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Scaling of Ice Stream Spacing and Flux from Numerical Simulations

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ABSTRACT. Ice streams dominate the discharge of contemporary ice sheets, and are points of vulnerability for ice sheet instabilities. Therefore, to understand past and future ice sheet change we need to understand ice stream behaviour. Computer simulations can replicate the spacing and flux of palaeo and contemporary ice streams, but for accurate future projections we need confidence that simulated ice streams will evolve realistically.

To explore controls on the spacing and flux of ice streams, we run simulations of a circular ice sheet on a flat bed. We simulate a series of idealised circular ice sheets of various radii, finding that simulated ice stream spacing and flux broadly resembles observations even on a flat bed, with total ice stream flux and frequency scaling with ice volume. We apply the model to the bed of an idealised Icelandic Ice Sheet, resulting in a greater streaming flux relative to the circular case. The realistic setting makes ice stream position insensitive to changes in geothermal heat flux, and the ice stream configuration alters when adjusting the topographic setting. These simulations demonstrate the sensitivity of ice stream behaviour to ice sheet size, with implications for how we simulate ice sheet change over medium and long timescales.

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INTRODUCTION

The Greenland and Antarctic ice sheets are projected to be the dominant contributors to sea level rise by 2100 (Edwards and others, 2021). This makes the quantification of their future mass balance and associated uncertainties a critical scientific challenge. Numerical modelling provides the only robust approach for predicting ice sheet evolution. However, such simulations are inherently sensitive to uncertainties in both climate and oceanic forcing, as well as poorly constrained ice sheet processes. Simulations of the future evolution of the Greenland Ice Sheet find that the majority of uncertainty this century comes from ice dynamic processes, rather than climate forcing (Aschwanden and others, 2019).

Ice streams play a fundamental role in ice sheet mass balance, acting as conduits that transfer accumulated ice from the interior to the margins (Bennett, 2003). The significance of ice streams is further heightened by their vulnerability to instabilities and rapid retreat, making them key drivers of the future evolution of the Antarctic (e.g., Favier and others, 2014; Nias and others, 2016; Waibel, 2017) and Greenland (e.g., Joughin and others, 2008; Gillet-Chaulet and others, 2012; Hogg and others, 2016) ice sheets. Given their crucial role, a deeper understanding of ice stream behaviour is essential for improving ice sheet projections and reducing uncertainty in future sea level rise estimates.

While there are examples of remarkable uniformity in the spacing of ice streams (e.g. The Siple Coast (Rignot and others, 2011)), we know from observations that the pattern of ice streaming around an ice sheet margin is not always uniform (Mouginot and others, 2012; Joughin and others, 2008). This non-uniformity is broadly caused by variations in four factors; bed topography, bed geology, hydrology, and the presence of calving margins (Winsborrow and others, 2010). Topographic troughs initiate ice streams because of a simple geometry problem; increased velocity maintains total discharge when ice flow is focussed into a narrow region. The increased velocity and ice thickness also increases basal melting, lubricating the bed (Paterson, 1994; Sugden, 1968). Topographic focussing is apparent in empirical mapping of palaeo ice sheets (Stokes and others, 2005; Sejrup and others, 2003; Margold and others, 2015; Sugden, 1978), and velocity field observations of contemporary ice sheets (Mouginot and others, 2012; Joughin and others, 2008). The impact of variations in other bed characteristics (such as bed roughness, geology, and presence of deformable sediment) is also well-established theoretically (e.g. Weertman, 1957; Nye, 1969; Schoof, 2004; Paterson, 1994), and apparent from empirical evidence (Bingham and Siegert, 2007; Alley and others, 1986; Clark and Stokes, 2001).

Related to these variations in topography, the increased presence of basal meltwater also increases

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ice velocities, through the saturation of sediments which can be easily deformed (Tulaczyk and others, 2000), and through high basal water pressure reducing bed friction (Weertman, 1972). Finally, mass loss at the margins can influence ice streaming with calving reducing the buttressing thus increasing the flow speed (Hughes, 1992), or surface melting altering the surface slope in a manner to encourage streaming (Robel and Tziperman, 2016). In observations, the factors controlling the preferential formation of ice streams are coincident and interrelated (changes in bed topography relate to bed hydrology, for example) so determining the most important cause of specific ice streams is not usually possible.

Two coupled processes are known to initiate and sustain fast flow on otherwise uniform beds: (i) thermomechanical feedbacks in which strain and frictional heating reduce viscosity and basal resistance, further accelerating flow (Payne and Dongelmans, 1997; Hindmarsh, 2009; Hulton and Mineter, 2000), and (ii) hydrological feedbacks in which basal meltwater enables sliding (Tulaczyk and others, 2000; Kyrke-Smith and others, 2015). Early experiments showed spontaneous streaming but also raised concerns about grid dependence under shallowice approximations (Bueler and others, 2007). Subsequent higherorder simulations with membrane stresses demonstrated that thermally induced ice streams emerge with regular widths and chaotic temporal variability (Brinkerhoff and Johnson, 2015).

Prior empirical and numerical evidence suggests that total ice stream flux scales with increasing ice sheet size (Stokes and others, 2016). Analyses of the Laurentide Ice Sheet reveal a positive correlation between ice sheet volume and both the number of ice streams and the proportion of the ice sheet perimeter affected by streaming. However, running higher-order simulations of continental-scale ice sheets over millennia remains computationally challenging, and it is unclear if more computationally efficient models of ice streaming with an approximation of subglacial hydrology reproduce the expected scaling relationship in a realistic manner. This study addresses this gap in knowledge.

Simulations of contemporary ice sheets can achieve a close fit to observed surface speeds using data assimilation techniques that tune ice sheet parameters such as basal friction (Gillet-Chaulet and others, 2012; Morlighem and others, 2013; Arthern and others, 2015; Gong and others, 2017), commonly referred to as the “inversion method". While this allows for minimal error against observations in the short-term (annual-decadal simulations), it does not account for long-term (centennial-millennial) changes to the ice sheet bed conditions, be that because of sediment exhaustion (Stokes and others, 2007), changing ice sheet geometry (Robel and Tziperman, 2016), or meltwater supply (Zwally and others, 2002). This means the inversion method ice sheet simulations may diverge considerably from actual ice sheet behaviour, even

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given a perfect climate forcing (Van der Veen, 1999). An inversion approach may be unsuitable for long simulations of future ice sheet change.

In addition, the inversion approach is not an option for simulations of palaeo ice sheets, where there are no observations of surface ice sheet velocities to invert basal parameters from. While there are preserved subglacial landforms on palaeo ice sheet beds which provide an indication of flow speed (i.e. the presence of Mega Scale Glacial Lineations would indicate a region of ice streaming (Clark, 1993; King and others, 2009)), practically these landforms are spatially and temporally discontinuous, and do not provide a quantifiable value of ice velocity. While these landforms have been used to inform basal traction maps for palaeo ice sheets (Pollard and others, 2023; Gowan and others, 2016; Clark and others, 2022; Gandy and others, 2018), they provide a constraint of relative velocity, rather than absolute velocity values. Hence subglacial landforms are more useful as a validation of existing simulations (e.g., Gandy and others, 2021, 2019; Ely and others, 2021; Archer and others, 2023), rather than as a boundary condition for new simulations.

