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Modelling the effects of proglacial lake filling and drainage on lake-terminating glacier dynamics

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Abstract. The rapid retreat of glaciers worldwide is leading to the formation and expansion of proglacial and ice-marginal lakes. Proglacial lakes not only influence glacier dynamics and contribute to accelerated mass loss, but also pose a growing risk of Glacial Lake Outburst Floods (GLOFs), particularly as warming intensifies in polar and high-mountain regions. Despite important feedbacks between glacier behaviour and lake expansion, ice–lake interactions remain understudied compared to ice–ocean processes, introducing considerable uncertainty in projections of future mass loss. In this study, we use the Ice-sheet and Sea-level System Model (ISSM) in a semi-synthetic domain to explore a critical, yet often overlooked, aspect of ice–lake interaction: lake level fluctuations driven by filling and drainage events. We find that lake-terminating glaciers experience thinning and enhanced velocities compared to glaciers with a land terminus, consistent with widely observed responses to proglacial lake damming; these responses manifest even at low water levels but increase with lake depth. The lake influence extends beyond the immediate basin, as ice thickness and velocity changes propagate upstream and to neighbouring outlets. Our results also reveal that glacier responses to lake level fluctuations are highly non-linear. The onset of flotation due to rising lake levels dramatically increases grounding line mass flux and, depending on relative magnitudes of lake filling and glacier thinning, may lead to rapid retreat. Steady lake drainage instead reduces mass loss. However, we find that rapid drainage events (seasons to years) can destabilise the ice front by altering the stress regime sufficiently to enhance crevasse formation and calving. Our findings imply that while sudden drainage events may exacerbate lake-triggered glacier instability, controlled, gradual lake drainage may serve as a viable geoengineering approach to mitigate glacier mass loss and related flood hazards.

1. Introduction

Glaciers across the globe are experiencing accelerated mass loss and retreat in response to a rapidly warming climate (e.g. Hugonnet et al., 2021). This retreat frequently leads to the formation of proglacial lakes through flooding of newly exposed, eroded, and over-deepened beds at the frontal margins of glaciers, transforming land-terminating glaciers into lake-terminating systems (Carrivick & Tweed, 2013; Dye et al., 2022). Once a lake forms at the glacier terminus, the glacier's behaviour becomes increasingly influenced by interactions between the lake and the ice front, which can surpass the effects of climate conditions alone on glacier dynamics (Carrivick et al., 2020; Pronk et al. 2021; Sato et al., 2022).

When a glacier terminates in water, whether in a lake, fjord or ocean, the ice front is subject to melting and mechanical erosion by water, iceberg calving, and buoyancy-related changes to the ice-marginal stress balance, typically resulting in enhanced mass loss and accelerated retreat (e.g. Meier & Post 1987; Warren & Kirkbride 2003; Benn et al., 2007; Nick et al. 2009; Carrivick & Tweed, 2013; O'Leary & Christoffersen, 2013; Slater et al., 2017; Sutherland et al., 2020; Dye et al. 2025). In this regard, marine- and lake-terminating glaciers share important similarities, where calving and subaqueous melting are critical drivers of ice margin stability and mass balance (Trüssel et al. 2013; Sugiyama et al. 2019; Minowa et al. 2021; Caldwell et al. 2025) and where positive feedbacks between flow acceleration, ice surface slope, thinning, basal effective pressure and buoyancy contribute to enhanced mass loss (Boyce et al. 2007; Muto & Furuya, 2013; Tsutaki et al. 2019; Pronk et al. 2021; Sato et al. 2022; Holt et al. 2024). While lake-terminating glaciers are thought to be less sensitive than their marine-terminating counterparts due to slower frontal ablation (Benn et al. 2007; Truffer & Motyka 2016; Sugiyama et al. 2019; Mallalieu et al. 2021), multiple studies demonstrate that lake-terminating glaciers are consistently more dynamic than those terminating on land, exhibiting enhanced velocity, thinning rates and frontal retreat (Tsutaki et al., 2013, 2019; King et al. 2019; Mallalieu et al. 2021; Sato et al., 2022; Holt et al. 2024). Interactions between proglacial lake formation, expansion, drainage and glacier dynamics are widely observed in High Mountain Asia, the Alps, Patagonia, Alaska, and Greenland (Tweed & Russell, 1999; Tsutaki et al., 2013; Muto & Furuya, 2013; Sato et al., 2022; Dømgaard et al., 2023; Caldwell et al., 2025), and also in geological evidence from palaeo-ice sheets (Teller et al., 2002; Perkins & Brennand, 2015; Utting & Atkinson, 2019; Regnéll et al., 2023; Ploeg & Stroeven, 2025). However, few studies have attempted to isolate and quantify specific mechanisms of glacier–lake coupling using numerical models; research has predominantly concentrated on ice–ocean interactions, particularly in polar regions, leaving glacier–lake interactions relatively underexplored. Processes specific to lake-terminating settings, and the magnitude of these glacier responses, remain poorly constrained.

A key distinction between ice–ocean and ice–lake systems lies in the highly variable nature of lake level. Unlike sea level variations, which are relatively small, gradual and predictable, proglacial lake levels can fluctuate on the order of tens of metres over short timescales. Rapid drainage events, triggered by moraine breaches, ice retreat or flotation-induced failure of ice dams, can release massive volumes of water in short periods (days to months). These events are becoming more frequent today (Carrivick et al., 2017; Dømgaard et al., 2023, 2024), and also have been observed in the palaeo-record (Hjelstuen et al., 2018; Jakobsson et al., 2007; Teller et al., 2002; Regnéll et al. 2019, 2023; Høgaas et al. 2023, 2025). Rapid lake level changes have the potential to

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significantly modify stress regimes at glacier fronts, influencing crevasse formation, grounding line stability, and overall glacier dynamics (Carrivick et al., 2020; King et al., 2018). Furthermore, such drainage events are a recognised and growing hazard and may have important natural feedbacks (Lützow et al., 2023; Veh et al., 2025). In Arctic environments, jökulhlaups inject large volumes of freshwater into fjords and oceans, altering marine ecosystems and circulation patterns (Tweed & Russell, 1999; Kjeldsen et al., 2014). In high mountain regions, the downstream impacts of glacial outburst floods are amplified by steep topography, posing serious threats to lives, infrastructure, and livelihoods (Nie et al., 2017; Rinzin et al., 2023; Sattar et al., 2025).

The number and volume of proglacial lakes are steadily increasing in regions such as High Mountain Asia and around the Greenland Ice Sheet (Shugar et al., 2020), and recent observations from Greenland document the formation, filling, and rapid drainage of ice-dammed lakes at the ice sheet margin (How et al., 2021; Dømgaard et al., 2024). As glaciers continue to retreat, the likelihood of lake formation, expansion, and drainage events will grow, drawing increasing scientific and policy interest in understanding how lakes influence glacier behaviour, and how their interactions mutually influence both glacier and lake stability. Developing a mechanistic understanding of how lake level changes influence ice dynamics would improve the accuracy of future projections of glacier mass loss and contributions to sea level rise, and also inform mitigation strategies for glacier lake-related hazards.

To address this knowledge gap, we investigate the influence of dynamic lake level changes on glacier behaviour using numerical ice flow modelling. We conduct a series of controlled experiments on a semi-synthetic model domain, designed to isolate the role of lake level change by holding other parameters constant (e.g., surface mass balance, bed geometry, and calving parameterisations). Specifically, we compare the flow dynamics of land-terminating versus lake-terminating glaciers under fixed lake level conditions, examine glacier response to gradual rising and falling lake levels, and explore the impact of rapid lake drainage on stress balance and potential crevasse formation near the grounding line.

2. Methods and model set up

We use the Ice-sheet and Sea-level System Model with the Shallow Shelf Approximation (SSA) (ISSM, Larour et al., 2012) to investigate glacier–lake interactions in the Narsarsuaq glacier catchment, southwest Greenland, under a semi-synthetic setting. ISSM has been extensively applied to both Antarctic and Greenland ice sheets to investigate ice–ocean interactions, grounding line stability, and sea level contributions (Morlighem et al., 2019; Seroussi et al., 2017; Schlegel et al., 2018). Its modular design allows the integration of boundary forcings such as subglacial hydrology, lake and ocean pressure perturbations, and bed topography, making it particularly suitable for exploring ice–ocean interactions in marine-terminating glacier systems. For a lake-terminating ice sheet catchment in southwest Greenland, we explore glacier responses to lake level change – a process unique to the ice–lake setting. Narsarsuaq catchment has land-, marine- and lake-terminating outlet glaciers (Fig. 1), and we leverage its known ice geometry, flow velocity and surface mass balance (Fig. 2) to explore the impact of prescribed lake level changes. Our goal is not to project the future behaviour of this catchment, but to investigate the dynamic response of the glaciers to lake filling and drainage.

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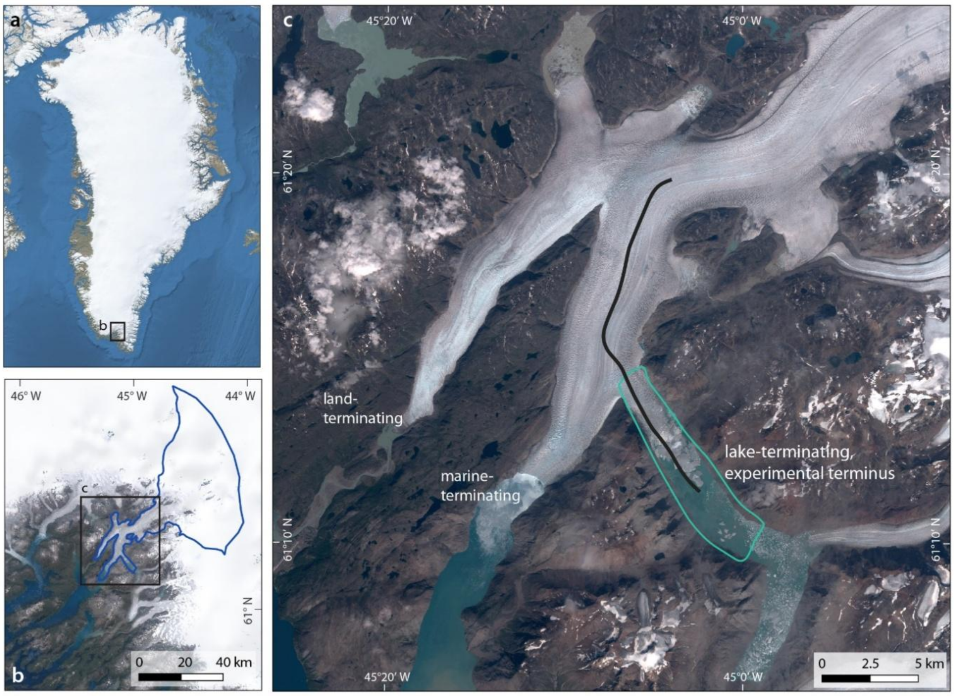

Fig. 1: Model domain covering the Narsarsuaq glacier in south Greenland, which features land-terminating, tidewater, and lake-terminating outlets. Catchment outline in blue (b), modified from Mouginot et al. (2019). Lake mask boundary is shown in (c) in green, with central profile line of the lake-terminating glacier in black, as plotted in Figs. 3 and 6. Although the model domain is an existing glacial system, our aim is not to reproduce the historical evolution of this glacier.

