on MATLAB. Displacement was obtained in a resolution of 120 m by using an orientation correlation method with a 21×21 pixel target window and 61×61 pixel search window. A threshold of signal to noise ratio (SNR <6) was used to remove uncertain data as outliers. The threshold was determined by trial and error with a visual inspection of the output velocity-field.



200 **Figure 3. Spatial distribution of surface flow velocity obtained from the 12 August and 6 September 2019 Sentinel-2 image pair. The Sentinel-2 background image was acquired on 1 November 2020. Boxes indicate the sampling areas for each terminus (Areas N, G, L). Orange lines represent flux gates for calculate frontal ablation.**

The velocity magnitude was averaged within the sampling areas (Areas N, S, B, G, Gt, and L) (Figs 1a, 3, and S2). Mean speed for each period of interest was taken using all data available in the period. Ice speed at the calving front, v_f , was
 205 estimated from the velocity of sampling areas, by multiplying a glacier-specific scaling factor (44–88% depending on the glacier) determined by linear regression between mean velocity across flux gates nearby the sampling area (Fig. 3) and mean



velocity of sampling area. The value v_f was used to compute the frontal ablation as explained in the next subsection. The uncertainty in the ice-flow speed was estimated for each image pair from displacements in an off-glacier area within <1 km from each glacier terminus. The uncertainty range was $9\text{--}491$ m a^{-1} (mean: 98 m a^{-1}). Temporal separations of the median
 210 dates of image pairs were $3\text{--}118$ days with a mean of 44 days.

We also used the glacier velocity product from RETREAT (Friedl et al., 2021) derived from Sentinel-1 backscatter images. Velocity maps are available with a spatial resolution of 200 m. The uncertainty was estimated to be $0.5\text{--}490$ m a^{-1} (mean: 25 m a^{-1}). Temporal separations of median dates of image pairs were $1\text{--}42$ days with a mean of 5 days.

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3.4. Frontal ablation

Frontal ablation was computed from glacier flow speed and ice-front displacement rates following the method as used by Sakakibara and Sugiyama (2020). Frontal ablation A_f was calculated as the residual of ice speed at the calving front v_f and the ice-front displacement rate $\frac{dL}{dt}$ ($A_f = v_f - \frac{dL}{dt}$). The uncertainty was estimated to be <40 m a^{-1} from the uncertainties in
 220 the ice-front position and ice-flow speed.

3.5. Subglacial topography

Because no bed elevation measurements are reported near the terminus of the glaciers studied, we utilized a bed-elevation dataset (Fürst et al., 2024) and ice thickness datasets (Farinotti et al., 2019; Millan et al., 2022) estimated from models. Bed
 225 elevation was obtained from thickness data sets, using surface elevation from the nearest DEM grid point.