Understanding how ice stream behaviour evolves as ice sheets evolve is essential for predicting their future stability. If ice stream flux declines in response to ice sheet shrinkage, a stabilising effect may emerge, mitigating mass loss. Conversely, climate-ice stream feedbacks (Robel and Tziperman, 2016; Gandy and others, 2021) could exacerbate ice sheet mass loss over the coming millennia. Resolving these uncertainties requires an assessment of whether existing efficient modelling approaches (capable of simulating large ice sheets over millennia) remain valid for ice sheets of varied sizes. This manuscript uses an approach to modelling ice streams that is capable of simulating dynamic evolution efficiently to explore the behaviour and configuration of ice streams for ice sheets of increasing size, subsequently applying the configuration to a more realistic use-case of an idealised Icelandic Ice Sheet.

METHODS

We use the BISICLES ice sheet model to investigate ice stream behaviour. BISICLES is a vertically integrated ice sheet model with L1L2 physics retained from the full Stokes flow (Schoof and Hindmarsh, 2010), which has been used simulate ice stream response on contemporary (Cornford and others, 2015; Nias and others, 2016) and palaeo (Gandy and others, 2021; Matero and others, 2020; Sherriff-Tadano and others, 2022) ice sheets. To simulate ice streams dynamically, without the requirement for an imposed bed friction or ice softness boundary condition, BISICLES includes an implementation of an idealised subglacial hydrology scheme to simulate ice streams without the need to invert from velocity observations. The basal

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sliding scheme has been used as part of palaeo simulations where inversion is not possible due to lack of observations (Gandy and others, 2019, 2021; Sherriff-Tadano and others, 2022). Gandy and others (2019) describe the sliding scheme in detail. In brief, the dual Weertman-Coulomb sliding law is used (Tsai and others, 2015), where the basal shear stress is the minimum of two stresses,

$$|\tau_b| = min[C(|u_b|)^{\frac{1}{m}}, f(\sigma_0 - p_w)], \tag{1}$$

where C is in the friction coefficient (set at 3000 Pa m$^{-1/3}$ a$^{1/3}$ in all experiments), u_b is the basal velocity, m is Glen's flow law exponent (set at 3 in all experiments), f is the coulomb friction angle (set at 0.5 in all experiments), σ_0 is the ice pressure, and p_w is the water pressure. An enthalpy transport scheme is used from Aschwanden (2012), where an energy density E,

$$E = H_c T + Lw, \tag{2}$$

is conserved rather than temperature T alone. H_c is the specific heat capacity, w is the water fraction, and L is the specific latent heat of fusion. Basal hydrology is approximated according to Van Pelt and Oerlemans (2012), considering hydrology in a vertical column with no vertical transport. This idealised approach to simulating basal hydrology has been coined the "leaky bucket" approach, and the resulting ice stream behaviour compares favourably with more complex approaches (Drew and Tarasov, 2023), despite the lack of horizontal transport and lack of mass-conserving subglacial scheme. The thickness of the till-stored water layer W evolves through the equation,

$$\frac{\delta W}{\delta t} = \frac{m_b}{p_w} - D, \tag{3}$$

where m_b is the basal melt rate, p_w is the density of fresh water, D is the vertical till drainage rate. These adaptations allow for ice stream formation, as have previously been approximated in PISM (Van Pelt and Oerlemans, 2012), here with the addition of the combined Weertman-Coulomb sliding law. Basal water pressure, P_{bw} is calculated with,

$$P_{bw} = \alpha \rho g H (\frac{min(W, W_0)}{W_0}), \tag{4}$$

where W_0 is the till saturation point, set at 2 m in all experiments, α is a factor defining the maximum

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ratio of pore-water pressure to overburden pressure, set at 0.99 in all experiments, and g is gravitational acceleration. To examine the simulated ice stream behaviour on a fundamental level, without the noise caused by attempting to simulate a more realistic glaciological setting, we simulate a series of idealised circular ice sheets of increasing radius. A circular domain provides a radially symmetric geometry that eliminates topographic and boundary-condition biases, ensuring that any streaming pattern arises from internal thermomechanical and hydrological feedbacks rather than imposed asymmetries. Ice is initialised on a flat circular island at sea level, surrounded by a 2000 m deep ocean. We imposed 0.3 m/y accumulation across the island, allowing for an ice sheet build-up over 10,000 years. All simulations have a uniform surface temperature forcing of 268 K, and a geothermal heat flux of 150 mW/m^2 (except for a sub-set of simulations with spatially variable geothermal heat flux, described later).

This ice margin is simulated with the vertically integrated stress-balance approximation coupled to a thickness evolution equation on an adaptively refined mesh. The lateral boundary at the calving front satisfies the hydrostatic pressure condition, as described in Cornford and others (2013). Calving is represented using a Continuum Damage Mechanics approach based on crevasse penetration, described in detail in Sun et al., (2017). The vertically integrated damage variable evolves at both the surface and base of the ice sheet. Sub-shelf melting is imposed as a uniform basal melt rate of 100 m/y beneath floating ice. Practically, this minimises the size of simulated ice shelves, with margin transect shown in the appendix.

These simulations are run at a 4 km horizontal resolution, with no use of the BISICLES mesh refinement capability (we checked for resolution dependence with simulations with up to 3 levels of refinements, or 500 m horizontal resolution). Simulations are run with an island radius of 250, 500, 750, 1000, 1250, and 1500 km. In our analysis of simulations (i.e. determining ice stream spacing or total flux) we identify the ice stream boundaries where the ice velocity exceeds 100 m/y. This ensures consistent comparison between the simulations, but the choice of this velocity threshold will impact the absolute values calculate, like percentage ice routed through ice streams.

Later, we applied this idealised set-up to the geographic context of an idealised Icelandic Ice Sheet. We kept the initialisation set-up the same, with the exception of introducing a realistic bed topography and bathymetry to examine ice stream behaviour, and reducing the basal melt rate beneath floating ice to 10 m/y to allow ice shelves to form. We chose to base this exploration on an Icelandic Ice Sheet because of the relative similarity to the idealised set-up; quasi-circular ice sheet with a radius within the range simulated, with mass lost at the marine margin. These simulations are not intended to be a realistic reproduction

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of the Icelandic Ice Sheet, rather as a setting to explore simulated ice stream behaviour. The idealised Icelandic Ice Sheet simulations were run with the same uniform accumulation of 0.3 m/y. We used an increased horizontal resolution, refining the mesh at the margin twice to simulate at a 1 km resolution, approaching the resolution required to simulate accurate grounding line migration (Cornford and others, 2016). Further simulations begun to vary the geothermal heat flux and topographical setting, described in the sections “Smoothed Topography” and “Variable Geothermal Heat flux”.

RESULTS AND DISCUSSIONS

Circular Ice Sheets

Simulations of a circular ice sheet on a flat bed produced a pattern of ice streaming despite the lack of topographic variations. Our results are consistent with the concept of thermomechanical instability as a driver of streaming (Payne and Dongelmans, 1997; Hindmarsh, 2009), and align with Brinkerhoff and Johnson (2015), who demonstrated similar spontaneous streaming on radially symmetric ice sheets using a higher-order model. Unlike their study, which explored chaotic temporal variability and statistical convergence of stream widths, our focus is on geometric scaling with ice sheet size. In simulations with an ice sheet radius of 500 km and above, a regular pattern of streaming is observed (Figure 1). The number of ice streams increases as the ice volume grows from zero, equilibrating with the equilibrating ice volume. Animations of the simulation spin-up are available in the Supplementary Information. The individual ice streams have a broadly comparable width and length in each of the simulations. Even with this idealised configuration, the ice stream spacing and flux broadly resembles observations (Truffer and Echelmeyer, 2003; Bennett, 2003), with an ice stream spacing of 10-100s of kilometres, and an ice stream velocity > 100 m/y. The precise behaviour of steaming (including spacing, flux, and radius of initiation) will depend on uncertain model parameters (tested in Gandy and others (2019)), not varied in these experiments.

