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Fast retreat of a marine outlet glacier in western Norway at the last glacial termination

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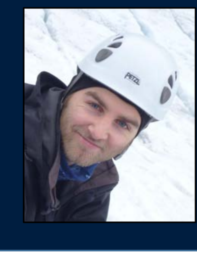


Introduction

Observations of marine outlet glaciers covering the last few decades show speedup and accelerated retreat, and the geologic record testaments that abrupt changes occurred also in the past. However, the **time scales** of rapid outlet glacier retreat and the underlying **drivers** are still unclear. Here, we study the **collapse of Hardangerfjorden glacier** (Fig. 1), an outlet glacier of the **Scandinavian Ice Sheet**, during climate warming from the Younger Dryas cold period to the early Holocene. We use **dated terminal and lateral moraines** as constraints for a 1.5-D ice flow model suitable for fast-flowing outlet glaciers.

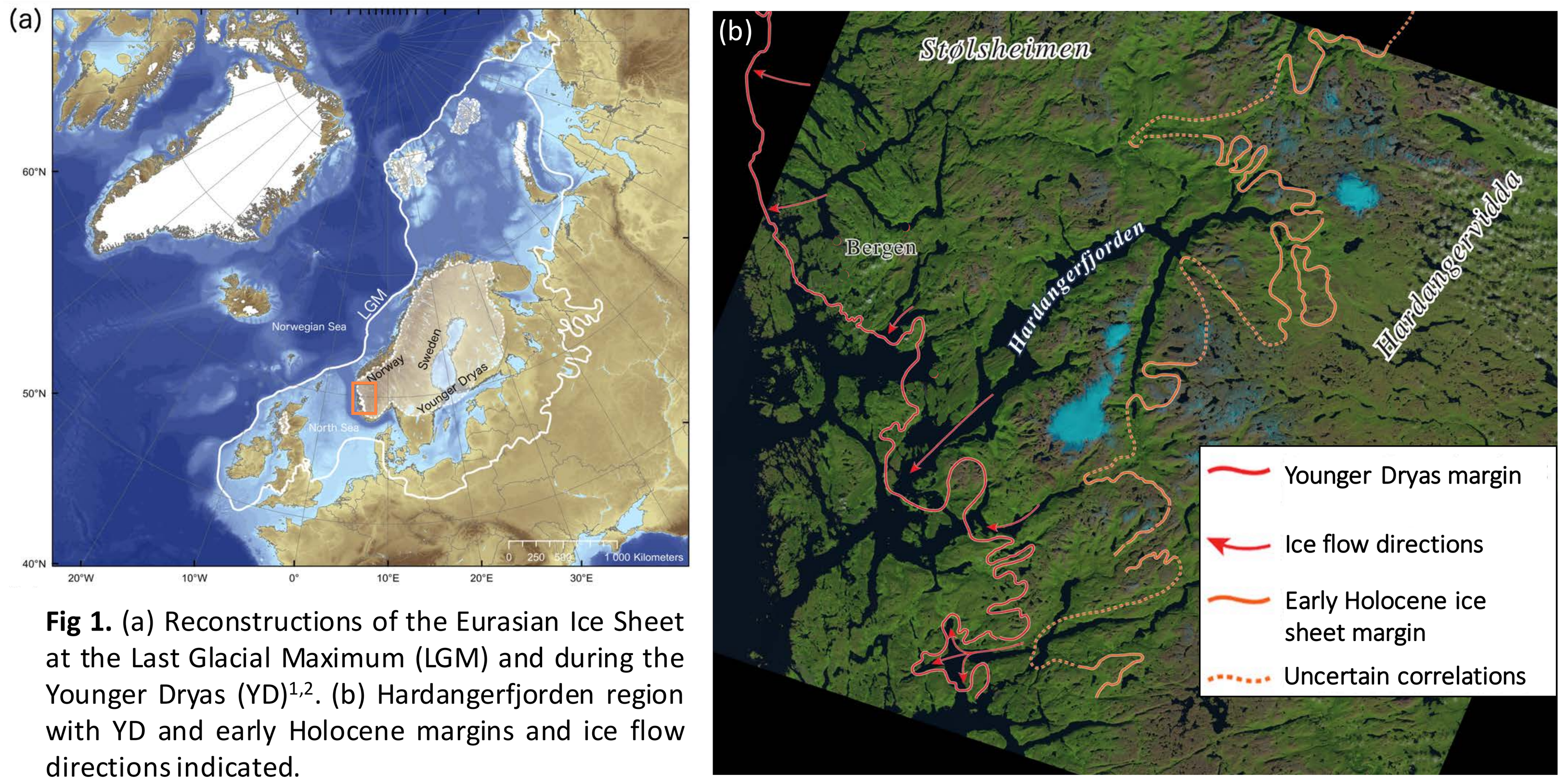