2.1 Ice geometry and basal conditions

Ice thickness and bed topography are obtained from the BedMachine v3 dataset (Morlighem et al., 2017; Fig. 2a, 2b). We impose a flat lake bathymetry in order to exclude the influence of topography on grounding line dynamics, and isolate the effects of lake level change. We use surface velocity mosaic of the MEaSUREs dataset between 1995 and 2015 (Joughin et al., 2018) to invert for spatially varying basal friction using the Budd sliding law, a commonly used empirical law that relates basal shear stress to basal sliding velocity and effective pressure (Budd et al., 1979). The Budd sliding law expresses basal shear stress as:

$$\tau_b = C\, N^p u_b^q \tag{1}$$

where τ_b is the basal shear stress, u_b is the basal sliding velocity, N is the effective pressure (ice overburden pressure minus subglacial water pressure), and C is the spatially varying basal friction coefficient (inverted). p and q are empirical exponents, where p=1 and q= 1.

In ISSM, this law allows for pressure-sensitive sliding, where increased subglacial water pressure (as induced by a proglacial lake) reduces effective pressure and increases sliding (Larour et al., 2012). The physical process governing the velocity of a lake-terminating glacier is the change in basal water pressure due to change in proglacial lake level. The effective pressure is defined as

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$$N = P_i - P_w \tag{2}$$

where P_w is the subglacial water pressure and P_i is the ice overburden pressure. In the absence of a subglacial hydrology model-derived water pressure, it is represented in the following way:

$$P_w = \max\left(0, \rho_w g\,(sl - b)\right) \tag{3}$$

where *sl* is the sea level (here also used for lake level), and *b* is the bed elevation. Thus, when sea level is varied, the basal water pressure changes, leading to change in effective pressure and subsequently the sliding velocity. Here we leverage the sea level field of ISSM to investigate the effect of lake level change on glacier dynamics.

We follow the standard ISSM inversion procedure (e.g. Morlighem et al., 2013), minimising a cost function that balances misfits between observed and modelled surface velocities with a regularisation term to avoid overfitting and facilitate convergence. The inversion produces a spatial map of the basal friction coefficient C, which is then kept constant for all transient simulations. In our case, the inversion yields higher-than-observed velocities near the lake front (Fig. 2e), which we attribute to the flattened or poorly unknown lake bathymetry and potential inaccuracies in local ice thickness or stiffness. Despite these limitations, the inverted velocity field is physically plausible and further refinement is not pursued, as our primary interest lies in differential responses under varying lake levels rather than the absolute state.

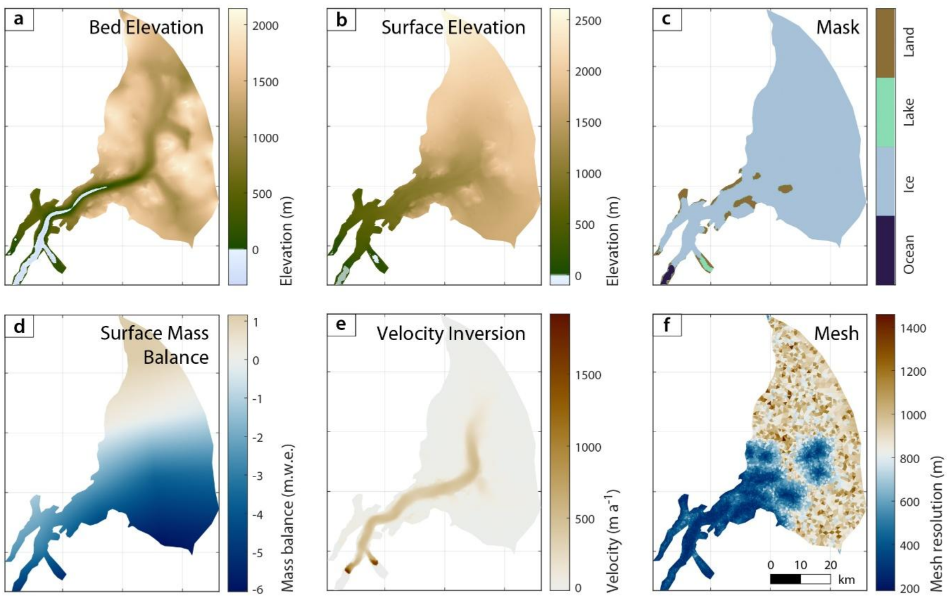

Fig. 2: Initial model conditions including bed elevation (a), surface topography (b), mask (c), prescribed surface mass balance (d), velocity after inversion (e), and the model mesh resolution (f).

2.2 Mass balance and boundary conditions

Surface mass balance is prescribed as the 1960-2000 mean, derived from regional climate model MAR (version 3.11.3; Amory et al., 2021), which has a value of -2.65 m.w.e. per year (Fig. 2d). Surface balance is held

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constant across simulations to isolate the impact of lake level variations on glacier dynamics. Our experiments use a fixed glacier front, across which ice is lost without explicit consideration of calving and subaqueous melting, while allowing the glacier to develop a floating extension. With this set up, we isolate the hydrostatic effects of lake presence in our experiment results.

2.3 Experiment design

To investigate the dynamic response of lake-terminating glaciers to varying lake levels (lake filling and draining), we leverage the sea-level adjustment feature in ISSM (Larour et al., 2012). We outlined a mask for the lake (Fig. 1), within which we can change the 'sea level' (called lake level henceforth) independently, keeping actual sea level unchanged elsewhere. In our model domain, the topography of the lake-terminating front is below sea level; the lake floor is at -200 m with respect to sea level (Fig. 2). Our experiments describe lake water depths relative to the lake floor, which therefore has 0 m water depth. We design the mesh such that the mesh resolution scales with velocity and becomes finer towards the lake area, where the smallest mesh element is 200 m (Fig. 2d).

We design three sets of experiments in which we vary the lake level at the present-day lake-terminating outlet, under identical climate forcing and with no explicit frontal ablation. Each experiment runs for 100 years with one week time steps. Before performing the transient model runs (Experiments 2 and 3), we conduct 20-year spin-up simulations with a 100 m lake level to allow the model to stabilise and minimise the influence of artificial effects imposed by the initial conditions.

Experiment 1: Lake vs Land-terminating glacier

To quantify glacier dynamics attributable to the presence of a proglacial lake, we simulate the evolution of the glacier catchment over a 100-year period under two different terminus conditions:

i) land-terminating;
ii) lake-terminating with a fixed lake level of 100 metres.

Experiment 2: Steadily rising and falling lake levels

To investigate the impact of steady lake filling and drainage, we simulate glacier evolution over a 100-year period as:

i) a rising lake scenario: lake level increases linearly from 100 to 200 m over the first 50 years of the simulation, and then kept constant; and
ii) a falling lake scenario: lake level decreases linearly from 100 to 0 m over the first 50 years.

We additionally perform follow-up experiments with intermediate lake levels.

Experiment 3: Rapid lake drainage and stress response

To simulate sudden glacial lake outburst flood (GLOF) scenarios and assess their impact on ice dynamics, we consider a set of experiments in which the lake level falls by 100 m in 1, 2, 3, and 4 years. We consider these drainage scenarios from two initial lake levels:

i) 200 m, where the ice front is initially floating; and
ii) 100 m, where the ice front is initially grounded.

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3. Results

3.1 Experiment 1: Lake-terminating versus land-terminating glacier dynamics

Our simulations reveal fundamental differences in terminus morphology, ice thickness distribution and flow velocity between lake- and land-terminating glaciers under identical topographic and climatic conditions (Fig. 3, 4). The land-terminating glacier displays a tapering profile, where ice thickness decreases smoothly to zero at the terminus. In contrast, the lake-terminating glacier develops a near-vertical terminus face, maintained by the balance between glaciostatic pressure (ice column weight) and hydrostatic pressure (water column weight). While the ice surface profile lowers over 100 years in both the land- and lake-terminating cases (Fig. 3), driven by the negative surface mass balance, ice thinning is greatest when the glacier is lake-terminating (Fig. 4). Importantly, ice thinning propagates upstream over time, as well as to the other outlet glaciers of this catchment, particularly the neighbouring marine-terminating outlet (Fig. 4). This pattern indicates that the lake's influence extends well beyond the immediate terminus region, causing broader adjustments in the glacier's longitudinal profile and flow dynamics. The lake-terminating outlet also exhibits a notable velocity increase compared to when the same outlet is land-terminating, though the spatial extent of the velocity anomaly is more limited than the thinning response. These thickness and velocity trends are sustained over time (Fig. 5). After ca. 20 years, the difference between lake and land continues to increase approximately linearly: for as long as a lake exists, the glacier continues to thin and accelerate. After 100 years, the catchment with a modelled lake terminus is ~1.1% thinner and 2.5% faster than the land-terminating scenario, primarily driven by the dynamics in the lake area. In the lake region itself, a lake-terminating glacier is ~7% thinner and ~20% faster than its land-terminating counterpart. These may be modest amounts, but represent systematic departures from the reference state over decades-centuries. Notably, these dynamics emerge independently of any changes in climate forcing and in the absence of frontal ablation; they arise purely from the mechanical, hydrostatic (i.e. buoyancy) effects of lake presence.

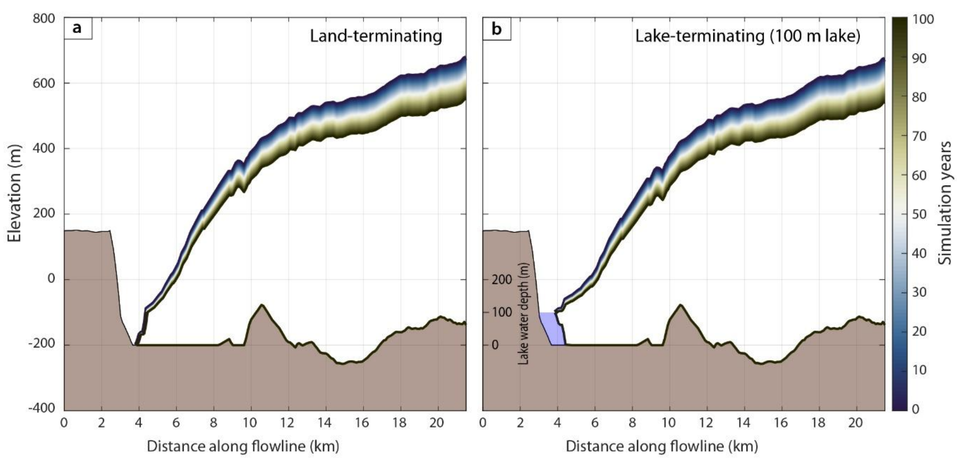

Fig. 3: Evolution of ice thickness profile along the central line of the glacier over 100 years, when the glacier is (a) land-terminating (no lake) and (b) lake-terminating (100 m water depth).