Notably, the 250 km simulation does not exhibit ice streaming behaviour, indicating that there is a size threshold between the 250 and 500 km simulations where ice flux is significant enough to initiate ice streaming. The lack of streaming for small ice sheets is consistent with the absence of ice streams at small ice caps (Wuite and others, 2022), and suggests a lower limit for the scaling of ice streaming with ice sheet size (Stokes and others, 2016). We also ran the 250 km and 1000 km simulations with 3 levels of mesh refinement at the margin (resulting in a 500 m horizontal resolution), demonstrating consistent results and no resolution dependence (Appendix C). Our flatbed experiments reach quasisteady spatial streaming

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at equilibrium. Brinkerhoff and Johnson (2015) obtained persistent, irregular temporal variability and stream migration using a higherorder stress balance with explicit membrane stresses. The L1L2 approach and our idealised hydrology scheme appear to dampen oscillations. We therefore interpret our equilibrium patterns as physically plausible velocity fields under constant boundary conditions, while acknowledging that higherorder formulations and climatic asymmetries can drive nonsteady, chaotic cycles.

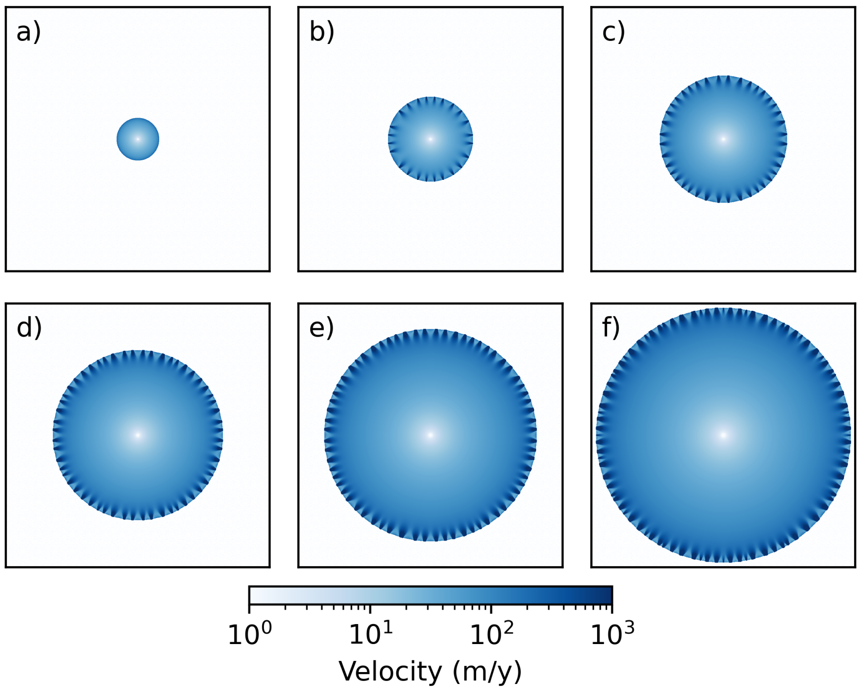

Fig. 1. The equilibrium velocity field for the idealised ice sheets simulated with a radius of 250 km (a), 500 km (b), 750 km (c), 1000 km (d), 1250 km (e), and 1500 km (f). A more detailed view, showing just the top-left quarter of the ice sheets, is included in the Supplementary Information.

The observed increase in ice streaming as the ice sheet radius increases results from a simple geometry change as ice sheets grow. In this idealised case, there is a linear relationship between the ice sheet radius and perimeter, but a non-linear relationship between radius and ice volume (Figure 2). Essentially, at equilibrium mass gain and loss must be in balance, and that is achieved by increasing ice flux. In these simulations the requirement for increased flux at the margin is met by increasing the frequency of ice streams (Figure 2c); ice streams spacing is roughly 140 km centreline to centreline in the 500 km radius simulations, but 110 km centreline to centreline in the 1,500 km radius simulations. This quasi-regular

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spacing likely reflects the influence of membrane stresses retained in the L1L2 formulation, which act to spread deformation laterally, leading to a preferred wavelength of streaming (Hindmarsh, 2009).

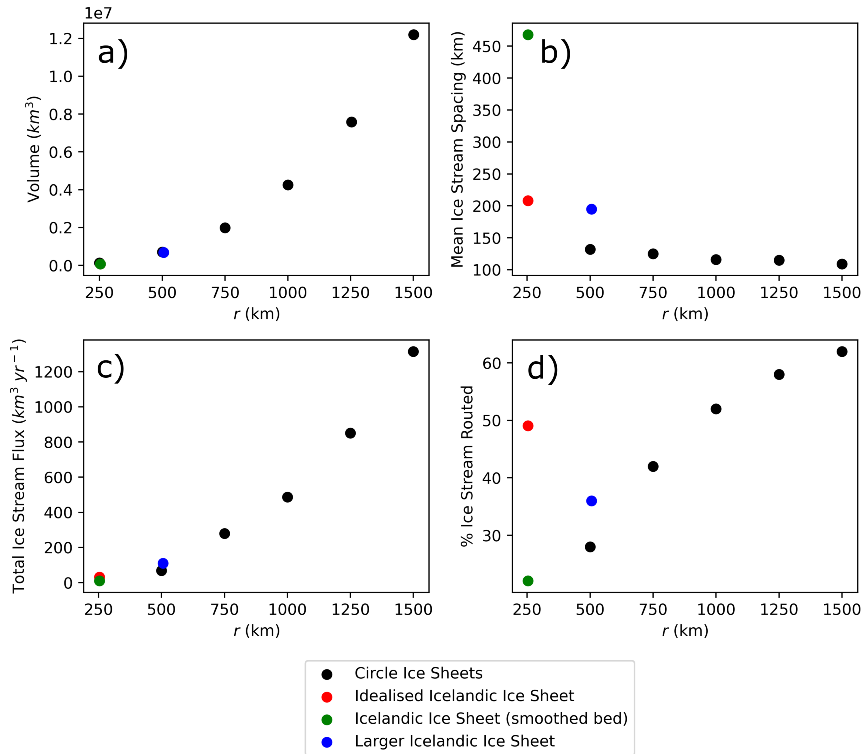

Fig. 2. The scaling of ice streaming with a change in ice sheet radius. a) Ice volume with ice sheet radius, b) Mean Ice Stream frequency (centreline to centreline) with radius, c) Total ice stream flux with radius, and d) the percentage of ice routed though ice streams with radius. Black points show the circular ice sheets (section "Circular Ice Sheets"), red points show the idealised Icelandic Ice Sheet (section "Idealised Icelandic Ice Sheet"), green points show the idealised Icelandic Ice Sheet with smoothed topography (section "Smoothed Topography"), and blue points show a scaled-up Iceland Ice Sheet (section "Appendix A: A Larger Icelandic Ice Sheet").

The increased ice stream frequency, along with an increased flux of individual ice streams causes a non-linear increase in total ice stream flux with increasing radius. When corrected into a percentage of overall ice sheet flux, we find that almost 30% of flux is routed through ice streams in the 500 km radius simulation, increasing to just over 60% of flux in the 1,500 km radius simulation. The rapid increase in the percentage of ice routed through ice streams in the 500 - 1,000 km radius ice sheets increases much less rapidly at 1,250 and 1,500 km.

The simulated model behaviour, broadly in line with empirical evidence (Bennett, 2003; Truffer and Echelmeyer, 2003) (with an ice stream spacing of 10-100s of kilometres, and an ice stream velocity >100 m/y), should increase the confidence in using the BISICLES ice sheet model to simulate ice streams at a variety of scales. Testing of the "leaky bucket" hydrology scheme used the relatively small British-Irish Ice

Sheet (Gandy and others, 2019), but these results suggest sufficient model skill to simulate larger ice sheets such as the Laurentide (Sherriff-Tadano and others, 2022) or Eurasian ice sheet (Patterson and others, 2025, in review).