Fig 1. (a) Reconstructions of the Eurasian Ice Sheet at the Last Glacial Maximum (LGM) and during the Younger Dryas (YD)[1,2]. (b) Hardangerfjorden region with YD and early Holocene margins and ice flow directions indicated.

Improved representation of topography in flowline-type models

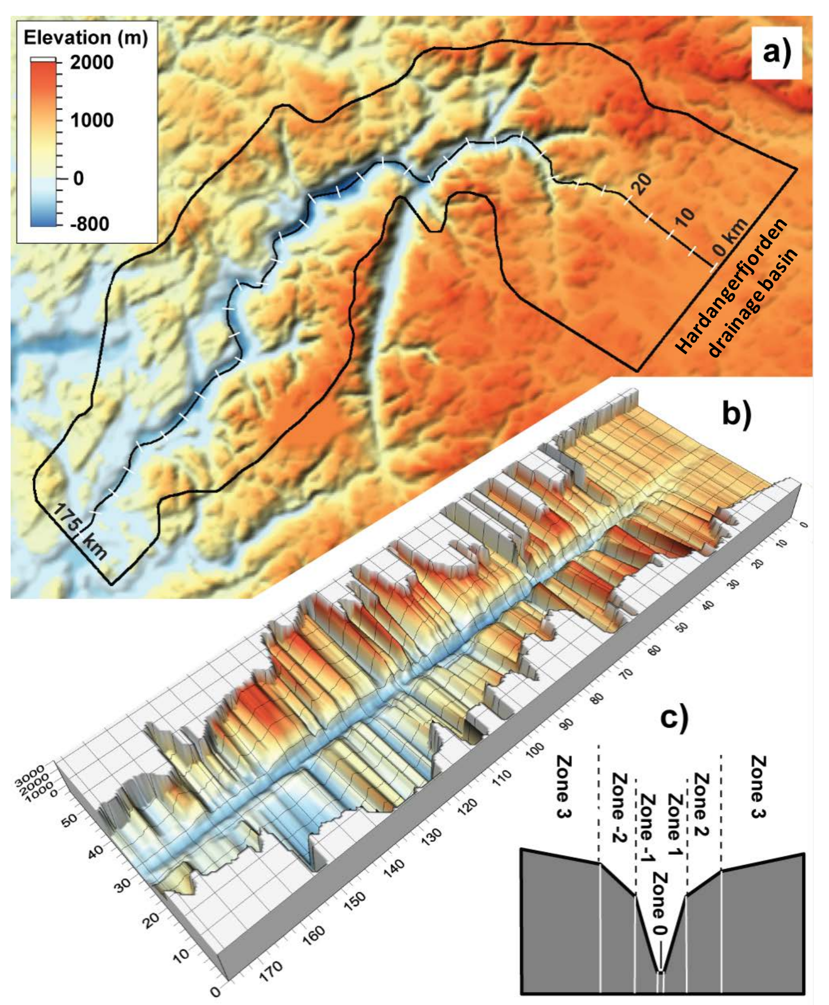


Fig 2: (a) Topography in the model domain, (b) model representation of the topography, (c) cross-sectional view of how the lateral model topography is constructed, using zones of varying width from the flowline, with linearly regressed slopes for each zone. (d) Hardangerfjorden. Photo: F. Loftesnes

Model approach

We apply a numerical, 1.5-D flowline model[3,4] using an improved representation of fjord topography (Fig. 2), with a crevasse-depth calving criterion[4,5] (Fig. 3). From the YD cold period, we change the Equilibrium Line Altitude (**ELA**) and **ocean forcing** according to paleoclimate data and reconstructions.

