LETTERS
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Large-scale changes in Greenland outlet glacier dynamics triggered at the terminus

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The recent marked retreat, thinning and acceleration of most of Greenland's outlet glaciers south of 70° N has increased concerns over Greenland's contribution to future sea level rise[1–5]. These dynamic changes seem to be parallel to the warming trend in Greenland, but the mechanisms that link climate and ice dynamics are poorly understood, and current numerical models of ice sheets do not simulate these changes realistically[6–8]. Uncertainties in the predictions of mass loss from the Greenland ice sheet have therefore been highlighted as one of the main limitations in forecasting future sea levels[9]. Here we present a numerical ice-flow model that reproduces the observed marked changes in Helheim Glacier, one of Greenland's largest outlet glaciers. Our simulation shows that the ice acceleration, thinning and retreat begin at the calving terminus and then propagate upstream through dynamic coupling along the glacier. We find that these changes are unlikely to be caused by basal lubrication through surface melt propagating to the glacier bed. We conclude that tidewater outlet glaciers adjust extremely rapidly to changing boundary conditions at the calving terminus. Our results imply that the recent rates of mass loss in Greenland's outlet glaciers are transient and should not be extrapolated into the future.

Two main hypotheses have been advanced to explain the rapid dynamic changes of Greenland's outlet glaciers. The first postulates that the dynamical changes result from processes that act at the terminus and trigger a retreat and reduce along-flow resistive stresses (backstress)[2,3,10]. This leads then to faster ice flow and thinning that propagates rapidly upstream and leads to further retreat. Several climate-related processes may initiate these near-terminus changes, such as surface-melt induced thinning and increased calving due to enhanced hydro-fracturing of water-filled crevasses from increased surface melt[11]. For Helheim Glacier, the sensitivity to such processes may be further enhanced by a basal overdeepening in the fjord[12], as has been suggested for tidewater glaciers[13–15].

The second hypothesis is that warmer air temperatures increase the amount of surface meltwater reaching the glacier bed, increasing basal lubrication and the rate at which ice slides over its bed, leading to glacier acceleration, thinning and retreat[16,17].

To better understand the processes driving rapid outlet glacier change and assess their potential future impact, we developed a numerical flow model for Helheim Glacier that includes horizontal (along-flow and lateral) stress transfer and a dynamically determined adjustment of the grounded calving front (see the Methods section and Supplementary Information, Model).

We test the above hypotheses and triggering mechanisms by carrying out a series of modelling experiments in which we perturb the boundary condition and then run the model forward in time and compare the output to the observations (Fig. 1a,b). First, we carry out a step increase in the longitudinal stress boundary condition at the calving front ('front-stress perturbation', see Supplementary Information, Model). Physically this can be interpreted as an along-flow rheological weakening of the ice at the terminus or a reduction in backstress. The modelled surface elevation, velocity and terminus position generally agree with the observed changes (Fig. 1c,d). An instantaneous velocity increase occurs through the transfer of longitudinal stresses and extends up to 20 km upstream of the terminus. This acceleration initiates thinning near the terminus, which steepens the surface, increases the driving stress and leads to further acceleration. This interaction between increased driving stress and flow acceleration causes thinning and acceleration to propagate upstream.

As a result of the thinning, the ice near the calving front approaches flotation and causes the terminus to retreat (Fig. 2a). Within the first few months after the perturbation, rates of acceleration and retreat decrease (Figs 1c and 2a), which is mainly a result of the applied step change in perturbation. Applying an extra experiment with a gradual perturbation with time produced a continuous acceleration similar to that observed. When the terminus eventually retreats over the bedrock high into deeper water, ice speed and discharge begin to increase again leading to further thinning and retreat (Figs 1c,d,2a). This positive feedback between thinning and retreat results in an unstable retreat over the reversed bed slope and thinning of more than 100 m in two years. In our model, this feedback is solely the result of enhanced ice flux with increasing ice thickness, as hypothesized by the 'marine ice sheets instability'[18]. Other effects, such as a thinning-induced decrease in effective pressure near the terminus, may contribute to the instability[19], but here we find they are not necessary to explain the observations.