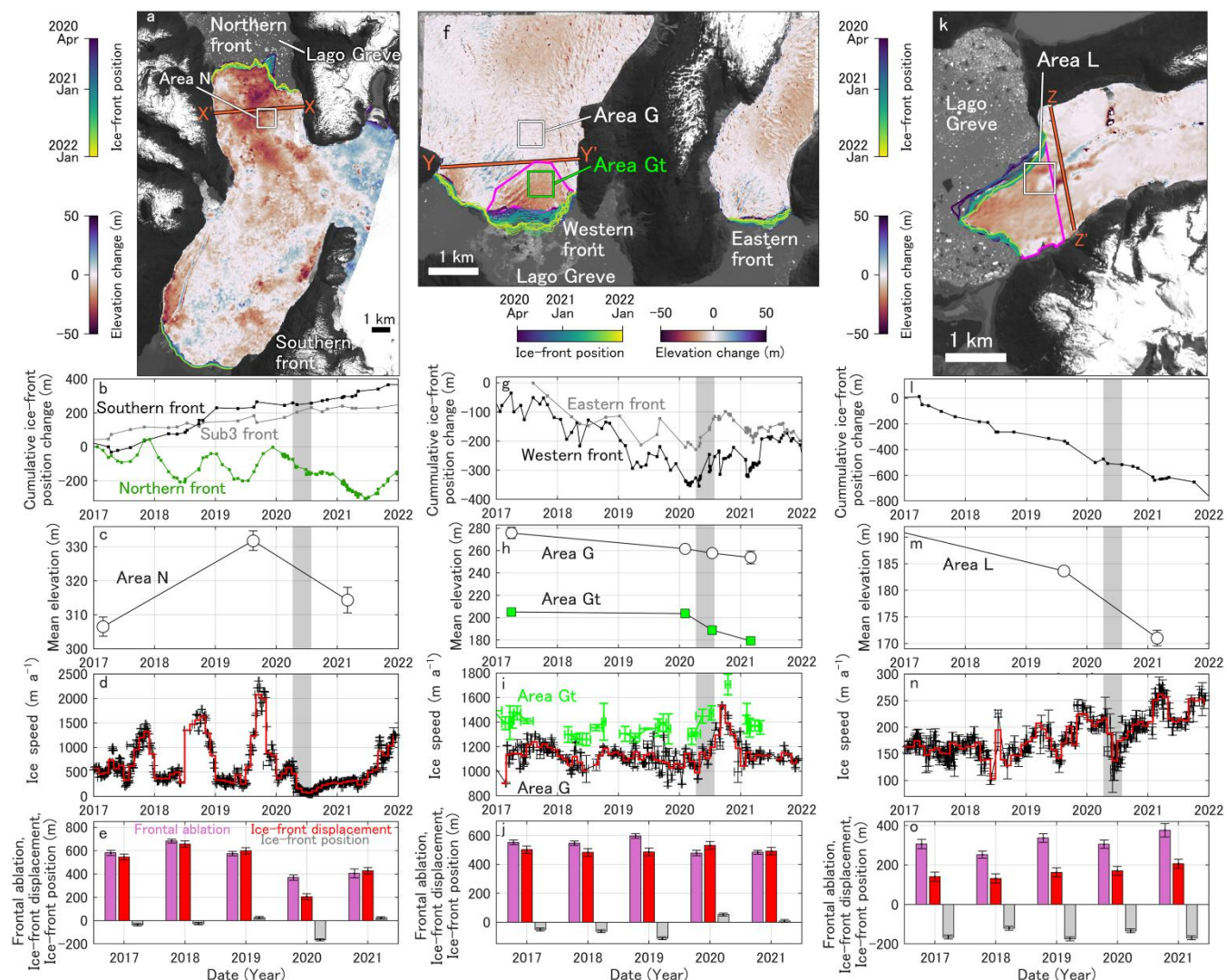
4. Results

4.1. Glaciar Pío XI: Deceleration, changes in flow direction and seasonal variations

Glaciar Pío XI, the largest glacier in the Andes, underwent drastic changes after the drainage event in terms of ice-front
 230 position, surface elevation, ice velocity, and frontal ablation. Before the drainage event in April 2020, the northern glacier terminus showed seasonal frontal variations within a range of 150 m, whereas the southern and Sub 3 termini progressively advanced (Figs 4a and b) (see Fig. 1a for the locations of the three glacier termini). The seasonal variations of the northern terminus vanished after the event and retreated by 233 m from April 2020 to July 2021. Surface elevation at 2.3–3.3 km from the northern front (Area N in Fig. 1a) decreased by 17.5 ± 4.7 m between August 2019 and March 2021 (Figs 4a and c).



235 Over the region covered by data in Fig. 4a, surface elevation change showed a transition from an increase of 1.7 ± 0.6 m during 2017–2019 to a rapid decrease of -4.7 ± 0.2 m from 2019 to 2021 (Fig. S1).



240 **Figure 4.** (a) Surface elevation change of Glaciar Pío XI from 15 August 2019 to 2 March 2021. Icefront positions of the northern and southern terminus are also represented. The background is a Sentinel-2 image acquired on 1 November 2020. Cross section used for calculation of v_f is shown as an orange line. (b) Timeseries of cumulative ice-front position change of the northern (green), southern (black), and Sub3 (gray) termini, (c) mean elevation in Area N, and (d) image-pair velocity (black) and monthly stack (red) of mean ice-speed in Area N. (e) Bar charts of annual frontal ablation, ice-displacement, and ice-front retreat of the northern terminus. The Grey dashed lines indicate the average frontal ablation slope obtained over the period from 2017–2019. Grey hatches in (b-e) indicate the timing of the Lago Greve drainage event. (f–j, k–o) similar diagrams for Glaciar Greve (f–j), and for Glaciar Lautaro (k–o).