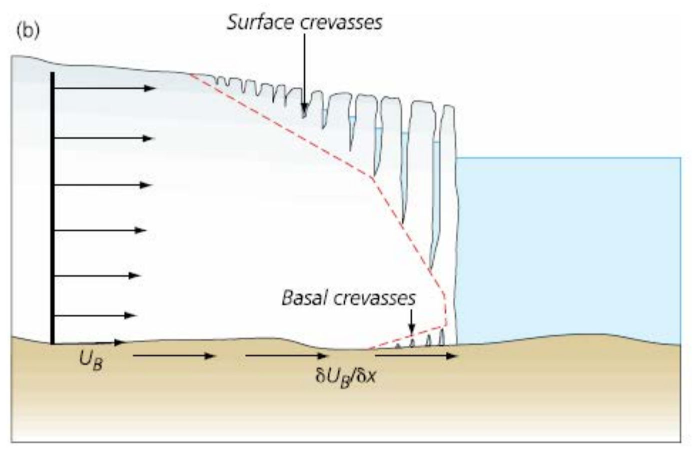


Fig 3. Calving occurs when surface and basal crevasses meet, or when surface crevasses penetrate the full ice thickness. A time-adaptive grid allows for continuous tracking of grounding line migration[4].

Younger Dryas–Holocene retreat of a Jakobshavn-like outlet glacier

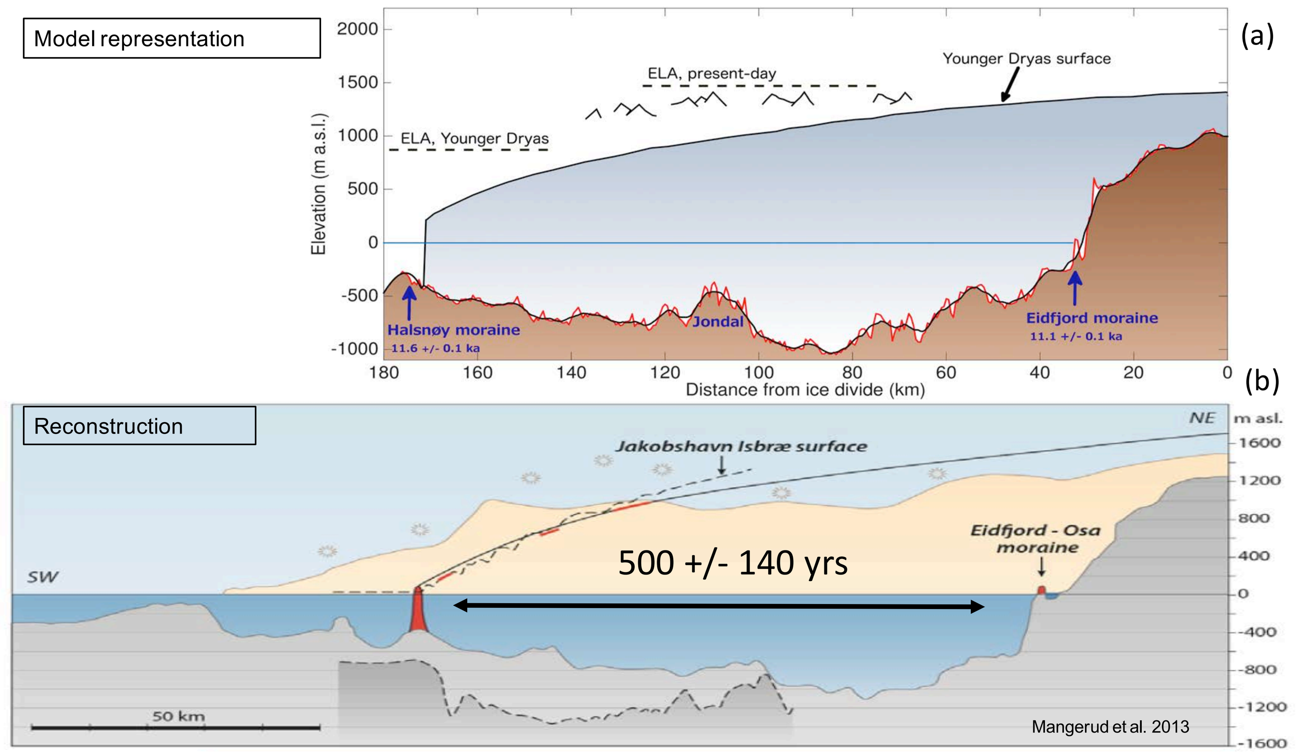
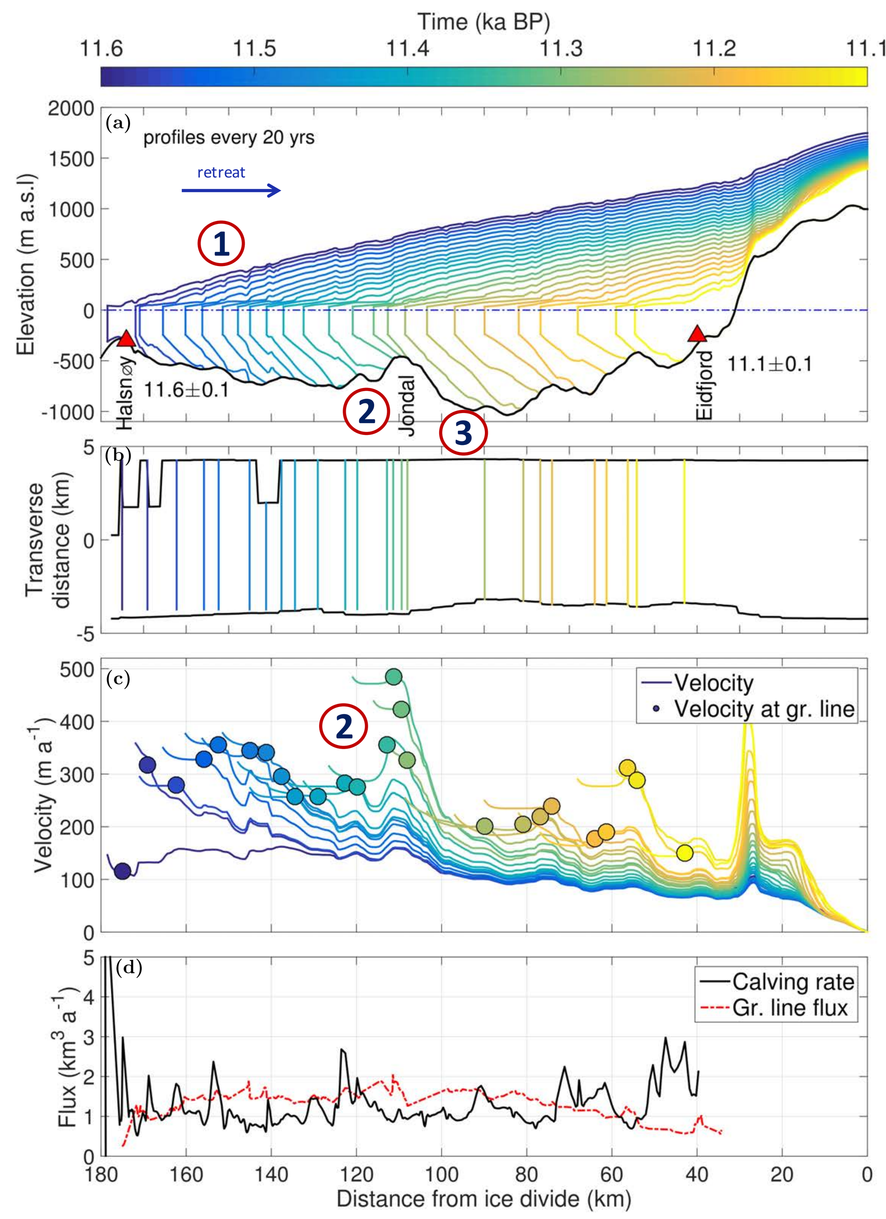


Fig 4. (a) Along-flow surface and bed topography of Hardangerfjorden glacier at the end of Younger Dryas[6], observed and smoothed bedrock topography. Mountain peaks along the fjord are shown schematically. Postglacial sediments are removed and bed topography corrected for postglacial uplift. (b) Reconstructed Younger Dryas surface profile along the deep trough of. As a comparison similar profiles (dashed) are given for present-day (2007) Jakobshavn Isbræ[7].