The model successfully reproduces both the acceleration to 12 km yr^{-1} near the front, as it retreats down the reversed bed slope into deeper water, and the subsequent deceleration once the bottom of the overdeepening is reached (Fig. 1d). Despite this deceleration and stabilization of the terminus, a wave of acceleration and thinning continues to diffuse upstream as observed. In our experiment, the perturbation imposed at the terminus has been removed when the terminus reaches the 2005 position, enhancing the deceleration. Without this removal, the calving front still decelerates, but retreats over another bedrock low before stabilizing

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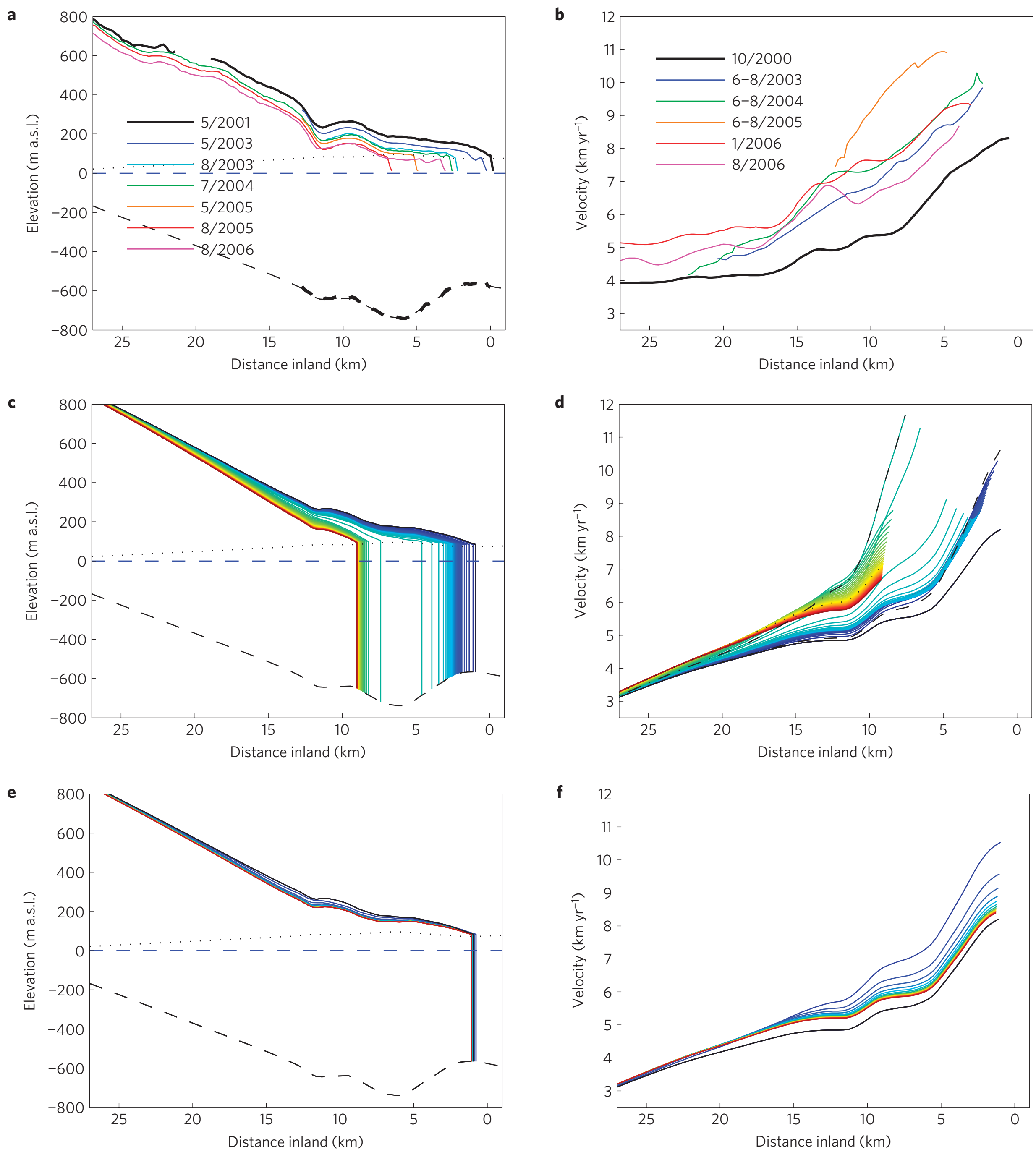

Figure 1 | Observed and modelled surface elevation and velocity. a,**b**, Observed along-flow profiles of surface elevation (**a**) and velocity (**b**) of Helheim Glacier obtained from remote sensing[12]. The black solid lines correspond to the stable phase of 2000 and 2001. In **a**, the dashed black lines show interpolated (thin) and observed (thick) basal topography and the black dotted line refers to the flotation height. Also note the newly formed floating ice tongue in 2006. **c**,**d**, Modelled profiles of surface elevation (**c**) and velocity (**d**) for the stress-front perturbation experiment, shown at two-week intervals over a total time period of three years. The lines are colour-coded for time and go from black (initial unperturbed steady state) to blue, green, yellow to red. The black dashed line in **d** shows the instantaneous velocity response to the perturbation due to longitudinal stress transfer and the dotted and dashed–dotted lines illustrate the frontal deceleration while upstream the velocities still increase. **e**,**f**, Profiles of surface elevation (**e**) and velocity (**f**) for the basal lubrication experiment. The colour-coding is the same as that used in **c**,**d**.