Before the event, seasonal ice speed variations were observed in Area N, with amplitudes greater than 1000 m a^{-1} and peak velocities in September–November (Figure 2d and S2b–d). Similar speed variations were observed in Areas S and B (Fig. S2). After the drainage, ice speed in Area N sharply decreased and remained at a low level without seasonal speed-up (Fig. 4d). Mean speed from 21 April–3 May (11–24 days after the onset of the event) and from 26 July –7 August (109–121 days after the onset) were $202 \pm 73 \text{ m a}^{-1}$ and $46 \pm 64 \text{ m a}^{-1}$, which correspond to 41% and 9% of the pre-event speed ($497 \pm 9 \text{ m a}^{-1}$ from 26 March to 7 April). Sharp reduction was also observed in the frontal ablation at the Northern terminus. Annual frontal ablation in 2020 was 54% of the mean from 2017–2019 (Fig. 4e).

Before the drainage event, the glacier showed a seasonal speed-up toward the northern terminus, as clearly observed in the speed patterns from 14 March to 6 May 2019 and from 12 August to 9 September 2019 (Figs 5a and b). A significantly different speed-up pattern was observed in the year of the drainage, from 20 February–8 March to 29 July–2 October 2020 (Figs 3c and d), in which the flow direction after the speed up was toward the southern terminus (Fig. 5d). The data demonstrated a significant impact of the lake drainage on the glacier flow regime (Fig. S3).

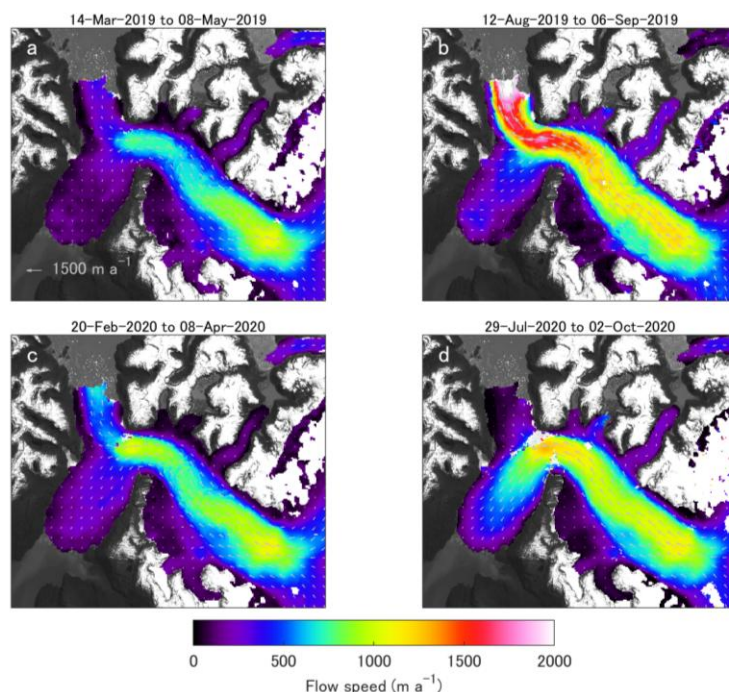


Figure 5. Ice speed maps of Glaciar Pio XI for periods (a) from 14 March to 8 May 2019, (b) from 12 August to 6 September 2019, (c) 20 February to 8 April 2020, and (d) from 29 July to 2 October 2020.



4.2. Glaciar Greve: Advance, thinning, and speed-up

Ice fronts on the western and eastern termini of Glaciar Greve began to advance following the drainage event (see Fig. 1a for the locations of the termini). The western terminus advanced by 112 m between April 2020 and December 2021, in contrast to the 226 m retreat prior to the event (January 2017 to 8 April 2020; Figs 4f and g). After the retreat of 77 m during 2017–2020, the ice front position of the eastern terminus became more stable (Fig. 4g). Substantial surface lowering near the western terminus was also seen after the drainage event. Between 5/6 February and 15 July 2020, the area within 1 km of the terminus lowered by 11.9 ± 0.9 m on average (magenta polygon in Fig. 4f). Pronounced elevation change was observed ~ 0.5 km from the glacier front (Area Gt, 14.9 ± 1.6 m), where the change before the drainage was within the uncertainty range (Fig. 4h). In contrast to the rapid change near the glacier front, the site located 1 km upstream (Area G) exhibited only 4.0 ± 1.6 m of surface lowering (Fig. 4h).