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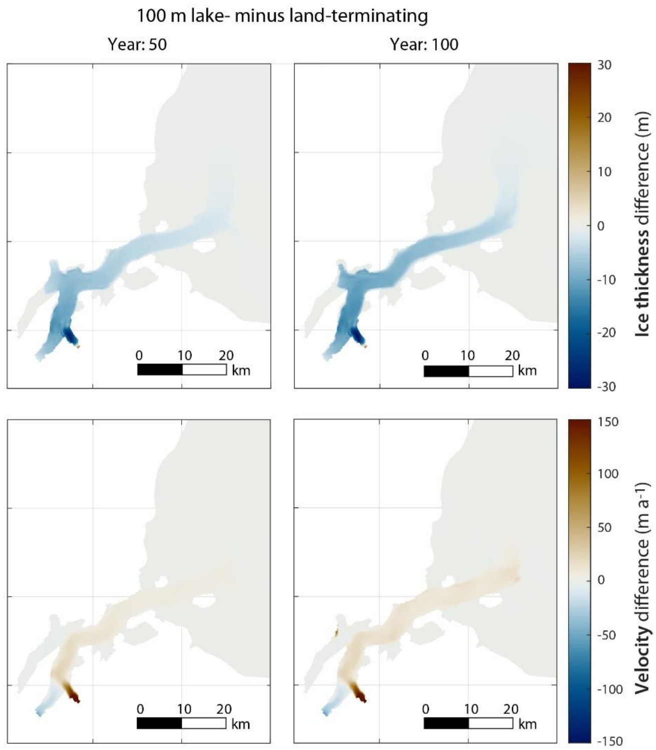

215 **Fig. 4: Ice thickness and velocity difference between a lake-terminating glacier (with 100 m deep lake) and a land-terminating glacier, at model years 50 and 100.**

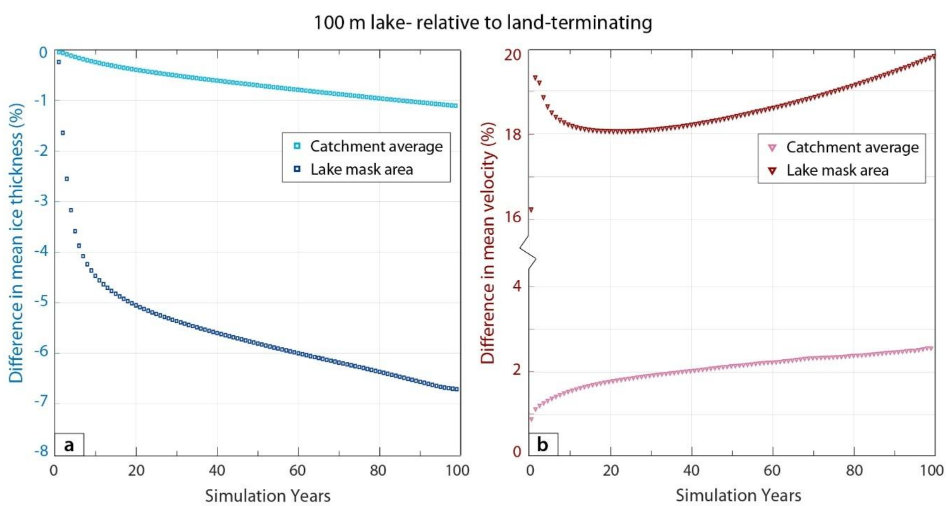

Fig. 5: Mean percentage difference in (a) ice thickness and (b) velocity between lake-terminating glacier (100 m deep)
220 **and land-terminating glacier, over 100 years.**

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3.2 Experiment 2: Glacier response to lake level fluctuations

To examine the effects of lake level variations on glacier dynamics, we conducted controlled experiments comparing rising (Fig. 6, 7) and falling (Fig. 6, 8) lake level scenarios against the fixed lake level baseline of Experiment 1. We find that when the level of an initially 100 m deep lake gradually rises to 200 m over 50 years, the terminus begins to float: the glacier front changes from an ice cliff to floating extension (Fig. 6). This arises from the combined effects of water depth increase and ice thinning, such that ice at the terminus becomes buoyant. Compared to the fixed lake scenario, ice thins during lake level rise and continues to thin, at a slower pace, as the higher lake level (200 m) is sustained (Fig. 7, 9). Ice velocity is, similarly, faster than in the fixed lake scenario, accelerating during the period of active lake level rise and stabilising thereafter at a higher flow speed (Fig. 9). Within the lake area, during the 50-year period of lake level rise, mean velocity increases by almost 12% compared to the fixed lake scenario, while the ice thickness decreases by ~5%.

In our falling lake level experiment, the initial 100 m deep lake drains completely over 50 years, such that the glacier gradually transitions toward land-terminating. The falling lake level instigates a contrasting response to lake level rise. The terminus evolves from a steep calving face toward the characteristic tapering profile of a land-terminating glacier (Fig. 6). The glacier decelerates compared to the fixed lake level scenario (~17% slower within the lake area), and ice thinning is reduced (~7% difference within the lake area) (Fig. 8). These thinning and velocity responses are immediate, even while the glacier still has a lake terminus; the lower water level is insufficient to drive the glacier responses seen in Experiment 1. This diminished glacier response to a lake reflects the increasing importance of basal and lateral drag relative to driving stress as the effective pressure at the terminus increases.

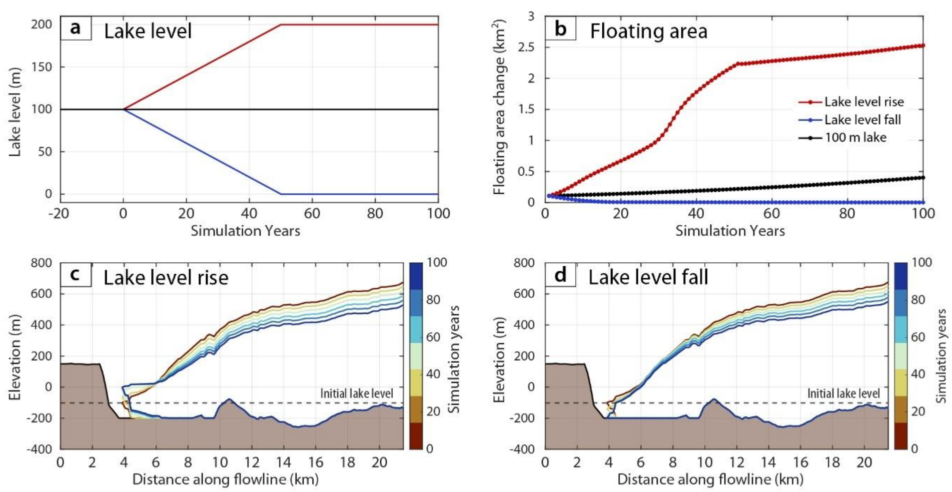

Fig. 6: (a) Prescribed lake level rise (from 100 to 200 m) and fall (from 100 to 0 m) scenarios, from a stable 100 m deep lake, with 20-year spin up. (b) Change in floating area (equivalent to loss of grounded area) for all three simulations over 100 years. (c-d) Central line profile of ice thickness and frontal geometry after 100 years' simulation for (c) rising lake level and (d) falling lake level experiments.

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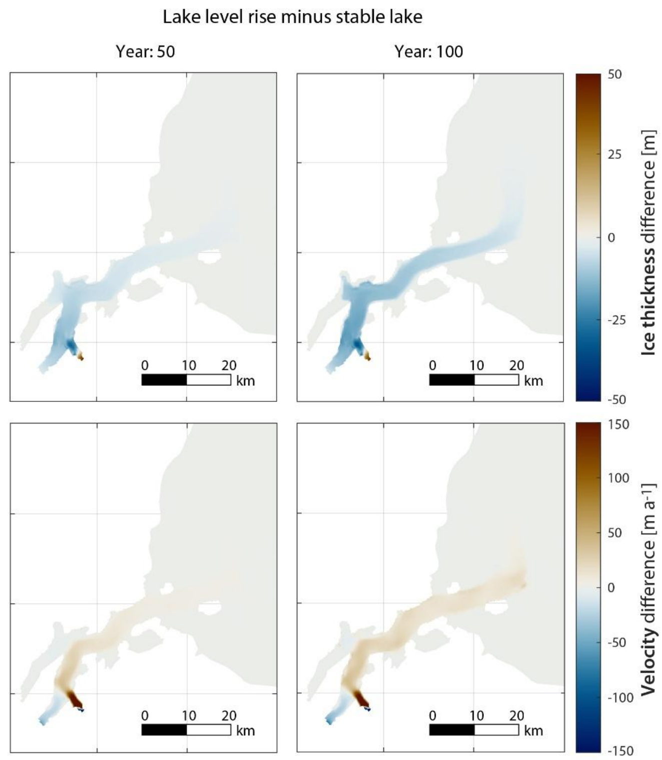

Fig. 7: Differences in ice thickness and velocity between lake level rise and 100 m fixed lake experiments, for years 50 and 100.

In both lake rise and fall scenarios, ice thickness change propagates upstream during the period of lake change, and the response is sustained, at a slower pace of change, even after the lake stabilises. This upstream propagation reflects the kinematic wave response of the glacier profile to changes in terminus boundary conditions. As seen in Experiment 1, thickness changes spread not only upstream but also to the neighbouring outlets (Fig. 7, 8), which in this case is marine-terminating: lake changes trigger feedbacks not only at the ice–lake interface but at the ice–ocean interface too. Velocity changes exhibit similar *spatial* patterns to the ice thickness response, albeit more restricted to the marginal zone and the lake-terminating outlet. The velocity response has important *temporal* differences to the thinning response: velocity adjustments occur rapidly during the active lake level change phase (years 0-50) but stabilise abruptly, at the new flow speed, as soon as the lake level stabilises (Fig. 9).

In our experiment set up, the magnitude of deviation from the fixed lake level scenario is greater over the whole catchment, and the upstream propagation more pronounced, when lake level rises; by contrast, absolute differences in thickness and velocity are smaller in the lake level fall scenario (Fig. 9). We interpret that this asymmetric response to lake rise and fall reflects the importance of flotation and associated non-linear feedbacks. In our experiments, lake level rise drives the ice margin to flotation (Fig. 6) and causes grounding

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line retreat; we therefore further explore the impact of flotation in a set of intermediate lake-rise and lake-fall experiments.

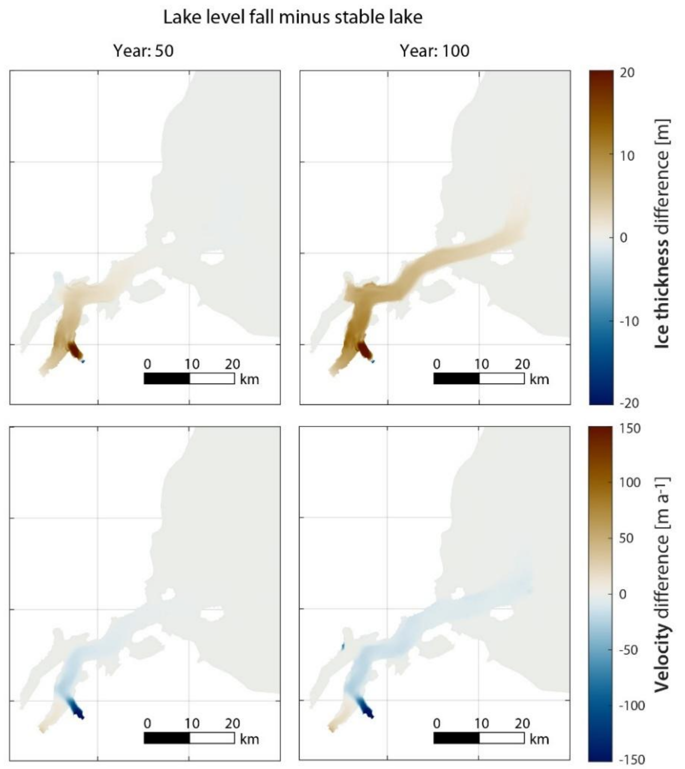

Fig. 8: Differences in ice thickness and velocity between lake level fall and 100 m fixed lake experiments, for years 50 and 100.