5.5 km farther upstream (Fig. 2a). Physically, we view this removal of the perturbation as analogous to the increase in backstress that would be expected from the observed re-advance and partial re-grounding of a floating ice tongue as was observed during the anomalously cold year of 2006 (refs 12,20).

Next, we test enhanced basal lubrication as a possible forcing for the observed dynamical changes, by applying a step increase in basal slipperiness in the terminus region (see the Methods section and Supplementary Information, Model). The resulting enhanced basal sliding induces substantial thinning mainly restricted to upstream areas (Fig. 1e). Initially at the glacier terminus, there is slight thickening and advance (Fig. 2b), which accounts for extra mass transfer from upstream. The terminus then starts to retreat and stabilizes just 150 m behind its initial position, in

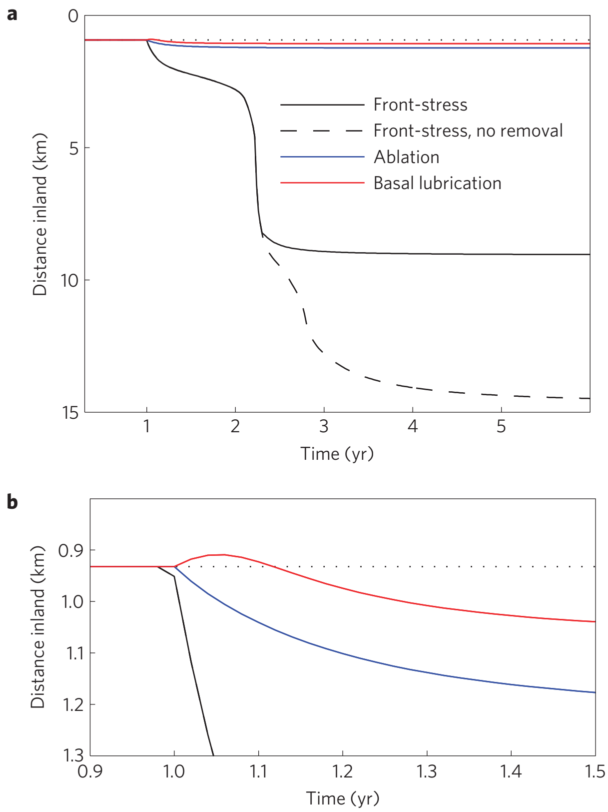

Figure 2 | Response of the glacier terminus to different model perturbations. a, Evolution of calving-terminus position with model time for the labelled perturbation experiments. **b**, A detail of **a** for the initial phase after the perturbation applied at time 1 year.

contrast to the observed 7 km retreat. More extreme perturbations in lubrication did not change these results substantially. The key to understanding this stability lies in the spatial pattern of thinning. Although there is substantial thinning upstream, it diminishes towards the terminus (see Supplementary Information, Fig. S1). The glacier adjusts to the reduced basal resistance by flattening its surface profile and thereby reducing the driving stress (Fig. 1e). Therefore, our modelling does not support enhanced basal lubrication as the governing process for the observed changes. This conclusion still holds when we include an effective pressure-dependent sliding relation[19] and is consistent with recent observations from Jakobshavn Isbrae, which show only minor sensitivity to seasonal meltwater input[21].

In a final experiment, we perturb the model by increasing only the ablation rate to investigate melt-induced ice thinning as an alternative triggering mechanism for the observed changes. Even for an unrealistically high step increase in ablation by a factor 10, the model predicts only a slight thinning that does not trigger unstable retreat (Fig. 2a). Again, the results did not change substantially by including an effective pressure-dependent sliding relation. This insensitivity to melt-induced thinning is due to the small area of the ablation zone within the narrow outlet channel (see Supplementary Information, Fig. S2) and the high ice-flow rate, which limits the surface area exposed to increased ablation and results in an insignificant rate of surface mass loss compared with ice discharge.