The ice-front advance and surface lowering at the western terminus were accompanied by an acceleration, as represented by the ice-speed time series in Areas G and Gt (Fig. 4i). In Area G, the acceleration began shortly after the drainage and reached a monthly mean peak speed of 1535 ± 14 m a⁻¹ in September 2020, which was $38 \pm 5\%$ greater than the mean from January to March 2020 (1115 ± 36 m a⁻¹). Thereafter, ice speed gradually decreased until December 2020 with little seasonal variability (<70 m a⁻¹). Similarly, Area Gt experienced acceleration from April 2020, reaching 1760 ± 83 m a⁻¹ in October 2020. The frontal ablation of the Western terminus in 2020 was 16% smaller than the 2017–2019 average (Fig. 2j).

Ice-speed profiles along the central flowline showed the most significant acceleration within 1 km of the ice front, but a speed-up was also detected further upstream (Fig. 6). The region of the greatest acceleration near the western terminus coincided with pronounced surface lowering and steepening. Surface slope between Areas Gt and G increased by 1.2° from February to July 2020 (Fig. 6). These observations suggest a strong feedback mechanism among the changes in flow speed, terminus position, surface elevation and slope.

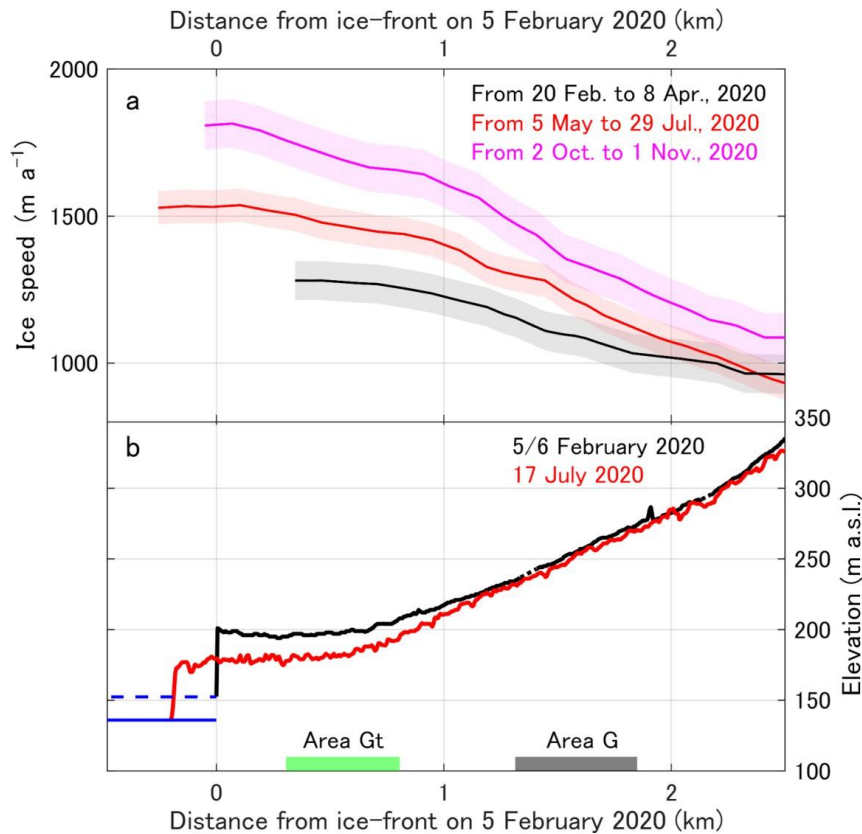


Figure 6. Ice speed along the flowline of the western terminus of Glaciar Greve. (a) Ice speed from 20 February to 8 April 2020 (black), from 5 May to 29 July 2020 (red), and from 2 October to 1 November 2020 (magenta). (b) Surface elevation on 5/6 February 2020 (black) and 17 July 2020 (red).

4.3. Glaciar Lautaro: Continuous retreat, surface lowering, and acceleration

In contrast to the other two glaciers, Glaciar Lautaro showed no clear changes in ice velocity, ice-front position, or surface elevation. The glacier continuously retreated and thinned throughout the study period. The total distance of the ice-front retreat was 667 m from 2017 to 2021 (148 m a^{-1}) (Figs 4k and l). The most pronounced retreat was found in the northern half of the terminus. The surface elevation 1 km from the ice front (Area L in Fig. 4k) lowered by $12.6 \pm 1.6 \text{ m}$ between 15 August 2019 and 25 February 2021 ($8.3 \pm 1.0 \text{ m a}^{-1}$; Fig. 4m). This rate was more than three times greater than the long-term mean between 2000 and 2019 ($2.7 \pm 0.1 \text{ m a}^{-1}$; Fig. S4). Surface elevation decreased most rapidly near the glacier front (Fig. 4k). Ice speed in Area L increased over the study period, showing an accelerating trend from at least 2019. The speed in March 2021 was $262 \pm 29 \text{ m a}^{-1}$, 60% higher than the mean during 2017–2019. No clear change was observed in the frontal ablation (Fig. 4o). Therefore, we conclude that Glaciar Lautaro responded little to the lake level drop.