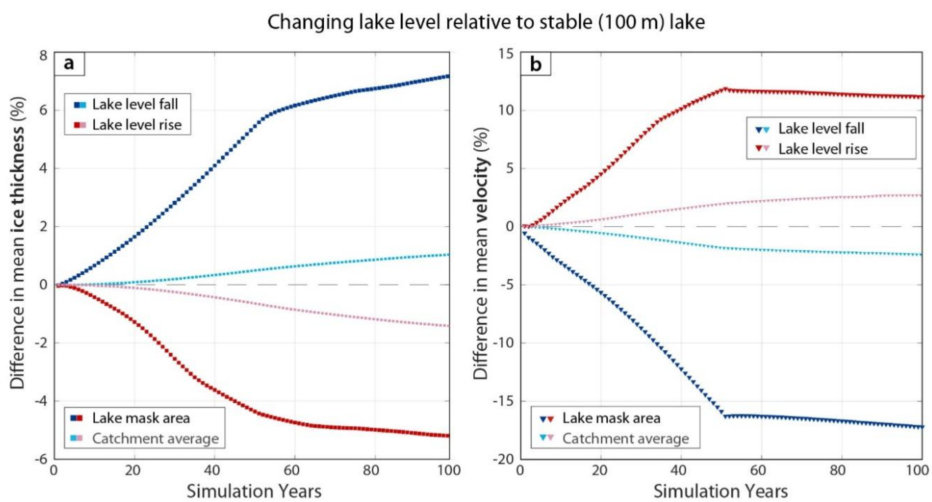

Fig. 9: Mean difference in (a) ice thickness and (b) velocity, between rising/falling lake level scenarios and a fixed 100 m lake.

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3.2.1 Grounding line mass flux response to flotation/grounding

The onset of flotation represents a critical threshold that transforms the mechanical boundary conditions at the glacier front. This means that small changes in lake depth can trigger large changes in glacier behaviour. In an additional set of experiments, we raise and drain the lake level over years 1-50 between 0 m water depth (land-terminating) and lake levels expected to be both below and above the threshold for flotation. We find a pronounced grounding line (GL) mass flux response to flotation or grounding driven by lake level change, across a range of lake level scenarios (Fig. 10, 11). The GL mass flux response exhibits a characteristic three-phase pattern: an initial steady decrease, followed by a period of abrupt change, followed again by a steady decline in mass flux.

During lake filling, GL mass flux initially decreases (Fig. 10). This is due to ice thinning, driven by both negative surface mass balance (e.g. Experiment 1) and the thinning response to increasing lake levels (e.g. Experiment 2); less ice is discharged through the grounding line. The near-identical magnitude and negative response of each of our scenarios in this initial phase indicates that the thinning effect is far more important in determining GL flux than enhanced ice velocity. With time, ice thinning and the increasing water level together drive the ice margin towards buoyancy. As ice begins to float, GL mass flux increases rapidly, more than doubling over 25 years in our two highest lake-rise experiments. The magnitude of GL mass flux increase is proportional to the rate and magnitude of lake level rise beyond the flotation threshold, which we find has three effects. Greater rates of lake filling (i) induce *faster increases* of GL mass flux that (ii) *occur earlier* during lake rise, and (iii) attain a *higher peak flux* at the higher eventual lake level.

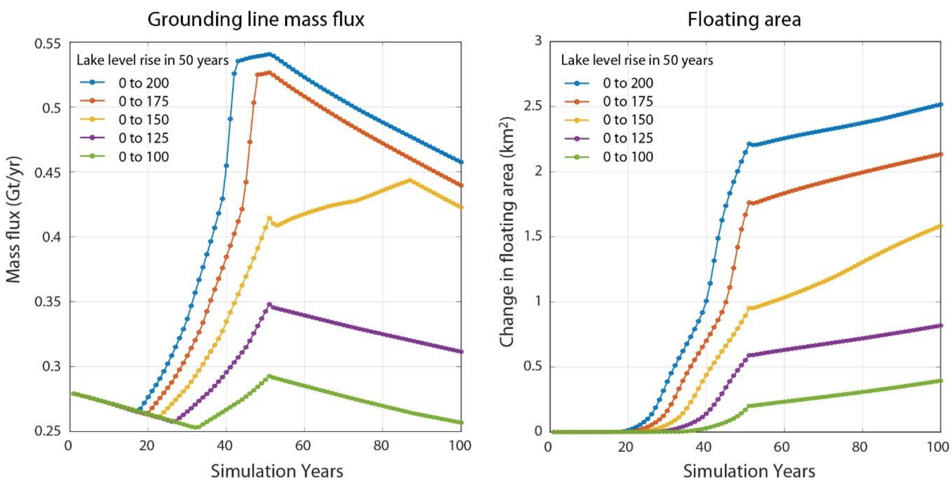

Fig. 10: Grounding line mass flux and floating area change for five rising lake level scenarios.

Once the rising lake level stabilises, GL mass flux generally decreases, at a rate similar to or even greater than the initial phase. The thinning effect of the higher lake level and the continued negative mass balance result in diminishing GL flux with time; a finite period of lake filling does not trigger sustained catchment discharge. This is despite enhanced velocity and a continued, modest increase in floating area (i.e. grounding line retreat).

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Thinning continues to increase the area of floating ice, but is insufficient to further increase the GL flux. This is true for all scenarios except 0-150 m, which demonstrates a unique behaviour: GL mass flux continues to increase even after the lake level stabilises, and the area of floating ice continues to increase at a faster rate than other scenarios. In a 'perfect storm' scenario of negative mass balance, thinning, buoyancy and velocity response, unique to the setting, there is a potential for runaway instability once critical thresholds are crossed, with the GL retreating deep into the catchment.

Lake drainage scenarios fundamentally differ, stabilising rather than destabilising the glacier. As the lake level begins to fall, GL mass flux declines almost immediately, irrespective of the lake's starting height and rate of fall. Simultaneously, there is a rapid decrease in floating area as the previously floating terminus grounds, restoring basal drag and mechanical coupling with the bed. We find that the rate of GL flux decline during grounding is slower than the rate of change during flotation induced by lake level rise. We interpret this slower pace to reflect the competing effects of SMB- and lake-induced thinning (favouring continued flotation) and lake level fall (favouring grounding). Once the ice front is grounded and the lake fully drained, all experiments show low rates of GL flux decrease, attributed to the negative surface mass balance.

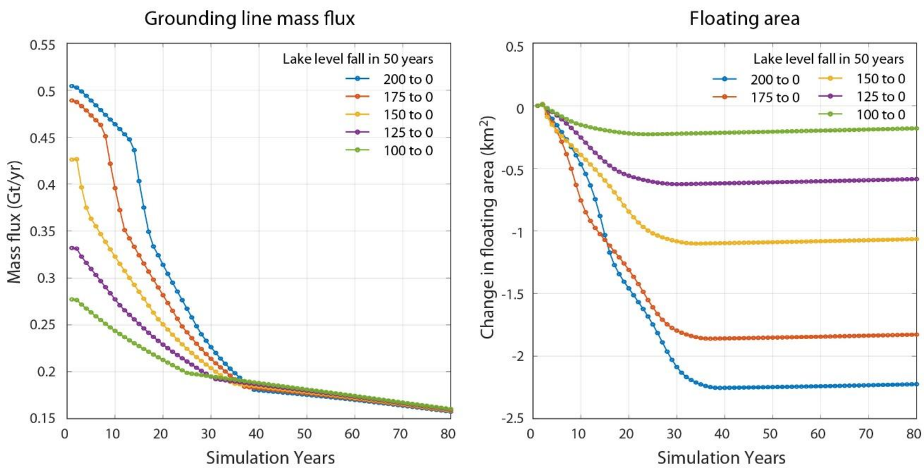

Fig. 11: Grounding line mass flux and floating area change for five falling lake level scenarios.

3.3 Experiment 3: Stress response to rapid lake drainage and implications for glacier stability

Experiment set 2 has shown that slow and steady lake drainage has a stabilising effect, producing a marked decline in GL flux. Yet, lakes are known to drain much more rapidly (Tweed & Russell 1999; Veh et al. 2019; Dømgaard et al. 2023, 2024; Regnéll et al. 2025), and rapid lake drainage events represent one of the most dynamic perturbations that lake-terminating glaciers can experience. In experiments in which we prescribe lake level fall of 100 m in 1, 2, 3, and 4 years, we find that there is a pronounced stress response in the near-marginal area (Fig. 12), in both tensile (Fig. 13 a, b) and compressive (Fig. 13 c, d) fields. Peak stress changes occur within 1-2 years of drainage, followed by exponential recovery toward equilibrium values over 5-10 years. This timescale reflects the viscoelastic relaxation of ice and the kinematic adjustment of the glacier profile to new boundary conditions.

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The magnitude of the glacier stress response scales directly with drainage rate, with faster drainage events producing proportionally larger stress perturbations (Fig. 13). The absolute magnitude of stress changes depends also on the initial flotation state. For identical drainage magnitudes, initially floating termini (with a water depth of 200 m) experience stress changes that are about 4 times greater than when the initial terminus is grounded (lake level at 100 m).

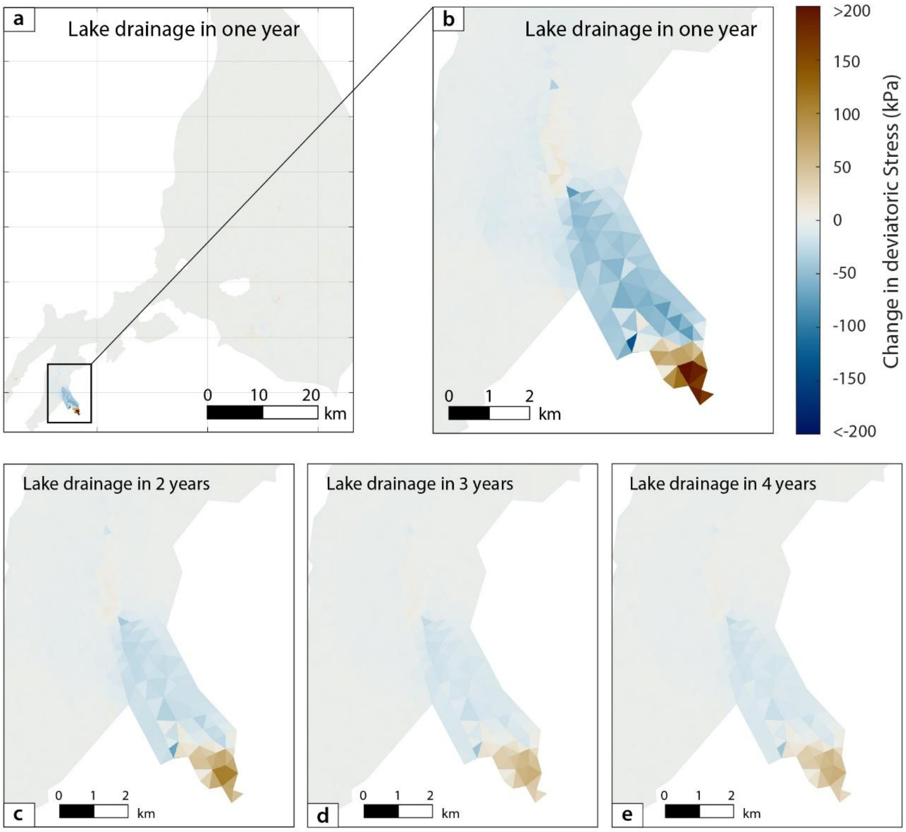

Fig. 12: Changes in deviatoric stress in the first year after initiating a 100 m lake drainage of 1, 2, 3 and 4-years duration, from an initially floating glacier terminus.