The ability of the front-stress perturbation experiment to reproduce the observations supports the hypothesis that changes at the glacier terminus could have triggered the observed unstable retreat. The identification of the exact process responsible is more uncertain and relies on a physical interpretation of the front-stress perturbation. Such a perturbation could be caused by a rheological weakening of the ice through enhanced hydro-fracturing of water-filled crevasses as a result of increased surface melting[11], or alternatively, by a decrease in backstress through the reduction in the extent of floating ice in winter. The calving rate, a control for the amount of floating ice in front of the glacier, may also be influenced by inter-annual changes in the seasonal extent of sea ice filling the fjord[11,21]. These processes are directly coupled to air or ocean temperatures, implying a high dynamical sensitivity of such outlet glaciers to fluctuations in climate or ocean conditions. This interpretation is consistent with recent observations at Jakobshavn Isbrae suggesting warming ocean waters as a trigger for its acceleration[22] and showing seasonal fluctuations in ice speed in phase with expansion and contraction of its floating tongue[11,21]. Our independent modelling approach supports a similar conclusion: that the dynamics of outlet glaciers are highly sensitive to near-front conditions and that the recent years of atmospheric or oceanic warming are probably a direct forcing for the synchronous dynamic changes observed for many Greenland outlet glaciers[20,23,24].

Neglecting the effect of unstable retreat, the basic process of upstream propagation of changes is similar for all experiments. The initial instantaneous acceleration by along-flow transfer of stresses induces a time-transient upstream propagation of a change in surface geometry[25–27], which can be described by Nye's kinematic wave theory applied for ice streams[28] (see Supplementary Information, Discussion). For the front-stress perturbation experiment, our modelled steady-state discharge of 28 $km^3\,yr^{-1}$ and peak discharge of 42 $km^3\,yr^{-1}$ (Fig. 3) agree within $\pm 1\,km^3\,yr^{-1}$ with estimates from remote sensing, both in terms of maximum peak and their short duration[1,12]. An extra experiment with a slightly reduced perturbation that does not trigger unstable retreat shows only a minor increase in ice discharge (Fig. 3). This suggests that the unstable thinning–retreat feedback provides the governing process for the observed mass loss. The duration of the peak discharge anomaly is short, dropping to ~10% of its maximum within just three years, emphasizing the rapid nature of the dynamical adjustment. It further implies that such extreme mass loss cannot be dynamically maintained in the long term, and that the recent rates of mass loss through increased outlet discharge should not be extrapolated to the future.

Averaged over the next 50 years, our model predicts an increase in dynamic discharge of ~0.5 $km^3\,yr^{-1}$, which is only ~2% of the steady-state discharge. Assuming a more pessimistic future scenario with no removal of the front-stress perturbation, the terminus retreats another 5.5 km upstream but stabilizes owing to shallowing of the fjord. The peak discharge is then of longer duration, but decays rapidly resulting in an average mass loss of only 1.0 $km^3\,yr^{-1}$ over the next 50 years, which is below 10% of previous short-term projections[1]. Therefore, we suggest that in the long term, non-dynamical processes, such as direct surface melt under a warming climate[29], may dominate the future mass loss of the Greenland ice sheet.

Many of Greenland's tidewater outlet glaciers flow through basal troughs similar to that underlying Helheim Glacier. In the short term, these may undergo similar rapid dynamic changes as has been observed for many of the glaciers along Greenland's southeast coast[1,23,24]. Most of these troughs do not extend far inland, however, limiting the potential for long-term mass draw-down driven by this mechanism. It is important to note that there are exceptions, where a substantial longer-term mass loss cannot be discounted, such as Jakobshavn Isbrae with its deep basal trough that extends well into the ice-sheet interior[30].

From our numerical modelling, we conclude that Greenland tidewater outlet glaciers are highly sensitive to changes in their terminus boundary conditions and dynamically adjust extremely rapidly, providing an explanation for their almost synchronous behaviour to short-term fluctuations in climate. This implies that