Temporal evolution

1. Floating ice tongue develops
2. Fjord shallows, width ~ constant, loss of shelf; → speedup at grounding line
3. Rapid grounding line retreat, ice shelf lengthening

Fig 5: Modelled response of Hardangerfjorden glacier during the Younger Dryas-Holocene transition, 11.6-11.1 ka BP. Profiles are shown every 20 years.
(a) Glacier geometry, with dated moraines at Halsnøy and Eidfjord,
(b) planview grounding lines and model fjord geometry,
(c) velocity *along* the flowline and *at* the grounding line,
(d) calving rate and grounding line flux.

How do water depth and bedrock slope influence retreat rates?

We find **grounding line retreat rates** largely **independent** of **water depth** (Fig. 6a), more paced by local **up-fjord bedrock slopes** (Fig. 6b) and ice shelf **buttressing** (Fig. 7d).

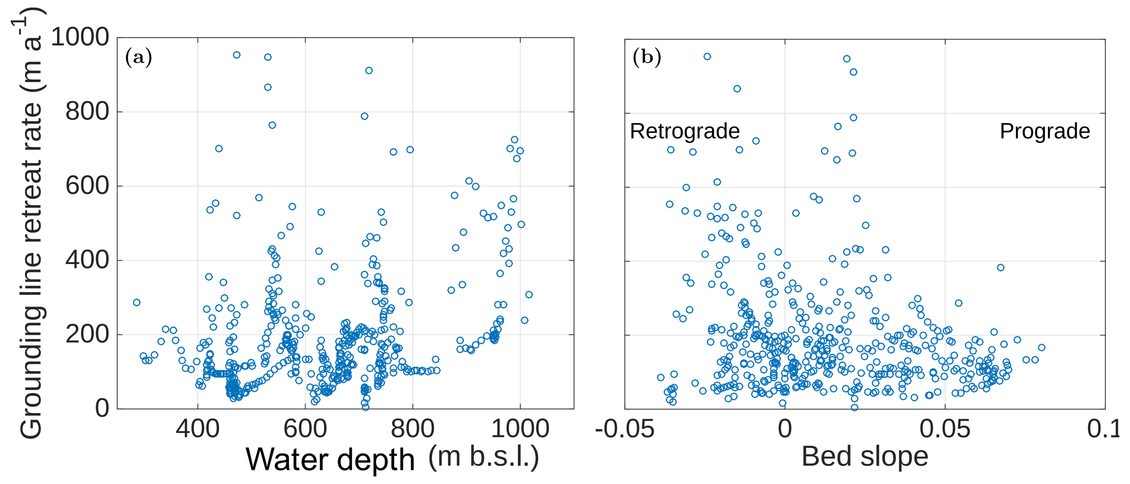


Fig 6: How grounding line retreat rates are influenced by (a) water depth, and (b) bedrock slopes around the grounding line. Positive slopes imply a prograde (seaward-sloping) bed, negative means a retrograde bed (deepening inland).

Bathymetry and ice shelf buttressing pace grounding line retreat

Our experiments show a **highly variable retreat history** (Fig. 7) paced by fjord bathymetry and ice shelf dynamics (Fig. 7d). Grounding line **retreat** in response to the early Holocene warming is simulated at **rates below 200 m/a**, punctuated by **brief spells** of swift retreat **exceeding 500 m/a** (Fig. 7b). Our simulations suggest that an abrupt rise of the ELA was a likely trigger for the 125 km retreat in 500 years. This retreat was probably sustained by the ensuing increased **surface melt** and concomitant **warming fjord waters**, as manifested in proxy records.