The observed stress patterns arise from several interacting physical mechanisms. During rapid drainage, the sudden withdrawal of hydrostatic support creates an immediate imbalance between driving stress (gravitational forcing) and resistive stresses (basal and lateral drag, back-pressure from water). This imbalance manifests as enhanced longitudinal stretching near the terminus and compression further upstream (Fig. 12) as the glacier adjusts to the new stress regime; we find that the spatial pattern holds irrespective of lake drainage rate. For floating termini, the loss of buoyant support effectively increases the vertical stress component, leading to enhanced basal coupling and altered stress transmission through the ice column. The resulting stress concentrations are particularly pronounced at the former waterline, where the transition from hydrostatic to atmospheric pressure boundary conditions creates sharp gradients in the stress field.

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The changes in the magnitude of tensile stress (first principal stress) and compressive stress (second principal stress) by 4-10 times and 2-8 times, respectively, indicate that rapid drainage preferentially creates conditions conducive to tensile failure and fracture propagation. In the tensile regime, the values exceed typical ice tensile strength (~300 kPa) during peak drainage phases. These conditions favour the nucleation of new fractures and the propagation of existing crevasses, potentially compromising the structural integrity of the terminus region. Using established relationships between stress and crevasse depth (Nye, 1997; van der Veen, 1998; Reynolds et al., 2025), we estimate that stress increases of ~400 kPa (observed for 100 m rapid drainage from floating conditions) could drive surface crevasses to depths of around 85 metres, potentially reaching the waterline and initiating calving processes. The equivalent crevasse depth propagation due to lake drainage when the glacier front is already grounded is much less, at 21 m, suggesting that lake drainage has substantially more impact on the glacier's structural integrity when the glacier has a floating terminus, a scenario that would favour unstable feedbacks. However, fracture propagation depends not only on stress magnitude but also on stress duration and ice temperature. The relatively short duration of peak stress conditions (1-2 years) may limit deep fracture penetration, while the temperature-dependent rheology of ice influences both fracture toughness and healing rates. Our experiments suggest that rapid lake drainage events may reduce the structural integrity of the glacier outlet and trigger discrete calving episodes, but is unlikely to drive complete structural collapse.

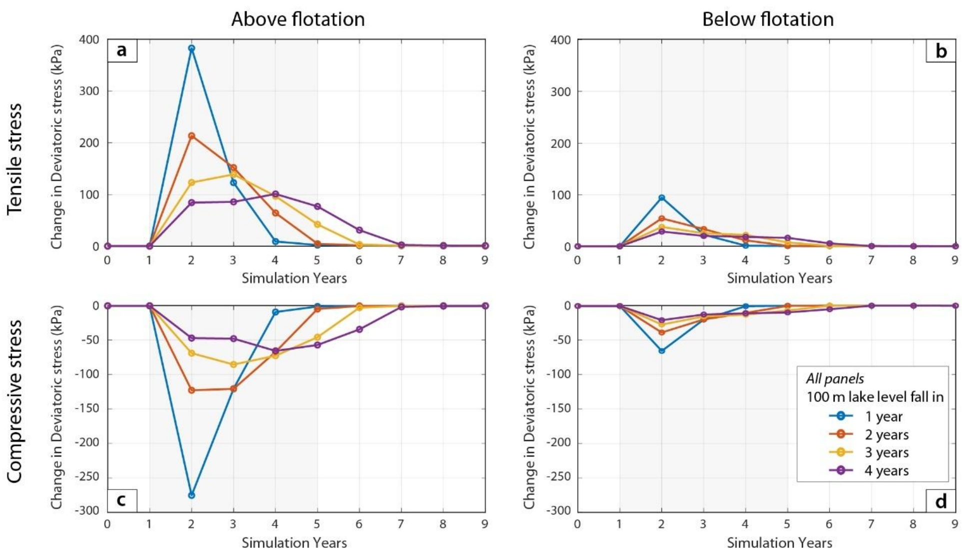

Fig. 13: Change in deviatoric stress in tensile (a, b) and compressive (c, d) stress regimes, during rapid lake level fall from a lake level that is initially above (a, c) and below (b, d) the terminus flotation threshold. The shaded area marks the maximum duration of lake drainage (4 years).

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4. Discussion

4.1 Lake level controls on glacier dynamics: mechanisms, thresholds and responses

Our study demonstrates that the presence of a proglacial lake, and fluctuations in lake level over years-to-decades, exert a fundamental control over glacier dynamics. Compared to a land-terminating glacier, a proglacial lake causes enhanced ice thinning and acceleration. These responses occur even when the water depth is shallow and the glacier terminus is grounded. However, flotation of the terminus further enhances both thinning and acceleration, and has a profound impact on the grounding line flux. In our experiments, which omit explicit frontal ablation, these responses are entirely due to hydrostatic pressure variations modulating ice flow. In particular, the onset of flotation represents a critical threshold that transforms the mechanical boundary conditions at the ice front. Under higher lake levels and under floating conditions, the glacier experiences reduced effective stress and enhanced longitudinal stretching, leading to accelerated ice flow and increased mass flux across the grounding line.

These responses are consistent with theoretical predictions, model experiments and field observations from both marine-terminating and lake-terminating systems. Expansion of proglacial lakes in the Himalayas has been associated with widespread glacier thinning (Nie et al. 2017; King et al. 2019). Studies on neighbouring lake- and land-terminating glaciers, and those that have undergone a transition from land- to lake-terminating, in the Himalayas and elsewhere, confirm that under the same climate conditions lake-terminating glaciers experience faster thinning rates (Tsutaki et al. 2013, 2019; Baurley et al. 2020; Sato et al. 2022; Holt et al. 2024). Acceleration is similarly observed where glaciers are lake-terminating, although this trend is more nuanced and not universal (Muto & Furuya 2013; Thakuri et al. 2016; King et al. 2018; Pronk et al. 2021; Minowa et al. 2023; Wu et al. 2025). Observations suggest that buoyancy forces at the ice–lake interface are key, with pulses of rapid acceleration – and in some cases marked grounding line retreat – reported where thinning toward floating conditions has detached the glacier from bed pinning points (Holt et al., 2024; Minowa et al., 2023; Somos-Valenzuela et al., 2014; Tsutaki et al., 2013). Bed over-deepenings and retrograde slopes, coupled with ice sheet and glacier thinning, are widely linked to unstable retreat and increased discharge in both lake and marine settings via the so-called Marine Ice Sheet Instability (Weertman 1974; Meier & Post 1987; Schoof 2007; Benn et al. 2007; Joughin et al. 2014). Here we show that proglacial lake filling independently drives the same buoyancy-governed dynamics.

Studies of individual – or even regional – cases of glacier–lake behaviour are typically limited in timescale and consider either uniform forcing (a stable lake) or a single direction of change. Here, we have explored a range of lake filling and drainage scenarios and we find that, besides the general trends outlined above, glacier responses to lake changes are non-linear, asymmetric and exhibit hysteresis. These complex responses are especially manifest in glacier sensitivity to flotation, in feedbacks between ice thinning and lake level rise and fall, and in glacier response to the rate of lake drainage.

In our experiments, flotation of the ice front during lake level rise induces greater magnitude thinning and acceleration catchment-wide than the opposing responses to transition to a land-terminating setting, but locally transition to land has greater impact (Fig. 9). We find also that a steadily rising lake level produces a sharp increase in grounding line mass flux due to flotation, while grounding during steady lake drainage produces a

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much less abrupt response, albeit of similar magnitude (Fig. 10, 11). These contrasting behaviours arise from sensitive feedbacks between surface mass balance, water depth and velocity. Where negative surface mass balance is driving glacier thinning, buoyancy can be countered by steady lake drainage, such that no substantial change in grounding condition arises and the glacier margin is stable. Conversely, lake filling and negative surface mass balance both favour thinning and buoyancy, destabilising the grounding line. The vulnerability of a glacier to such destabilisation strongly depends on the local setting and initial conditions. Small changes in lake level can trigger disproportionately large changes in ice discharge, but only when the ice front is close to the threshold for buoyancy. In that case, lake level rise may cause flotation – and consequent profound increases in grounding line flux – more rapidly than surface thinning; otherwise, the same magnitude lake filling may be comparatively ineffectual. Deep lake waters arise in high relief topographic settings where basins are enclosed. Here, increases in GL flux into a contained basin may cause yet further lake rise, sustaining mass loss in a positive feedback. In such topographic settings, especially where the lake bed has a retrograde slope, water depth increase and lake level rise will typically outpace surface thinning and be the dominant control on buoyancy. Coupling between lake level and grounding line behaviour can therefore be more pronounced than the marine ice sheet instability, where grounding line discharge has a comparatively negligible effect on water (sea) level.

In contrast to the stabilising effect of slow, sustained lake drainage, we additionally find that high magnitude, rapid lake drainage events (e.g. within one year) produce a pronounced stress response that can initiate surface crevassing and discrete calving events, and this stress response increases markedly with the rate of drainage (up to ~400 kPa, Fig. 13). While sufficient to drive fracture propagation, the stress magnitudes we observe remain below thresholds for sustained structural failure and are unlikely to cause catastrophic collapse in typical proglacial lake settings that experience discrete drainage events. This finding is consistent with observations from natural drainage events where calving episodes are typically followed by restabilisation, rather than runaway retreat (Carrivick et al., 2017). The limited spatial extent of proglacial lakes and buttressing effects of calved icebergs provide natural constraints on instability propagation. However, the stress amplification we observe for floating termini suggests that glaciers near flotation thresholds may be particularly vulnerable to drainage-induced instabilities. As climate warming drives both glacier retreat and lake expansion, more systems may approach these critical conditions, potentially increasing the frequency and magnitude of drainage-triggered calving events.

4.2 Transient responses and propagation of effects

When lake drainage is rapid, but limited in duration, we observe an immediate and pronounced stress response that recovers to an equilibrium within years. Even during steady, sustained lake level change, most (if not all) of the velocity and grounding line flux response occurs only during the period of active lake filling or drainage. On the other hand, sustained filling and drainage of proglacial lakes appears to produce a more lasting change in ice thickness; velocity becomes stable at a new rate. Qualitatively, the temporal nature of these responses echoes observations indicating that acceleration and buoyant responses of lake-terminating glaciers may be pulsed or irregular (Muto & Furuya 2013; Pronk et al. 2021; Minowa et al. 2023; Holt et al. 2024), reflecting the non-linear nature of flotation dynamics. Thinning trends of such systems appears almost universal, however, widely observed whether the terminus lake is stable or evolving, newly formed or long-established (Tsutaki et al. 2013,

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2019; Thakuri et al. 2016; Muto & Furuya 2013; King et al. 2019; Sato et al. 2022). In part, this sustained thinning response to lake level change may reflect the time required for the glacier profile to adjust to new boundary conditions through kinematic wave propagation (Riel et al., 2021; van de Wal & Oerlemans, 1995). The glacier response persists long after the hydrological perturbation ends, with adjustment timescales that will vary according to glacier geometry, ice thickness, and perturbation magnitude. In addition, however, we show that thinning (as well as velocity and grounding line flux responses) scales with the absolute water level, such that lake level rise not only drives a dynamic response to the *active* change, but there is sustained enhanced thinning at a higher, *stable*, lake level. This ongoing thinning may trigger delayed or renewed grounding line flux changes, even after a lake filling or drainage event has stabilised, due to the evolving thresholds for ice margin buoyancy.