5. Discussion

The three glaciers exhibited contrasting changes in ice speed both during and after the drainage event. To compare the speed change of the glaciers with different magnitudes, ice speeds were normalized by the mean values from January–March 2020 (Fig. 7a). The rapid deceleration observed at Glaciar Pío XI was clearly linked to the lake-level drop. The speed change occurred within 15 days of the drainage initiation (Figs 7a and b). A strong correlation was found between velocity and lake level ($r = 0.97$, $p < 10^{-4}$). Glaciar Greve and Glaciar Lautaro accelerated and decelerated during the drainage period, respectively (Fig. 7a), but their associations with the lake level change were ambiguous (Figs 7c and d).

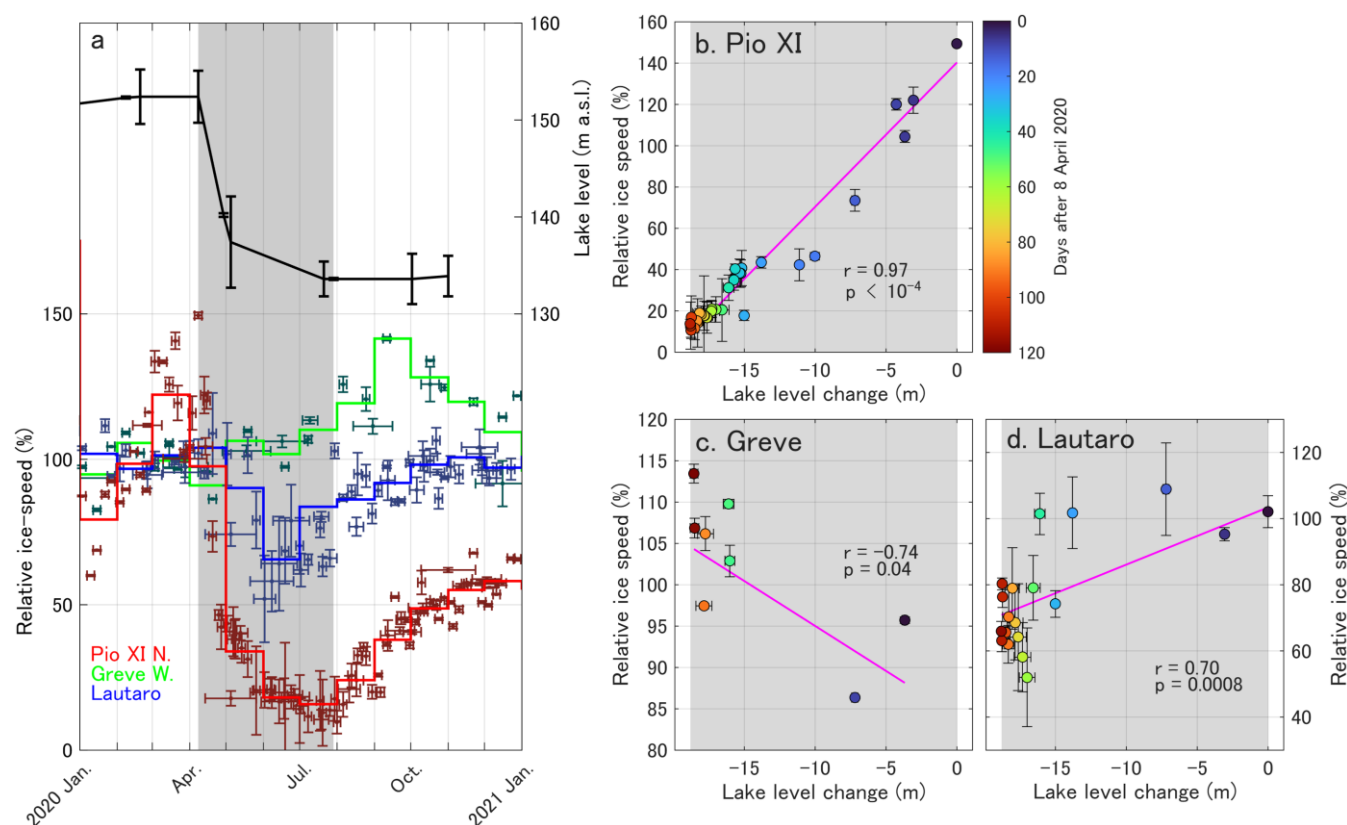


Figure 7. Lake level and ice speed of the glaciers studied. (a) Water level timeseries for Lago Greve (Hata et al., 2022; black), and ice speeds of Pío XI (red), Greve (green), and Lautaro (blue) relative to the each mean from January–March 2020. Grey hatch marks indicate the Lago Greve drainage period. (b–d) Water level vs. ice speed relative to pre-event values for (b) Pío XI, (c) Greve, and (d) Lautaro. The magenta lines are linear regressions of the data. Correlation coefficients and p-values are also shown in each panel. Grey hatches in (b–d) indicate the range of the lake level during the drainage event. The color scale shows the days after 8 April 2020.

The relationship between lake level and ice speed strongly suggests that Glaciar Pío XI responded to subglacial pressure variations driven by the lake level change. A link between water pressure and basal sliding is commonly accepted, based on

observational and theoretical studies (Iken and Truffer, 1997; Schoof, 2010). Relatively fast and variable flow of Glaciar Pío XI is dominated by basal ice motion (Mouginot and Rignot, 2015). Most likely, subglacial water pressure before the drainage was persistently high and seasonally modulated by meltwater input and the development of the drainage system (Fig. 8a). We assume that the subglacial drainage system was hydraulically connected to Lago Greve, so that subglacial water pressure dropped under the influence of the lake drainage. Subsequently, basal friction increased and ice decelerated as observed in Area N (Fig. 8b). The deceleration extended to ~5 km from the ice front (Fig. S5), indicating a widespread impact of the lake drainage on subglacial water pressure. The ice flow diverted toward the southern terminus likely because of increased basal drag beneath the northern terminus (Fig. 5d). A similar flow redirection was reported at ice streams feeding Dotson and Crosson ice shelves in West Antarctica. The ice streams changed the flow directions after the slowdown of nearby Kohler West Glacier (Selley et al., 2025).