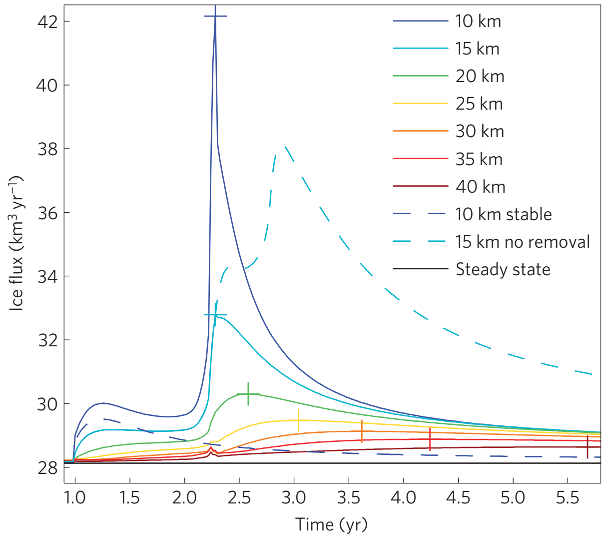

Figure 3 | Modelled response in ice flux. Modelled evolution for the front-stress perturbation experiment of ice flux with model time at different distances upstream from the initial calving terminus. The dark-blue line corresponds to the flux-gate location of previous discharge estimates from remote sensing[1,12]. The dashed dark-blue line shows the flux at the same location for a slightly reduced front-stress perturbation that does not trigger unstable retreat. The dashed light-blue line represents the experiment with removal of the front-stress perturbation and the solid black line the modelled unperturbed steady-state flux. Crosses mark the ice-flux peak in time at the different locations.

discharge changes near the glacier terminus reflect short-term dynamical adjustments, and do not provide a reliable measure for the longer-term mass balance of an ice sheet. We predict that longer-term rates of mass loss, at least for Helheim Glacier, may be less marked than observed in recent years. This modelling work also provides a step forward towards including outlet glacier dynamics in large-scale prognostic ice-sheet models used to predict sea level rise. The relatively simple physics behind our model is encouraging in terms of future model development; however, our study also underlines the crucial requirement of sufficiently high spatial resolution (below 1 km) to resolve along-flow variability of basal topography and width of such outlet glaciers. The high sensitivity to basal topography further stresses the need of future ice-sheet models to include a free-evolving calving terminus and of intensifying the collection of basal data to improve predictions of future ice-sheet change.

Methods

Numerical model. We use a numerical ice-stream model to calculate the surface evolution, flow and stress field along a flowline of Helheim Glacier. In this model, the driving stress is balanced by the resistive stresses from the base, the ice stream sides and the along-flow transfer of longitudinal stresses. The boundary condition at the glacier calving terminus is given by the longitudinal stress that balances the difference between hydrostatic pressure of the ice and the ocean water. The evolution of the ice surface includes along-flow variations in width and we assume a sliding law that relates basal drag linearly to basal flow. A crucial feature of the model is the ability to freely move the calving glacier terminus. Assuming a grounded terminus, a flotation criterion is used to calculate the position of the calving front, which keeps the surface at the terminus at a critical height above the flotation level. A moving spatial grid (with an average horizontal grid size of 350 m) is used to continuously follow the calving front and overcome numerical dependencies of fixed-grid models.

The modelled domain includes the full drainage basin of Helheim Glacier from the ice divide down to the calving front. In the ice-sheet interior, we used an existing digital elevation model for basal topography and for the narrow outlet channel, we used single-profile data where available. Surface mass balance input is set to average values between 1991–2000. To avoid adjustment effects from non-steady initial conditions, an initial reference surface geometry has been derived by running the model from the present surface geometry to a steady state and adjusting the basal sliding coefficient to fit the observed surface geometry, terminus position and flow speed for the pre-retreat 'stable' phase of Helheim around 2001 (Fig. 1). Unless otherwise indicated, the basal sliding coefficient is assumed to be constant with time. Extra model runs include an effective pressure-dependent sliding coefficient to investigate the effect on the dynamical behaviour in the situation of a basal overdeepening, and showed a slightly enhanced, but qualitatively very similar response.

Perturbation experiments. We apply the front-stress perturbation by modifying the longitudinal strain rate within the longitudinal stress boundary condition at the calving front by multiplying with a factor. For our standard front-stress experiment, we increase this factor from 1 to 2.8. Physically this means the longitudinal strain rate at the terminus increases by a factor 2.8. In the reduced experiment in Fig. 3 that does not trigger unstable retreat, this factor is set to 2.3.

Enhanced basal lubrication is simulated by increasing basal slipperiness by a factor that is here assumed to linearly increase from 15 km inland (factor 1) to the terminus (factor 10). A sensitivity analysis with different magnitudes and extents of this basal perturbation did not affect the main pattern of change.

Enhanced ablation is simulated by increasing the ablation rate by a factor 10, whereas in the accumulation area the values are unchanged. In the terminus area, this means the surface ablation increases from about 4–40 m yr^{-1}. This imposed increase greatly over-exaggerates the expected increases in ablation due to expected future warming but still does not trigger the observed changes.

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Author contributions

F.M.N. and A.V. contributed equally to this work and were responsible for the numerical modelling. I.M.H and I.J. provided the observational data for comparison. A.V. wrote the manuscript with substantial contribution from F.M.N., I.M.H and I.J.

Additional information

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