The glacier responses that we have observed are triggered from the terminus, propagating upstream from the ice–lake interface. We also find that thinning and flow velocity responses propagate into both other outlet glaciers that drain the same catchment, and in particular the neighbouring marine-terminating outlet. Lake filling and drainage dynamics thereby induce responses that may trigger additional feedbacks at the ice–ocean interface, where mass can be fully lost from the system and where there may be fewer stabilising influences. Our results suggest that even temporary lake level increases can commit glaciers to prolonged mass loss and not only from the lake-contact ice margin, emphasising the importance of incorporating transient ice dynamics and lake interactions in predictive glacier models.

4.3 Implications for lake-terminating systems

4.3.1 Ice sheet retreat/stability

Our findings have particular relevance for the Greenland Ice Sheet, where proglacial lake formation is accelerating as the ice margin retreats into over-deepened basins (How et al., 2021; Shugar et al., 2020). Recent observations document the rapid formation and expansion of ice-marginal lakes along both the western and eastern margins, with some systems transitioning from land-terminating to lake-terminating within single melt seasons (Carrivick et al., 2022; Holt et al., 2024).The non-linear response to lake level changes we identify suggests that these transitions may trigger rapid acceleration in ice discharge, contributing disproportionately to Greenland's mass balance. Our results also highlight the potential for lake-induced instabilities to propagate inland, particularly in regions with retrograde bed topography. This mechanism could contribute to the observed inland migration of acceleration and thinning patterns at several Greenland outlet glaciers (Hill et al., 2018). Of particular concern may be our finding that dynamic changes initiated at a lake-terminating outlet propagate also to neighbouring outlets of the same ice sheet catchment. Given Greenland's high-relief ice-marginal topography, many ice sheet catchments bifurcate into multiple outlets, land-, lake- and marine-terminating. Accelerated mass loss driven by lake-terminus feedbacks may propagate to marine-terminating outlets where beds are over-deepened and stabilising behaviour such as lake drainage is absent. Understanding and predicting these terminus transitions and instabilities is important for refining sea level projections.

Centennial-scale consequences of proglacial lake damming are evident in geological records of deglaciation, and our findings here can inform interpretations of the drivers of ice sheet retreat. Deglacial periods of high surface melting in high relief, over-deepened and/or isostatically depressed terrain, are known to have dammed

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proglacial lakes (e.g. Jansson 2003; Perkins & Brennand 2015; Høgaas & Longva 2018; Regnéll et al. 2019, 2023), creating ice-marginal zones primed for rapid thinning and enhanced mass loss at the grounding line. Lake coalescence during ice margin retreat (Regnéll et al. 2023) would have reduced lateral pinning stresses, and retreat rates reconstructed from such lake-terminating settings are comparable to those from marine outlets (100s ma^{-1}). Reconstructions of lake and ice-margin co-evolution in Fennoscandia, for example, show that where lakes were dammed, the ice sheet thinned to the extent that the ice sheet was repeatedly breached by lake water. The successive occurrence of high-magnitude, rapid (<1 yr) lake drainage events, together with lake-induced ice thinning, acceleration and enhanced mass loss, may have precipitated the structural failure and collapse of the late-stage Fennoscandian ice sheet.

4.3.2 Glacier lake hazard mitigation

In High Mountain Asia, home to ~200,000 glaciers, proglacial lake expansion poses dual challenges of enhanced glacier retreat and increased glacial lake outburst flood (GLOF) hazards (Nie et al., 2017; Veh et al., 2019; Zhang et al., 2015). Our finding that controlled, gradual drainage can stabilise glaciers while sudden drainage may trigger instabilities has direct implications for hazard mitigation strategies.

Several successful lake lowering projects have demonstrated the viability of engineered drainage as a hazard reduction measure (Rana et al., 2000, ICIMOD 2011). Our results provide quantitative support for gradual drainage approaches while highlighting the risks of uncontrolled rapid drainage events. The predictable scaling relationships between drainage rate and stress response enable assessment of the likelihood of drainage-triggered calving events. The dependence of the stress response on initial flotation state, and the likelihood that a warming climate with deeper lakes, thinning glaciers and more frequent drainage events will push some systems closer to critical instability thresholds, emphasises the need for enhanced monitoring and potentially active management interventions. Notably, the asymmetric response to lake level changes suggests that efforts to prevent initial lake expansion may be more effective than later drainage stabilisation measures. This argues for proactive monitoring and intervention in systems approaching critical flotation thresholds.

4.4 Model limitations and future research directions

Even though our simplified approach does not explicitly include frontal ablation mechanisms, we find that hydrostatic effects alone have important dynamic effects on lake-terminating glaciers. Our exclusion of calving and subaqueous melting likely leads to conservative estimates of glacier sensitivity, as these processes can account for a substantial proportion of mass loss in lake-terminating systems (Carrivick & Tweed, 2013; Minowa et al. 2021; Caldwell et al. 2025). Incorporating these processes would likely amplify the lake level effects we identify, through delivering more water into the proglacial basin, and could reveal additional instability mechanisms. Recent advances in calving law development (Benn et al., 2007) and subaqueous melt parameterisations (O'Leary & Christoffersen, 2013; Slater et al., 2017) provide pathways for more comprehensive future modelling. The assumption of simplified basal hydrology also limits our ability to capture the full spectrum of ice-lake interactions. Fully coupled ice-hydrology models (Ehrenfeucht et al., 2023; Sommers et al., 2018) could better represent the complex feedbacks between subglacial water pressure, basal sliding, and lake level fluctuations.

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We highlight here the influence of proglacial lakes on glacier dynamics, but also the setting-specific nature and magnitude of glacier-lake feedbacks. Future work should prioritise targeted application of our modelling framework to specific glacier systems that are expected to be most vulnerable to ice-lake interaction. Such studies demand good constraint on local boundary conditions; high-resolution topographic data from satellite and airborne surveys are increasingly providing the geometric constraints needed for realistic simulations.

Important research directions include:

- *Coupled glacier-lake modelling*: Dynamic simulation of lake evolution alongside glacier retreat, incorporating glacier sediment transport, lake thermal stratification and circulation patterns, and lake drainage pathways.
- *Multi-scale process integration*: Seamless coupling of calving laws, subaqueous melt parameterisations, and hydrology models within comprehensive ice flow frameworks.
- *Probabilistic hazard assessment*: Development of probabilistic frameworks for assessing GLOF risks under different climate scenarios, incorporating the non-linear thresholds identified in our study.
- *Observation-model integration*: Systematic comparison of model predictions with high-resolution observations from satellite imagery, GPS measurements, and autonomous sensors.

5. Conclusions

In this study, we have systematically investigated the influence of stable, growing and draining proglacial lakes on the dynamics of an outlet glacier and its ice sheet catchment. By comparing glacier behaviour in both lake-terminating and land-terminating scenarios, under simplified conditions of a flat lake bathymetry and constant mass balance, we isolate the direct impact of the lake on glacier dynamics. Our results demonstrate that lake-terminating glaciers thin and accelerate compared to those terminating on land, but that glacier mass loss accelerates significantly through grounding line mass outflux once flotation conditions are reached, driven by rising lake levels and surface mass loss. This highlights the dominant role of proglacial lake level changes in governing glacier stability.

Importantly, our analysis reveals that steadily lowering lake levels, whether through natural drainage or engineered interventions, reduces grounding line mass flux and enhances glacier stability. This finding suggests that controlled, gradual lake drainage could serve as a promising geoengineering approach to mitigate glacier retreat and its downstream impacts. However, we caution that rapid lake drainage (within seasons to years) may disrupt the glacier's stress equilibrium, increasing crevasse formation and calving potential. Glacial lake outburst floods may therefore undermine the stability of the glacier catchment, as well as constituting profound hazard risks in themselves. Our quantitative results underscore the importance of lake level management in modulating glacier dynamics.

Code & data availability

ISSM is freely available at https://github.com/ISSMteam/ISSM. The code specific to lake level change simulations will be made available on GitHub upon publication. All the output data will be deposited to Bolin Centre repository upon publication of the paper.

Author contributions

AP, SLG, RG conceived the idea and designed experiments. AP set up the model with the help of MM, JB, and FH. AP conducted the model simulations and analysed results. AP and SLG wrote the manuscript. All authors participated in discussing results and reviewing the manuscript.

Competing interests

The authors declare that they have no conflict of interest.

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Review Statement

References

Amory, C., Kittel, C., Le Toumelin, L., Agosta, C., Delhasse, A., Favier, V., & Fettweis, X. (2021). Performance of MAR (v3.11) in simulating the drifting-snow climate and surface mass balance of Adélie Land, East Antarctica. Geosci. Model Dev., 14(6), 3487–3510. https://doi.org/10.5194/gmd-14-3487-2021

Benn, D. I., Warren, C. R., & Mottram, R. H. (2007). Calving processes and the dynamics of calving glaciers. Earth-Science Reviews, 82(3), 143–179. https://doi.org/10.1016/j.earscirev.2007.02.002

Boyce ES, Motyka RJ, Truffer M. (2007) Flotation and retreat of a lake-calving terminus, Mendenhall Glacier, southeast Alaska, USA. Journal of Glaciology. 53(181), 211-224. doi:10.3189/172756507782202928

Budd, W. F., Keage, P. L., & Blundy, N. A. (1979). Empirical Studies of Ice Sliding. Journal of Glaciology, 23(89), 157–170. Cambridge Core. https://doi.org/10.3189/S0022143000029804

Caldwell, N. G., Armstrong, W. H., McNabb, R., Enderlin, E. M., McGrath, D., Rick, B., Hanson, J., & Perry, L. B. (2025). Retreat and frontal ablation rates for Alaska's lake-terminating glaciers: Investigating potential physical controls with implications for future stability. Journal of Glaciology, 71, e67. Cambridge Core. https://doi.org/10.1017/jog.2025.37

Carrivick, J. L., & Tweed, F. S. (2013). Proglacial lakes: Character, behaviour and geological importance. Quaternary Science Reviews, 78, 34–52. https://doi.org/10.1016/j.quascirev.2013.07.028

Carrivick, J. L., How, P., Lea, J. M., Sutherland, J. L., Grimes, M., Tweed, F. S., Cornford, S., Quincey, D. J., & Mallalieu, J. (2022). Ice-Marginal Proglacial Lakes Across Greenland: Present Status and a Possible Future. Geophysical Research Letters, 49(12), e2022GL099276. https://doi.org/10.1029/2022GL099276

Carrivick, J. L., Tweed, F. S., Ng, F., Quincey, D. J., Mallalieu, J., Ingeman-Nielsen, T., Mikkelsen, A. B., Palmer, S. J., Yde, J. C., Homer, R., Russell, A. J., & Hubbard, A. (2017). Ice-Dammed Lake Drainage Evolution at Russell Glacier, West Greenland. Frontiers in Earth Science, 5-2017. https://www.frontiersin.org/journals/earth-science/articles/10.3389/feart.2017.00100

https://doi.org/10.5194/egusphere-2026-172
Preprint. Discussion started: 30 January 2026

Carrivick, J. L., Tweed, F. S., Sutherland, J. L., & Mallalieu, J. (2020). Toward Numerical Modelling of Interactions Between Ice-Marginal Proglacial Lakes and Glaciers. Frontiers in Earth Science, 8-2020. https://www.frontiersin.org/journals/earth-science/articles/10.3389/feart.2020.577068

Dømgaard, M., Kjeldsen, K., How, P., & Bjørk, A. (2024). Altimetry-based ice-marginal lake water level changes in Greenland. Communications Earth & Environment, 5(1), 365. https://doi.org/10.1038/s43247-024-01522-4

Dømgaard, M., Kjeldsen, K. K., Huiban, F., Carrivick, J. L., Khan, S. A., & Bjørk, A. A. (2023). Recent changes in drainage route and outburst magnitude of the Russell Glacier ice-dammed lake, West Greenland. The Cryosphere, 17(3), 1373–1387. https://doi.org/10.5194/tc-17-1373-2023

Dye, A., Bryant, R., & Rippin, D. (2022). Proglacial lake expansion and glacier retreat in Arctic Sweden. Geografiska Annaler: Series A, Physical Geography, 104(4), 268–287. https://doi.org/10.1080/04353676.2022.2121999

Dye, A., Bryant, R., Falcini, F., Mallalieu, J., Dimbleby, M., Beckwith, M., Rippin, D. & Kirchner, N. (2025). Warm proglacial lake temperatures and thermal undercutting enhance rapid retreat of an Arctic glacier. The Cryosphere, 19, 4471–4486. doi:10.5194/tc-19-4471-2025.