Idealised Icelandic Ice Sheet

Next, we altered the idealised model set-up to include a realistic bed topography for the Icelandic Ice Sheet. Terrestrial and marine topography is from GEBCO (GEBCO Compilation Group, 2024), with contemporary ice thickness removed (Millan and others, 2022). Through this process a pattern of ice streaming broadly similar to that of the palaeo record is produced (Figure 3), comparing favourably to mapped marine trough locations (Benediktsson and others, 2023). Growing from no ice, ice extends offshore within 5000 years, reaching roughly 220 m water depth at equilibrium extent. The simulated equilibrium extent is broadly in line with empirical (Benediktsson and others, 2023) and numerical reconstructions (Hubbard and others, 2009; Patton and others, 2017). These simulations are not intended to be a realistic reconstruction, but a broadly comparable extent aids with a comparison to the expected location of ice streams. At equilibrium, with 9 formed ice streams, the simulated mean radius of the ice sheet is 250 km, comparable to the smallest circular ice sheet simulated in section "Circular Ice Sheets".

Simulated ice streaming is concentrated in the north, with four ice streams flowing in Húnaflói, Skagafjörður, Eyjafjörður, and Skjálfandi. These ice streams are spaced roughly 40 km apart, much closer than the ice stream spacing in the idealised simulations (Figure 1). The mean spacing is increased by the significant reduction in streaming for the rest of the ice sheet margin, with just five other streams in the remaining 3,000 km of ice sheet margin. Circulating clockwise from Skjálfandi it is 220 km to an ice stream offshore of Vopnafjörður, 350 km to an ice stream offshore of Lónsfjörður, 170 km to an ice stream offshore to Skeiðarársandur, and 185 km to an ice stream crossing Heimaey.

Comparing these results to the idealised circular ice sheets (Figure 1), we can see that by including a realistic bed topography ice streaming is simulated at a radius where it would otherwise not be on a flat bed, 49.07% of ice flux is routed through ice streams in the idealised Icelandic simulation. This is less than the 62.01% of large flat-bedded ice sheets, but much more than the 27.23% simulated with an ice sheet of 500 km radius.

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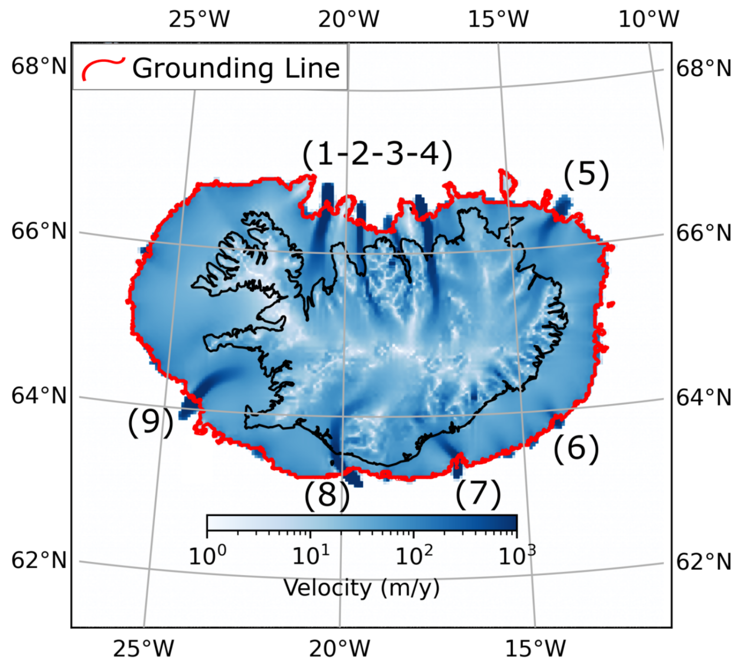

Fig. 3. The resulting equilibrium velocity field for the idealised Icelandic Ice Sheet simulation. Ice stream locations mentioned in the text as labelled; (1) Húnaflói, (2) Skagafjörður, (3) Eyjafjörður, (4) Skjálfandi, (5) Vopnafjörður, (6) Lónsfjörður, (7) Skeiðarársandur, (8) Heimaey, and (9) Faxaflói. The red line shows the Grounding Line.

Smoothed Topography

Next, we completed simulations of the idealised Icelandic Ice Sheet with a smoothed bed topography. These simulations aimed to explore the sensitivity of the ice stream behaviour to changes in topography, and to explore ice stream formation without the control of large marine troughs. Essentially, this is an exploration of a "chicken or egg" style problem. Numerical and empirical evidence suggests the presence of large marine troughs is a significant control on the formation and location of ice streams (Winsborrow and others, 2010; Gandy and others, 2019), but marine troughs primarily form through significant glacial erosion from ice streaming. We ask: what came first, the trough or the stream?

We created a smooth bed DEM which broadly retained the topographic characteristics of Iceland (location of major summits, geometry and shelf) without inferred small scale Quaternary erosional features. To do this we performed an Inverse Distance Weighting interpolation from a coarse point cloud derived from the initial set up and prescribed artificial elevations. We derived this point cloud from 100 local maxima, the current Icelandic coastline, and the shelf location. Of the 100 local maxima 63 were rejected

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for being within 2.5 km of another point. We artificially closed fjord mouths of the contemporary coast line and re-sampled the line at spacing 50 km and prescribing an elevation of 150 m. The boundary of the shelf was prescribed to -130 m above sea level transitioning to -999 over 5 km. Finally to fill the remaining domain the DEM used in the initial experiment was re-sampled to retain a point cloud density of <50 km per point. A key effect of this smoothing was to remove the topographic and bathymetric effect of fjords, though the coastline position is preserved.

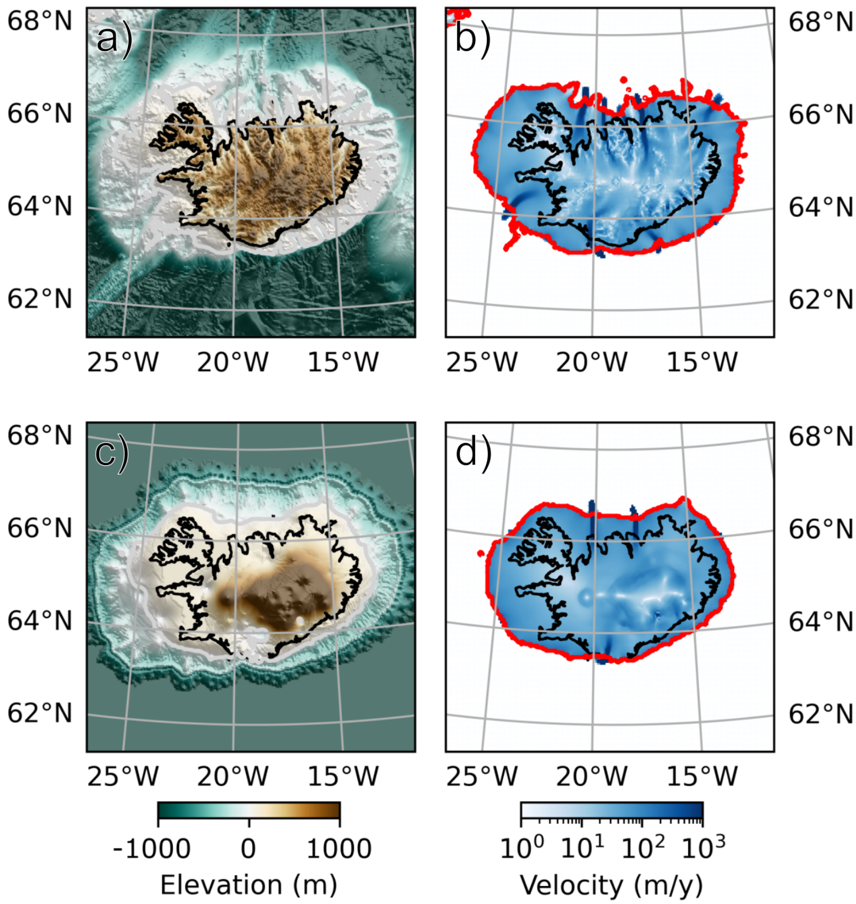

Fig. 4. A comparison of the unadjusted bed topography (a) and resulting equilibrium velocity field (b), with the smoothed topography (c) and resulting equilibrium velocity field (d).