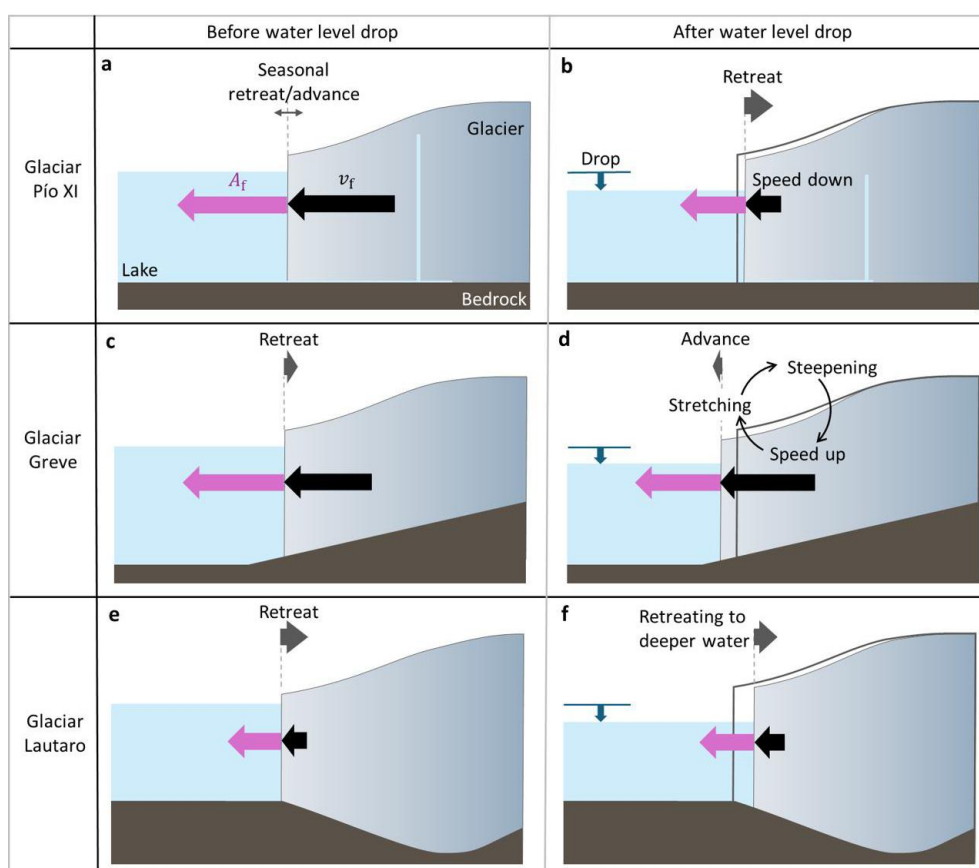


Figure 8. Schematic diagrams showing the glacier dynamics before and after lake drainage. The behavior and settings of Glaciar Pío XI (a) before and (b) after the drainage event. Similar diagrams for Glaciar Greve (c, d), and Glaciar Lautaro (e, f). Arrows indicate frontal ablation (magenta), ice speed at the calving front (black), frontal displacement (grey), and lake level drop (dark blue).



The response of Glaciar Greve was characterized by the transition from retreat to advance (Figs 8c and d). Ice speed accelerated within ~2 km of the terminus and the acceleration propagated upstream over the subsequent months. Surface lowering and steepening were also observed near the glacier front (Fig. 6). The sequence of the response can be interpreted as follows. The reduction in the hydrostatic pressure on the ice front triggered the initial acceleration (Fig. 4i). The glacier began advancing because of reduced frontal ablation as well as the enhanced forward ice motion (Figs 4g and j). The longitudinal stretching and thinning near the ice front caused steepening, which increased the driving stress and enhanced acceleration (Figs 8c and d). Once initiated, the positive feedback between ice geometry and ice flow sustained this acceleration, thinning, and steepening (Nick et al., 2013). The hypothesis linking speed-up to a drop in lake-level is supported by observations of tidal ice speed modulations (Sugiyama et al., 2025) and by theoretical studies on calving glacier dynamics (Mercenier et al., 2018; Seddik et al., 2019). Acceleration initiated near the front, and subsequently propagated inland over the course of the thinning and surface steepening. Similar observations are reported at other lake-terminating glaciers in Patagonia (Minowa et al., 2023) and marine-terminating glaciers in other regions (O'Neel et al., 2005; Nick et al., 2009; Enderlin et al., 2013; Joughin et al., 2014; Bevan et al., 2019). Such observations were obtained during glacier thinning (Nick et al., 2009), weakening of ice-mélange (Bevan et al., 2019), and retreat of the ice front from subglacial and lateral pinning points (O'Neel et al., 2005; Enderlin et al., 2013; Joughin et al., 2014). Our observations demonstrate that a sustained feedback mechanism between ice geometry and ice flow was initiated by the lake level drop.

Glaciar Lautaro decelerated during the drainage period (Figs 7a and d). However, a similar winter deceleration was observed in the previous year 2019 and later in 2020, irrespective of the lake level change (Fig. 4n). Therefore, lake draining influencing on ice speed is unlikely. The glacier had consistently retreated and thinned before the lake drainage (Figs 4l and m; Minowa et al., 2021), probably under the influence of the retrograde bed geometry as well as a warming climate (Figs 1d and S6). Glacier retreat into a retrograde slope promotes positive feedback of acceleration, thinning, and further calving retreats (Joughin et al., 2014; Minowa et al., 2023) (Fig. 8f). The terminus is bound by a narrow and deep valley (Figs 4k and S6), suggesting the ice was supported by the side drag exerted by the narrow and deep valley walls. Presumably, the glacier was insensitive to the lake drainage because changes in basal water pressure and hydrostatic pressure on the ice front were insignificant in the force balance (Enderlin et al., 2013). We conclude that the response of Glaciar Lautaro to the lake drainage was obscured by long-term trends in glacier dynamics and local topographic constraints.