Ehrenfeucht, S., Morlighem, M., Rignot, E., Dow, C. F., & Mouginot, J. (2023). Seasonal Acceleration of Petermann Glacier, Greenland, From Changes in Subglacial Hydrology. Geophysical Research Letters, 50(1), e2022GL098009. https://doi.org/10.1029/2022GL098009

Hill, E. A., Carr, J. R., Stokes, C. R., & Gudmundsson, G. H. (2018). Dynamic changes in outlet glaciers in northern Greenland from 1948 to 2015. The Cryosphere, 12(10), 3243–3263. https://doi.org/10.5194/tc-12-3243-2018

Hjelstuen, B. O., Sejrup, H. P., Valvik, E., & Becker, L. W. M. (2018). Evidence of an ice-dammed lake outburst in the North Sea during the last deglaciation. Marine Geology, 402, 118–130. https://doi.org/10.1016/j.margeo.2017.11.021

Høgaas, F. & Longva, O. (2018) The early Holocene ice-dammed lake Nedre Glomsjø in mid-Norway: an open lake system succeeding an actively retreating ice sheet. Norwegian Journal of Geology 98, 661–675.

Høgaas, F., Hansen, L., Berthling, I., Klug, M., Longva, O., Nannestad, H.D., Olsen, L. & Romundset, A. (2023) Timing and maximum flood level of the Early Holocene glacial lake Nedre Glomsjø outburst flood, Norway. Boreas, 52, 295–313. doi:10.1111/bor.12615.

Høgaas, F., Romundset, A., Aurand, K., Bendle, J., van Boeckel, M., Hansen, L. & Longva, O. (2025) A watery ice sheet demise: Formation and drainage of ice-dammed lakes in southern Norway during the Early Holocene. Quaternary Science Reviews, 355, 109250. doi:10.1016/j.quascirev.2025.109250.

Holt, E., Nienow, P., & Medina-Lopez, E. (2024). Terminus thinning drives recent acceleration of a Greenlandic lake-terminating outlet glacier. Journal of Glaciology, 70, e9. https://doi.org/10.1017/jog.2024.30

How, P., Messerli, A., Mätzler, E., Santoro, M., Wiesmann, A., Caduff, R., Langley, K., Bojesen, M. H., Paul, F., Kääb, A., & Carrivick, J. L. (2021). Greenland-wide inventory of ice marginal lakes using a multi-method approach. Scientific Reports, 11(1), 4481. https://doi.org/10.1038/s41598-021-83509-1

Hugonnet, R., McNabb, R., Berthier, E., Menounos, B., Nuth, C., Girod, L., Farinotti, D., Huss, M., Dussaillant, I., Brun, F., & Kääb, A. (2021). Accelerated global glacier mass loss in the early twenty-first century. Nature, 592(7856), 726–731. https://doi.org/10.1038/s41586-021-03436-z

Jakobsson, M., Björck, S., Alm, G., Andrén, T., Lindeberg, G., & Svensson, N.-O. (2007). Reconstructing the Younger Dryas ice dammed lake in the Baltic Basin: Bathymetry, area and volume. Global and Planetary Change, 57(3), 355–370. https://doi.org/10.1016/j.gloplacha.2007.01.006

Jansson, K. N. (2003). Early Holocene glacial lakes and ice marginal retreat pattern in Labrador/Ungava, Canada. Palaeogeography, Palaeoclimatology, Palaeoecology, 193(3-4), 473-501. https://doi.org/10.1016/S0031-0182(03)00262-1

Joughin, I., Smith, B.E. & Medley, B. (2014). Marine ice sheet collapse potentially under way for the Thwaites Glacier Basin, West Antarctica. Science, 344(6185), 735-738.

https://doi.org/10.5194/egusphere-2026-172
Preprint. Discussion started: 30 January 2026

Joughin, I., Smith, B. E., & Howat, I. M. (2018). A complete map of Greenland ice velocity derived from satellite data collected over 20 years. Journal of Glaciology, 64(243), 1–11. https://doi.org/10.1017/jog.2017.73

King, O., Dehecq, A., Quincey, D., & Carrivick, J. (2018). Contrasting geometric and dynamic evolution of lake and land-terminating glaciers in the central Himalaya. Global and Planetary Change, 167, 46–60. https://doi.org/10.1016/j.gloplacha.2018.05.006

King, O., Bhattacharya, A., Bhambri, R. & Bolch, T. (2019). Glacial lakes exacerbate Himalayan glacier mass loss. Scientific Reports, 9, 18145. https://doi.org/10.1038/s41598-019-53733-x

Kjeldsen, K. K., Mortensen, J., Bendtsen, J., Petersen, D., Lennert, K., & Rysgaard, S. (2014). Ice-dammed lake drainage cools and raises surface salinities in a tidewater outlet glacier fjord, west Greenland. Journal of Geophysical Research: Earth Surface, 119(6), 1310–1321. https://doi.org/10.1002/2013JF003034

Larour, E., Seroussi, H., Morlighem, M., & Rignot, E. (2012). Continental scale, high order, high spatial resolution, ice sheet modelling using the Ice Sheet System Model (ISSM). Journal of Geophysical Research: Earth Surface, 117(F1). https://doi.org/10.1029/2011JF002140

Lützow, N., Veh, G., & Korup, O. (2023). A global database of historic glacier lake outburst floods. Earth Syst. Sci. Data, 15(7), 2983–3000. https://doi.org/10.5194/essd-15-2983-2023

Mallalieu, J., Carrivick, J.L., Quincey, D.J. & Raby, C.L. (2021). Ice-marginal lakes associated with enhanced recession of the Greenland Ice Sheet. Global and Planetary Change, 202, p.103503. https://doi.org/10.1016/j.gloplacha.2021.103503

Meier, M.F. & Post, A. (1987). Fast tidewater glaciers. Journal of Geophysical Research: Solid Earth, 92(B9), 9051-9058. https://doi.org/10.1029/JB092iB09p09051

Minowa, M., Schaefer, M., Sugiyama, S., Sakakibara, D. & Skvarca, P. (2021). Frontal ablation and mass loss of the Patagonian icefields. Earth and Planetary Science Letters, 561, 116811. https://doi.org/10.1016/j.epsl.2021.116811

Minowa, M., Schaefer, M., & Skvarca, P. (2023). Effects of topography on dynamics and mass loss of lake-terminating glaciers in southern Patagonia. Journal of Glaciology, 69(278), 1580–1597. https://doi.org/10.1017/jog.2023.42

Morlighem, M., Seroussi, H., Larour, E., & Rignot, E. (2013). Inversion of basal friction in Antarctica using exact and incomplete adjoints of a higher-order model. Journal of Geophysical Research: Earth Surface, 118(3), 1746–1753. https://doi.org/10.1002/jgrf.20125

Morlighem, M., Williams, C. N., Rignot, E., An, L., Arndt, J. E., Bamber, J. L., Catania, G., Chauché, N., Dowdeswell, J. A., Dorschel, B., Fenty, I., Hogan, K., Howat, I., Hubbard, A., Jakobsson, M., Jordan, T. M., Kjeldsen, K. K., Millan, R., Mayer, L., Mouginot, J., Noël, B.P.Y., Ó Cofaigh, C., Palmer, S., Rysgaard, S, Seroussi, H., Siegert, M.J., Slabon, P., Straneo, F., van den Broeke, M.R., Weinrebe, W., Wood, M., Zinglersen, K. B. (2017). BedMachine v3: Complete Bed Topography and Ocean Bathymetry Mapping of Greenland From Multibeam Echo Sounding Combined With Mass Conservation. Geophysical Research Letters, 44(21), 11,051-11,061. https://doi.org/10.1002/2017GL074954

Morlighem, M., Wood, M., Seroussi, H., Choi, Y., & Rignot, E. (2019). Modelling the response of northwest Greenland to enhanced ocean thermal forcing and subglacial discharge. The Cryosphere, 13(2), 723–734. https://doi.org/10.5194/tc-13-723-2019

Mouginot, J., Rignot, E., Bjørk, A.A., Van den Broeke, M., Millan, R., Morlighem, M., Noël, B., Scheuchl, B. & Wood, M. (2019). Forty-six years of Greenland Ice Sheet mass balance from 1972 to 2018. Proceedings of the national academy of sciences, 116(19), 9239-9244. https://doi.org/10.1073/pnas.1904242116

Muto, M., & Furuya, M. (2013). Surface velocities and ice-front positions of eight major glaciers in the Southern Patagonian Ice Field, South America, from 2002 to 2011. Remote Sensing of Environment, 139, 50–59. https://doi.org/10.1016/j.rse.2013.07.034

Nick, F. M., Vieli, A., Howat, I. M., & Joughin, I. (2009). Large-scale changes in Greenland outlet glacier dynamics triggered at the terminus. Nature Geoscience, 2(2), 110-114.

https://doi.org/10.5194/egusphere-2026-172
Preprint. Discussion started: 30 January 2026

Nie, Y., Sheng, Y., Liu, Q., Liu, L., Liu, S., Zhang, Y., & Song, C. (2017). A regional-scale assessment of Himalayan glacial lake changes using satellite observations from 1990 to 2015. Remote Sensing of Environment, 189, 1–13. https://doi.org/10.1016/j.rse.2016.11.008

Nye, J. F. (1997). The distribution of stress and velocity in glaciers and ice-sheets. Proceedings of the Royal Society of London. Series A. Mathematical and Physical Sciences, 239(1216), 113–133. https://doi.org/10.1098/rspa.1957.0026

O'Leary, M., & Christoffersen, P. (2013). Calving on tidewater glaciers amplified by submarine frontal melting. The Cryosphere, 7(1), 119–128. https://doi.org/10.5194/tc-7-119-2013

Perkins, A. J., & Brennand, T. A. (2015). Refining the pattern and style of Cordilleran Ice Sheet retreat: Palaeogeography, evolution and implications of lateglacial ice-dammed lake systems on the southern Fraser Plateau, British Columbia, Canada. Boreas, 44(2), 319–342. https://doi.org/10.1111/bor.12100

Ploeg, K., & Stroeven, A. P. (2025). History and dynamics of Fennoscandian Ice Sheet retreat, contemporary ice-dammed lake evolution, and faulting in the Torneträsk area, northwestern Sweden. The Cryosphere, 19(1), 347–373. https://doi.org/10.5194/tc-19-347-2025