The simulation with smoothed topography shows significantly reduced ice streaming behaviour, most obviously in a reduction in the number of ice streams (Figure 4), but also a 15% reduction in the percentage of ice routed through ice streams. In the smoothed simulation, two ice streams to the north and one to the south remain. These ice streams are broadly (but importantly, not exactly) in the same position as the

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simulation with normal bed topography. The similar position may be controlled by the coastline shape, despite the removal of fjords. The marked reduction in stream number and flux indicates that trough depth exerts a strong influence on streaming, consistent with the hypothesis that erosion amplifies ice stream persistence over multiple glacial cycles.

Total ice stream flux is reduced than eliminated because the bed is only partially smoothed; it is not flat like the initial simulations presented in section “Circular Ice Sheets”. This could be an analogue for topography in a pre-glaciated state, with some topographic variation (i.e. of tectonic and fluvial origin) but no large marine troughs. This situation allows limited but confined ice streaming, which eventually would lead to preferential erosion of ice stream beds, and thus more significant ice streaming. This erosion mechanism is not included in the simulations, but the process has been explored for palaeo simulations of Antarctica (Paxman and others, 2020), with evidence that long term landscape evolution has increased the sensitivity of the Antarctic Ice Sheet over multiple glacial cycles, though primarily through the growth of reverse bed slopes rather than increasing trough depth. This feedback mechanism would suggest that over multiple glacial cycles ice stream total flux will increase, with their positions more likely to be fixed during and between cycles. This behaviour could explain the apparent increase in trough mouth fan sedimentation in north-west Europe from the mid-pleistocene (Vorren and Laberg, 1997), but any influence would be hard to disentangle from the significant climate changes of the mid-pleistocene. Records of trough mouth fan sedimentation rates within the last glacial cycle (rather than across multiple cycles) demonstrate the complexity and sensitivity of this record (Bellwald and others, 2020).

Variable Geothermal Heat flux

To aid comparison between the idealised circular ice sheets and the modelled idealised Icelandic Ice Sheet, the simulations in the previous section rely on the various simplifications highlighted in the methods section, including the spatially uniform geothermal heat flux, a simplification which may be particularly problematic for the Icelandic Ice Sheet given the higher than average background geothermal heat flux, and volcanism. We tested the sensitivity of the results to the realistic geothermal heat flux by repeating the simulations with a heat flux map from Hjartarson (2015). We did not explore the effect of focused very high geothermal heat flux associated with intermittent volcanic activity, which is likely to be a significant factor in Iceland. Again, these results are not intended to act as a reconstruction, but as a test for the sensitivity of the results to altering geothermal heat flux by a realistic magnitude.

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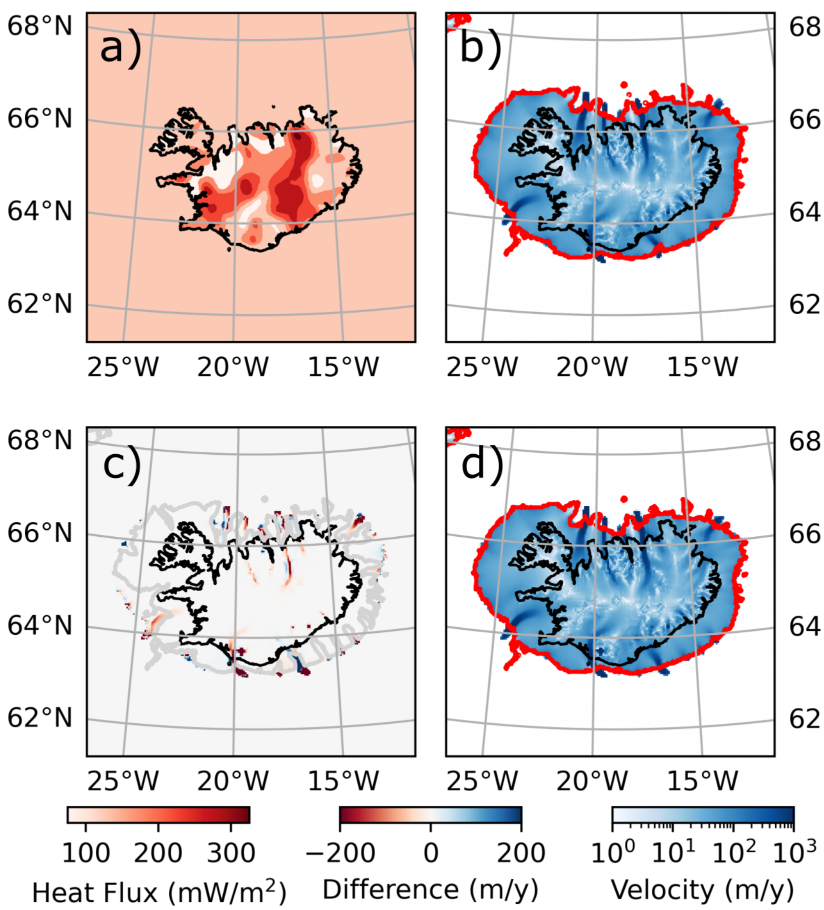

Fig. 5. The spatial variable geothermal heat flux field (a), the equilibrium velocity field with a spatially uniform (b) and spatially variable (d) geothermal heat flux. The velocity difference (b-d) is shown in panel c.

The resulting ice velocity field in a simulation including a spatially variable geothermal heat flux is marginally different from the spatially uniform geothermal heat flux (Figure 5). There are no significant changes in ice stream locations, activation or deactivation of ice stream locations, or a change in overall flux. In the list of factors controlling the location of ice streams (Winsborrow and others, 2010), these results would indicate that a geothermal hotspot is unlikely to be a first-order control upon ice stream formation in this region.

Including spatially variable geothermal heat flux produces negligible changes in ice stream location and activation, consistent with the finding that membrane stresses and frictional heating dominate ice stream initiation (Brinkerhoff and Johnson, 2015). If the inclusion of a spatially variable geothermal heat flux is insignificant to ice stream dynamics in Iceland, a region with very high geothermal heat fluxes, it

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questions the importance of background geothermal heat flux for determining ice stream location. Very high geothermal heat flux during volcanic activity (untested in these simulations) may be required to have a significant ice stream influence. This may have implications for the North East Greenland Ice Stream (NEGIS). The NEGIS is an unusually large ice stream, with no obvious initialisation mechanism, and it has proved to be a challenge to simulate in other modelling studies both with (Goelzer and others, 2018) and without (Aschwanden and others, 2016) the inversion approach. In the absence of a topographic cause, it has been hypothesized that a geothermal hotspot in the ice sheet interior could explain the formation of the ice stream. Smith-Johnsen and others (2020) attempted to simulate the NEGIS by imposing a geothermal hotspot, which could only be maintained with a heat flux of almost 1000 mWm^{-2}. This heat flux is too high to be purely geothermal, and they propose the hotspot could be supplemented by a local hydrothermal circulation. The presence of this hydrothermal circulation has not been observed. Neither a geothermal hot spot of this magnitude, nor a hydrothermal circulation are included in our model set-up. However, given the minimal impact on the pattern of ice streaming that geothermal heat flux has for the Icelandic simulations, our results suggests that geothermal heat flux alone is unlikely to cause the non-standard characteristics of NEGIS.