The three glaciers showed markedly different responses to the same magnitude of lake-level change. The observations carry important implications for the dynamics of paleo ice sheets as well as current lake-terminating glaciers over the world. Numerical simulations of the Laurentide Ice Sheet suggested ice front advance during the development of a proglacial lake (Hu and Haseloff, 2025), whereas glacier slowdown and retreat were observed after the drainage of a proglacial lake in Yukon (Main et al., 2023). Together with these previous studies, our results demonstrate that glacier response to lake-level change is dependent on the relative importance of physical parameters, and processes controlling the force balance and



375 frontal ablation. The controlling factors include ice thickness, water depth, lake bathymetry, and subglacial conditions near
the calving front (Figs 1b–d, 8). The response of glacier dynamics to changing lake levels can be understood only with the
analyses of force balance and frontal ablation based on accurate measurements, which are scarce especially near calving
fronts (Minowa et al., 2023). This applies to perturbations in other conditions, such as ice thickness change (Nick et al.,
2009), terminus advance/retreat into a deeper/shallower water or a wider/narrower valley (Enderlin et al., 2013), sea-level
380 rise, and changes in the buttressing force due to mélange or sea ice conditions (Bevan et al., 2019). An accurate
understanding of the force balance formulation is required to predict the dynamics of lake-terminating glaciers under
changing conditions.

6. Conclusion

385 This study investigated the short-term dynamic responses of lake-terminating glaciers to the sudden lake-level drop caused
by the 2020 drainage event at Lago Greve in the Southern Patagonia Icefield. We analyzed changes in the ice-front position,
surface elevation, flow speed, and frontal ablation for three glaciers terminating in the lake. Glaciar Pío XI exhibited
complex behavior, characterized by surface lowering and frontal retreat, which were driven by a rapidly reduced ice flux to
the terminus due to a drop in subglacial water pressure. Glaciar Greve accelerated by up to $38 \pm 5\%$ and thinned by $14.9 \pm$
390 1.6 m during and shortly after the drainage. The glacier subsequently switched from a retreating to an advancing trend,
gaining a distance of 112 m within 20 months. Presumably, these changes in thickness and front position were driven by the
acceleration due to reduced hydrostatic lakewater pressure acting on the ice front. In contrast to Pío XI and Greve, Glaciar
Lautaro displayed no distinct dynamic response to the drainage event, which we ascribe to drag exerted by the relatively
narrow valley topography. The responses of the glaciers to the lake drainage differed significantly depending on individual
395 glacier settings, e.g., ice flow regime, ice thickness, and subglacial geometry. In general, a greater response is expected when
the force balance near the ice front is more critically influenced by subglacial water pressure and hydrostatic lakewater
pressure, rather than by the drag from bed geometry. Our results demonstrate that lake-level change can drive substantial
changes in lake-terminating glaciers over short timescales ranging from days to months. As proglacial lakes continue to
increase in number and expand in area worldwide, the evolution of lake-terminating glaciers is increasingly important for
400 polar and mountain environments and global sea-level rise. Therefore, an accurate understanding of ice–water boundary
processes and bed geometry is required for projecting the dynamics of lake-terminating glaciers under the influence of lake
conditions.

Data availability

405 The data presented in this study is available at <https://doi.org/10.5281/zenodo.18676673>. Landsat images and SRTM DEM
were downloaded from <http://earthexplorer.usgs.gov/>. Sentinel images were downloaded from



<https://scihub.copernicus.eu/dhus/>. ASTER-VA DEMs were downloaded from <https://gbank.gsj.jp/madas/>. PlanetScope Images were provided by the Education and Research Program, downloaded from <https://www.planet.com/explorer/>. ICESat-2 data were downloaded from <https://openaltimetry.earthdatacloud.nasa.gov/data/icesat2/>. SPOT-6/7 and
410 WorldView-1 images were purchased from the Remote Sensing Technology Center of Japan and Japan Space Imaging Corporation. The RETREAT dataset was downloaded from <http://retreat.geographie.uni-erlangen.de>; however, the data portal is currently unavailable. The RETREAT-derived data used in this study are available in the Zenodo repository at <https://doi.org/10.5281/zenodo.18676673>.

415 **Code availability**

We generated the study site map (Fig. 1) using open-source GIS software (QGIS 3.22). Other figures were generated using MATLAB 2025b (<https://mathworks.com/products/matlab.html>). MATLAB scripts were written using standard MATLAB functions and functions that are included in a freely available toolbox M_Map version 1.4 m.

Author contributions

420 SH analyzed the data and produced the figures. SH and SS discussed the results. SH wrote the manuscript with contributions from SS.

Competing interests

All authors declare no competing interests.

425

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