Pronk, J. B., Bolch, T., King, O., Wouters, B., & Benn, D. I. (2021). Contrasting surface velocities between lake- and land-terminating glaciers in the Himalayan region. The Cryosphere, 15(12), 5577–5599. https://doi.org/10.5194/tc-15-5577-2021

Rana, B., Shrestha, A. B., Reynolds, J. M., Aryal, R., Pokhrel, A. P., & Budhathoki, K. P. (2000). Hazard assessment of the Tsho Roipa Glacier Lake and ongoing remediation measures. Journal of Nepal Geological Society, 22(0), 563–570. https://doi.org/10.3126/jngs.v22i0.32432

Regnéll, C., Mangerud, J., & Svendsen, J. I. (2019). Tracing the last remnants of the Scandinavian Ice Sheet: Ice-dammed lakes and a catastrophic outburst flood in northern Sweden. Quaternary Science Reviews, 221, 105862. https://doi.org/10.1016/j.quascirev.2019.105862

Regnéll, C., Peterson Becher, G., Öhrling, C., Greenwood, S. L., Gyllencreutz, R., Blomdin, R., Brendryen, J., Goodfellow, B. W., Mikko, H., Ransed, G., & Smith, C. (2023). Ice-dammed lakes and deglaciation history of the Scandinavian Ice Sheet in central Jämtland, Sweden. Quaternary Science Reviews, 314, 108219. https://doi.org/10.1016/j.quascirev.2023.108219

Regnéll, C., Greenwood, S.L., Gyllencreutz, R., Peterson, G., Regnéll, J., Öhrling, C., Hardeng, J., Johnson, E., Bakke, J. & Cederstrøm, J.M. (2025). Anchoring the Swedish Time Scale to the radiocarbon time scale—An absolute age for De Geer's zero varve. Geology, 53(7), 601-606. https://doi.org/10.1130/G53280.1

Riel, B., Minchew, B., & Joughin, I. (2021). Observing traveling waves in glaciers with remote sensing: New flexible time series methods and application to Sermeq Kujalleq (Jakobshavn Isbræ), Greenland. The Cryosphere, 15(1), 407–429. https://doi.org/10.5194/tc-15-407-2021

Rinzin, S., Zhang, G., Sattar, A., Wangchuk, S., Allen, S. K., Dunning, S., & Peng, M. (2023). GLOF hazard, exposure, vulnerability, and risk assessment of potentially dangerous glacial lakes in the Bhutan Himalaya. Journal of Hydrology, 619, 129311. https://doi.org/10.1016/j.jhydrol.2023.129311

Sakakibara, D., & Sugiyama, S. (2014). Ice-front variations and speed changes of calving glaciers in the Southern Patagonia Icefield from 1984 to 2011. Journal of Geophysical Research: Earth Surface, 119(11), 2541–2554. https://doi.org/10.1002/2014JF003148

Sato, Y., Fujita, K., Inoue, H., Sakai, A., & Karma. (2022). Land- to lake-terminating transition triggers dynamic thinning of a Bhutanese glacier. The Cryosphere, 16(6), 2643–2654. https://doi.org/10.5194/tc-16-2643-2022

Sattar, A., Cook, K. L., Rai, S. K., Berthier, E., Allen, S., Rinzin, S., de Vries, M. V. W., Haeberli, W., Kushwaha, P., Shugar, D. H., Emmer, A., Haritashya, U. K., Frey, H., Rao, P., Gurudin, K. S. K., Rai, P., Rajak, R., Hossain, F., Huggel, C., Mergili, M., Azam, M.F., Gascoin, S., Carrivick, J.L., Bell, L.E., Ranjan, R.K., Rashid, I., Kulkarni, A.V., Petley, D., Schwanghart, W., Watson, C.S., Islam, N., Gupta, M.D., Lane, S.N., Bhat, S.Y. (2025). The Sikkim flood of October 2023: Drivers, causes, and impacts of a multihazard cascade. Science, 387(6740), eads2659. https://doi.org/10.1126/science.ads2659

Schlegel, N.-J., Seroussi, H., Schodlok, M. P., Larour, E. Y., Boening, C., Limonadi, D., Watkins, M. M., Morlighem, M., & van den Broeke, M. R. (2018). Exploration of Antarctic Ice Sheet 100-year contribution to

https://doi.org/10.5194/egusphere-2026-172
Preprint. Discussion started: 30 January 2026

sea level rise and associated model uncertainties using the ISSM framework. The Cryosphere, 12(11), 3511–3534. https://doi.org/10.5194/tc-12-3511-2018

Schoof, C. (2007). Ice sheet grounding line dynamics: Steady states, stability, and hysteresis. Journal of Geophysical Research: Earth Surface, 112(F3). https://doi.org/10.1029/2006JF000664

Seroussi, H., Nakayama, Y., Larour, E., Menemenlis, D., Morlighem, M., Rignot, E., & Khazendar, A. (2017). Continued retreat of Thwaites Glacier, West Antarctica, controlled by bed topography and ocean circulation. Geophysical Research Letters, 44(12), 6191–6199. https://doi.org/10.1002/2017GL072910

Shugar, D. H., Burr, A., Haritashya, U. K., Kargel, J. S., Watson, C. S., Kennedy, M. C., Bevington, A. R., Betts, R. A., Harrison, S., & Strattman, K. (2020). Rapid worldwide growth of glacial lakes since 1990. Nature Climate Change, 10(10), 939–945. https://doi.org/10.1038/s41558-020-0855-4

Slater, D. A., Nienow, P. W., Goldberg, D. N., Cowton, T. R., & Sole, A. J. (2017). A model for tidewater glacier undercutting by submarine melting. Geophysical Research Letters, 44(5), 2360–2368. https://doi.org/10.1002/2016GL072374

Sommers, A., Rajaram, H., & Morlighem, M. (2018). SHAKTI: Subglacial Hydrology and Kinetic, Transient Interactions v1.0. Geosci. Model Dev., 11(7), 2955–2974. https://doi.org/10.5194/gmd-11-2955-2018

Somos-Valenzuela, M. A., McKinney, D. C., Rounce, D. R., & Byers, A. C. (2014). Changes in Imja Tsho in the Mount Everest region of Nepal. The Cryosphere, 8(5), 1661–1671. https://doi.org/10.5194/tc-8-1661-2014

Sugiyama, S., Minowa, M. & Schaefer, M. (2019). Underwater ice terrace observed at the front of Glaciar Grey, a freshwater calving glacier in Patagonia. Geophysical Research Letters, 46(5), 2602-2609. https://doi.org/10.1029/2018GL081441

Sutherland, J. L., Carrivick, J. L., Gandy, N., Shulmeister, J., Quincey, D. J., & Cornford, S. L. (2020). Proglacial Lakes Control Glacier Geometry and Behaviour During Recession. Geophysical Research Letters, 47(19), e2020GL088865. https://doi.org/10.1029/2020GL088865

Teller, J. T., Leverington, D. W., & Mann, J. D. (2002). Freshwater outbursts to the oceans from glacial Lake Agassiz and their role in climate change during the last deglaciation. Quaternary Science Reviews, 21(8), 879–887. https://doi.org/10.1016/S0277-3791(01)00145-7

Thakuri, S., Salerno, F., Bolch, T., Guyennon, N., & Tartari, G. (2016). Factors controlling the accelerated expansion of Imja Lake, Mount Everest region, Nepal. Annals of Glaciology, 57(71), 245–257. https://doi.org/10.3189/2016AoG71A063

Truffer, M., & Motyka, R. J. (2016). Where glaciers meet water: Subaqueous melt and its relevance to glaciers in various settings. Reviews of Geophysics, 54(1), 220-239. https://doi.org/10.1002/2015RG000494

Trüssel BL, Motyka RJ, Truffer M, Larsen CF. (2013) Rapid thinning of lake-calving Yakutat Glacier and the collapse of the Yakutat Icefield, southeast Alaska, USA. Journal of Glaciology. 59(213), 149-161. doi:10.3189/2013J0G12J081

Tsutaki, S., Sugiyama, S., Nishimura, D., & Funk, M. (2013). Acceleration and flotation of a glacier terminus during formation of a proglacial lake in Rhonegletscher, Switzerland. Journal of Glaciology, 59(215), 559–570. https://doi.org/10.3189/2013JoG12J107

Tsutaki, S., Fujita, K., Nuimura, T., Sakai, A., Sugiyama, S., Komori, J., & Tshering, P. (2019). Contrasting thinning patterns between lake- and land-terminating glaciers in the Bhutanese Himalaya. The Cryosphere, 13(10), 2733–2750. https://doi.org/10.5194/tc-13-2733-2019

Tweed, F. S., & Russell, A. J. (1999). Controls on the formation and sudden drainage of glacier-impounded lakes: Implications for jökulhlaup characteristics. Progress in Physical Geography: Earth and Environment, 23(1), 79–110. https://doi.org/10.1177/030913339902300104

Utting, D. J., & Atkinson, N. (2019). Proglacial lakes and the retreat pattern of the southwest Laurentide Ice Sheet across Alberta, Canada. Quaternary Science Reviews, 225, 106034. https://doi.org/10.1016/j.quascirev.2019.106034

https://doi.org/10.5194/egusphere-2026-172
Preprint. Discussion started: 30 January 2026

van de Wal, R. S. W., & Oerlemans, J. (1995). Response of valley glaciers to climate change and kinematic waves: A study with a numerical ice-flow model. Journal of Glaciology, 41(137), 142–152. https://doi.org/10.3189/S0022143000017834

van der Veen, C. J. (1998). Fracture mechanics approach to penetration of surface crevasses on glaciers. Cold Regions Science and Technology, 27(1), 31–47. https://doi.org/10.1016/S0165-232X(97)00022-0

Veh, G., Korup, O., von Specht, S., Roessner, S., & Walz, A. (2019). Unchanged frequency of moraine-dammed glacial lake outburst floods in the Himalaya. Nature Climate Change, 9(5), 379–383. https://doi.org/10.1038/s41558-019-0437-5

Veh, G., Wang, B. G., Zirzow, A., Schmidt, C., Lützow, N., Steppat, F., Zhang, G., Vogel, K., Geertsema, M., Clague, J. J., & Korup, O. (2025). Progressively smaller glacier lake outburst floods despite worldwide growth in lake area. Nature Water, 3(3), 271–283. https://doi.org/10.1038/s44221-025-00388-w

Warren, C. R., & Kirkbride, M. P. (2003). Calving speed and climatic sensitivity of New Zealand lake-calving glaciers. Annals of Glaciology, 36, 173–178. https://doi.org/10.3189/172756403781816446

Weertman, J. (1974). Stability of the junction of an ice sheet and an ice shelf. Journal of Glaciology, 13(67), 3-11.

Wu, K., Bolch, T., Cheng, P., Baldacchino, F., Duan, Y., Ma, D., & Liu, S. (2025). Assessing the dynamic changes and the effect of buoyancy of lake-terminating Yanong Glacier in the southeastern Tibetan Plateau with UAV surveys. Journal of Hydrology: Regional Studies, 59, 102385. https://doi.org/10.1016/j.ejrh.2025.102385

Zhang, G., Yao, T., Xie, H., Wang, W., & Yang, W. (2015). An inventory of glacial lakes in the Third Pole region and their changes in response to global warming. Global and Planetary Change, 131, 148–157. https://doi.org/10.1016/j.gloplacha.2015.05.013