CONCLUSIONS

Our experiments demonstrate that ice stream frequency and discharge scale non-linearly with ice sheet size, even in the absence of topographic controls. This finding extends earlier work on thermomechanical instability by quantifying how geometric scaling influences streaming and by testing these relationships in a realistic setting. Introducing Icelandic topography shows that bed geometry can override simple scaling, concentrating flux in troughs and reinforcing the feedback between streaming and erosion. Smoothing the bed reduces streaming, highlighting the long-term co-evolution of ice streams and landscape.

These results have implications for modelling future ice sheet evolution. First, the proportion of ice routed through streams increases as ice sheets grow, meaning that dynamic changes in streaming must be considered in millennial-scale projections. Second, inversion-based models tuned to present-day conditions may misrepresent future behaviour if they neglect evolving basal hydrology and topography. Finally, these simple scaling relationships could guide simplified representations of ice stream flux in coarse-resolution or long-timescale models, reducing reliance on inversion methods that assume static basal conditions.

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AUTHOR CONTRIBUTIONS

NG: Conceptualization, Methodology, Investigation, Visualization, Writing - original draft. RV: Investigation, Writing - review and editing. JE: Conceptualization, Writing - review and editing. RS: Investigation, Writing - review and editing. MS: Conceptualization, Writing - review and editing.

DATA AVAILABILITY

Gandy, Niall (2025), "Data for "Scaling of Ice Stream Spacing and Flux from Numerical Simulation"", Mendeley Data, V1, doi: 10.17632/n9hf9hfzm5.1

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APPENDIX A: A LARGER ICELANDIC ICE SHEET

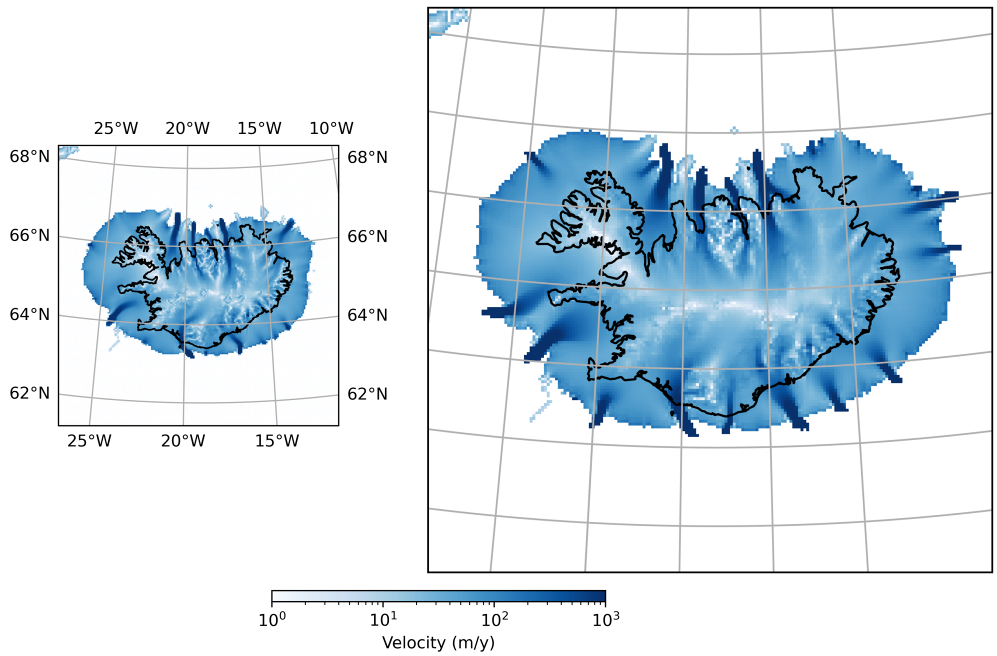

Fig. 6. The equilibrium velocity field for an Icelandic Ice Sheet (left) compared to a simulation where the domain has been rescaled by a factor of 2 (right).

We re-ran the idealised Icelandic Ice Sheet simulations rescaled by a factor of 2; doubling the x and y-axis length and maintaining the 4 km horizontal resolution, hence quadrupling the domain area. This simulation explored the ice stream response to simulating a larger ice sheet on similar topography. We emphasise “similar”, and not “identical”, because the rescaling means are wider and longer topographic features in the larger simulation.

The rescaling results in an ice sheet with a greater number of ice streams, and a 5.2% increase in the percentage of flex routed through ice streams. This is expected from the idealised simulations with presented in Figure 1. Most ice streams remain in the same position, with new additional ice streams forming in the larger case. An exception to this is in the east of the domain, where the Vopnafjörður does not form in the large simulation, and is replaced by two additional ice streams further east.

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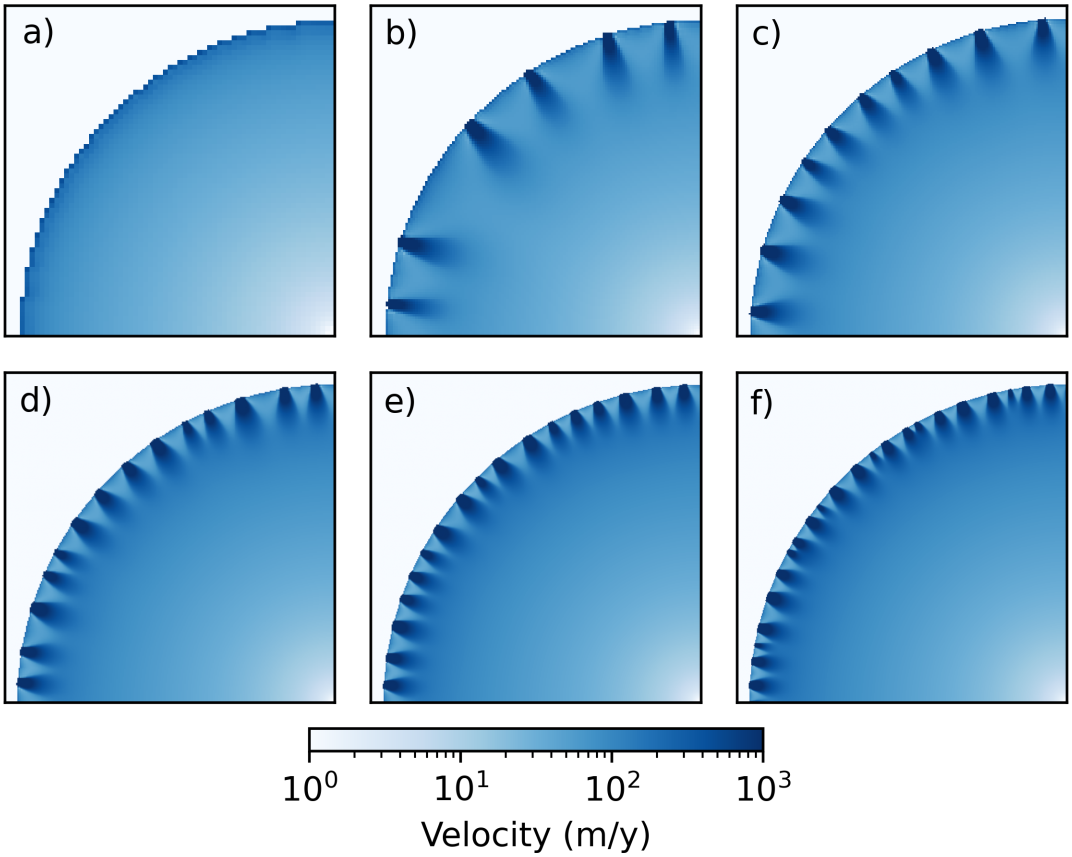