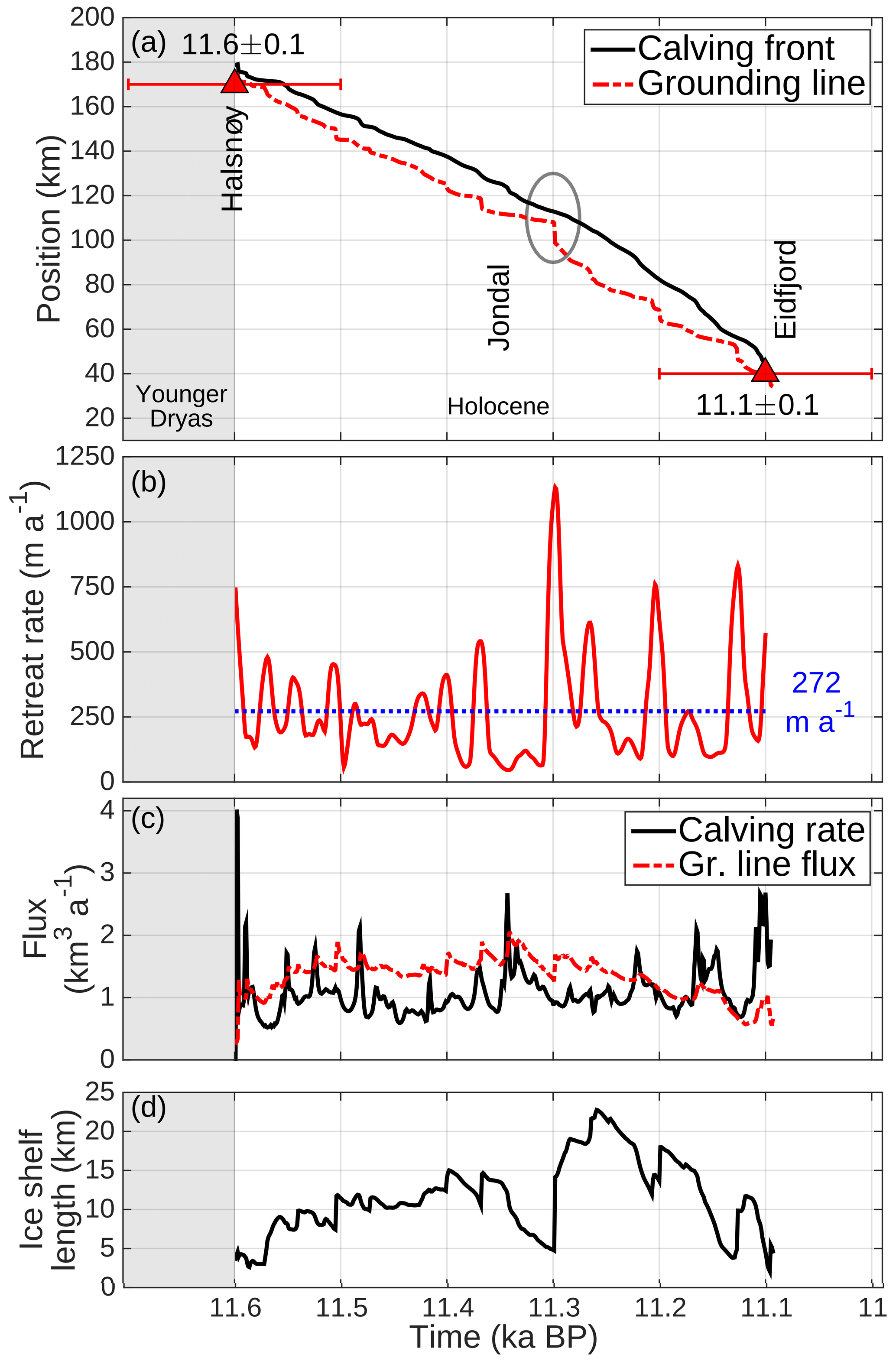


Fig 7. Simulated evolution of Hardangerfjorden glacier from the dated Younger Dryas moraine at the fjord mouth (Halsnøy) to the dated moraine at the fjord head (Eidfjord).
(a) Calving front and grounding line position,
(b) grounding line retreat rate (20-year moving average, red) and its 500-year mean (dashed blue),
(c) calving rate and grounding line flux,
(d) ice shelf length

Take home

FINDINGS

- **Combined atmosphere** + **ocean**-driven **retreat**
- Highly **variable retreat** governed by **bathymetry** and **ice shelf buttressing**

IMPLICATIONS

- Past or future **centennial ocean**-only-driven marine outlet glacier retreat **unlikely**
- **Extreme retreat** rates last a only few **decades**

Future work

- Calving sensitivity analysis
- Further parameter analysis
- Sedimentation and moraine formation

References
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