Fig. 7. The equilibrium velocity fields of the idealised ice sheets, as in Figure 1. Here we just show the upper-left quadrant of each ice sheet to allow a more detailed view of the ice stream structure. a) The 250 km radius simulation, b) The 500 km radius simulation, c) The 750 km radius simulation, d) The 1000 km radius simulation, e) The 1250 km radius simulation, and f) The 1500 km radius simulation. For a closer view, details of accessing the output files can be found the the Data Accessibility section.

APPENDIX B: QUARTER-ICE SHEET FIGURES

APPENDIX C: RESOLUTION DEPENDENCE

To test the resolution dependence of the results simulated the 250 km and 1000 km radius simulations with use of the BISICLES mesh refinement scheme, from 0 levels of refinement (4 km horizontal resolution), down to 3 levels of refinement (500 m horizontal resolution). These simulations tested for the possibility of resolution dependency, both in the position and magnitude of ice streaming, and in the lack of ice stream

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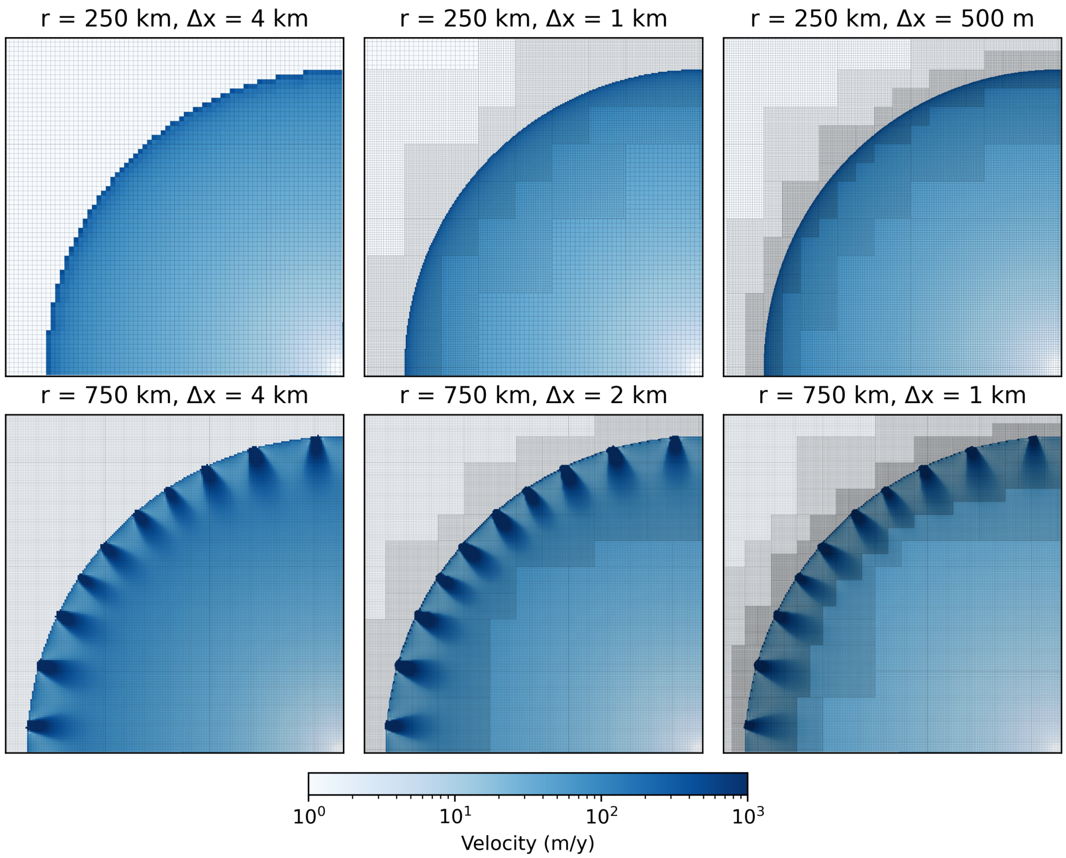

Fig. 8. Top row: A section of the 250 km radius simulation with no mesh refinement (Δx = 4 km), 2 levels of mesh refinement (Δx x = 1 km), and 3 levels of mesh refinement (Δx = 500 m). Bottom row: A section of the 750 km radius simulation with no mesh refinement (Δx = 4 km), 1 level of mesh refinement (Δx x = 2 km), and 2 levels of mesh refinement (Δx = 1 km).

formation in the 250 km radius case. Previous sensitivity experiments in Gandy and others (2019) showed horizontal resolutions finer than 5 km eliminated resolution dependency on a flat domain, and these new sensitivity experiments support that with a different boundary condition case.

APPENDIX D: SPIN-UP ANIMATIONS

Animations for the spin-up of each experiment are provided in the attached file ice_stream_radius_animations.zip.

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APPENDIX D: ICE MARGIN TRANSECTS

APPENDIX E: INTERNAL ICE TEMPERATURE

APPENDIX F: TRANSECT OF VELOCITY

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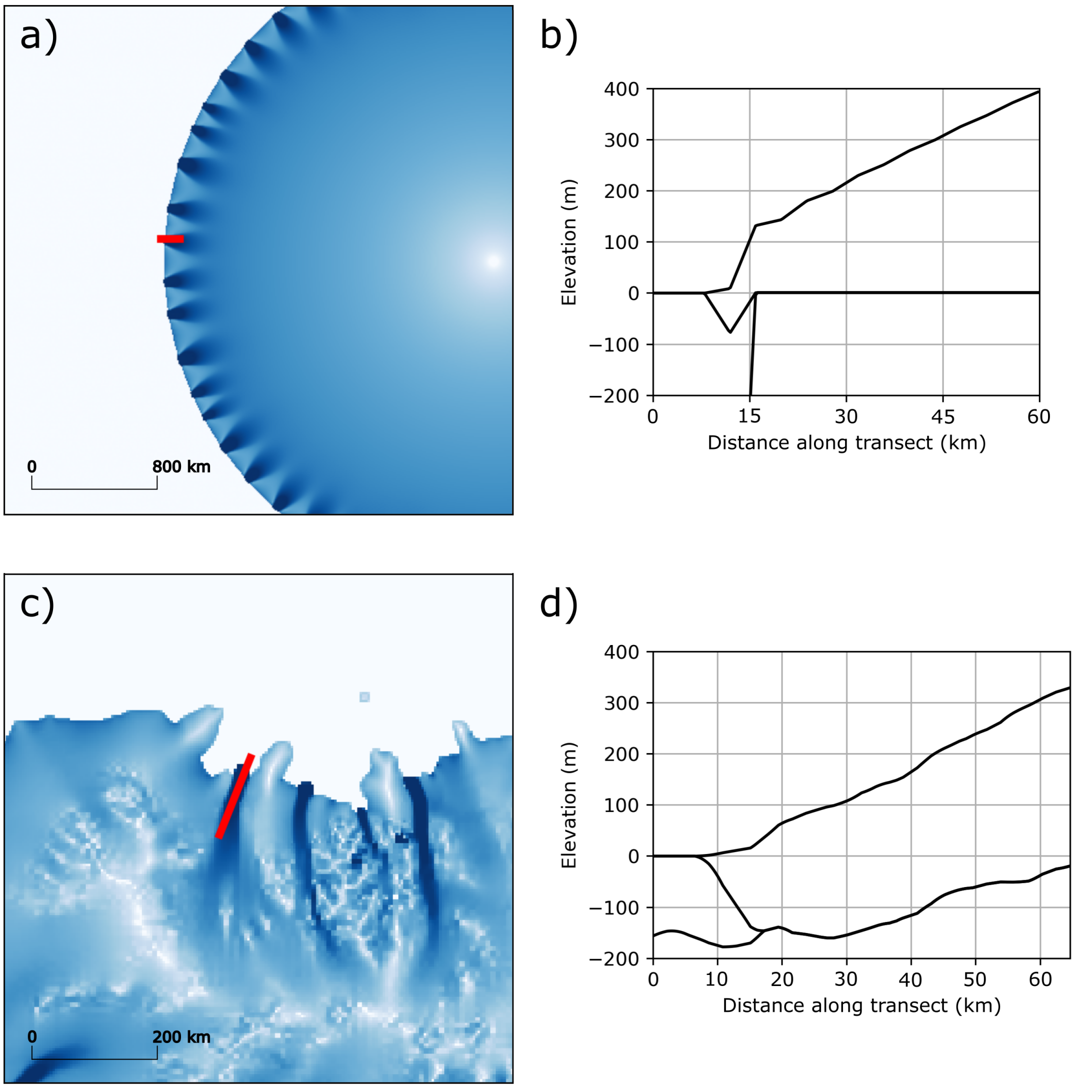

Fig. 9. a) A subset view of the 1000 km radius simulated ice velocity, with the transect location shown in red. b) The ice sheet surface, base, and bed along the red transect line shown in panel a. c) A subset view of the Icelandic Ice Ice Sheet simulated ice velocity, with the transect location shown in red. d) The ice sheet surface, base, and bed along the red transect line shown in panel c.

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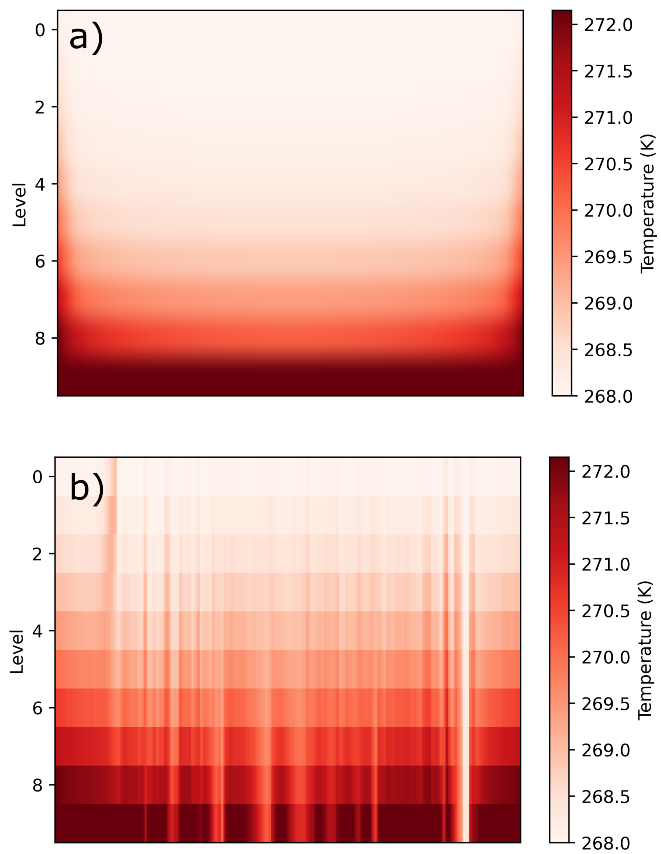

Fig. 10. The internal temperature of the 1250 km radius simulation (a) and the Icelandic Ice Sheet Simulation (b). Both plots are longitudinal slices through the ice sheets at maximum width. The y-axis is projected on levels (rather than absolute elevation), going from the surface (level 0) to the base (level 9).

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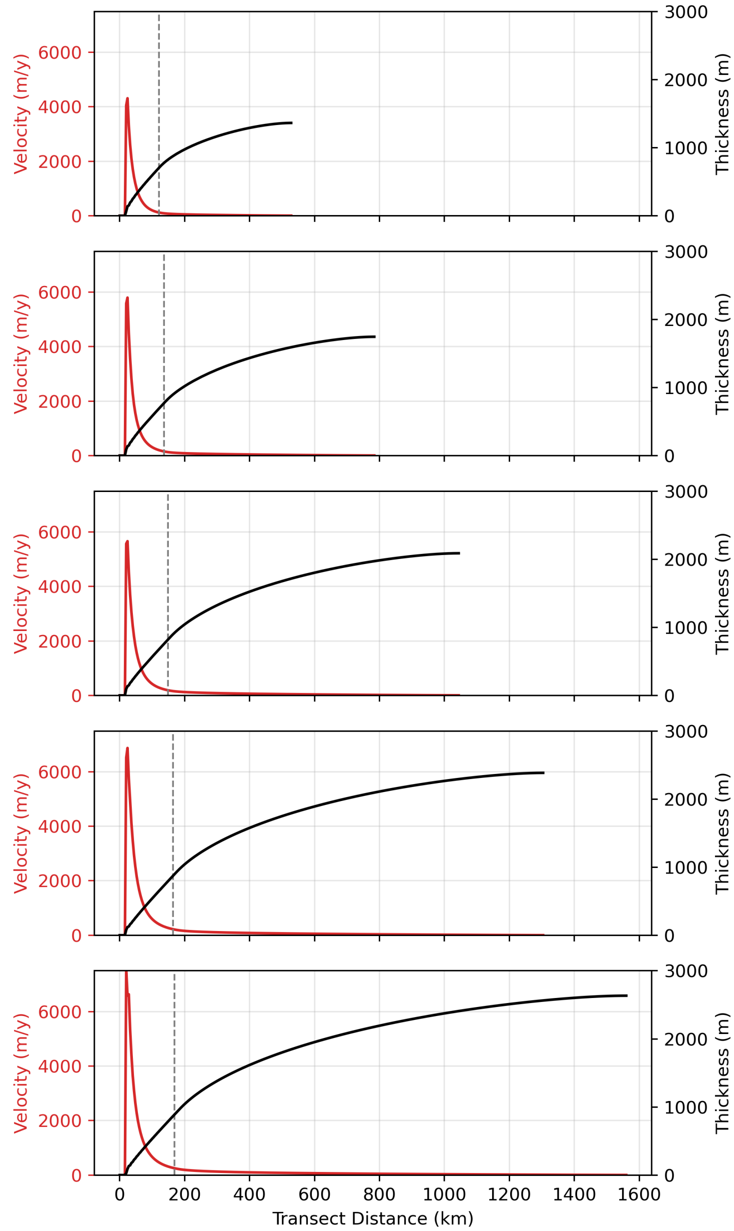

Fig. 11. Transects of velocity (red) and thickness (black) for the 500, 750, 1000, 1250, and 1500 km radius simulations. The dashed grey line indicates the point where the ice velocity increases by more than 10 m/y gridbox to gridbox along the transect. This point moves back by 8-16 km per 250 km increase in the ice sheet radius, and is coincident with a break in slope of the ice sheet surface.

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