Deriving a Physically-Based Calving Rate Law for Marine Ice-Cliff Instability

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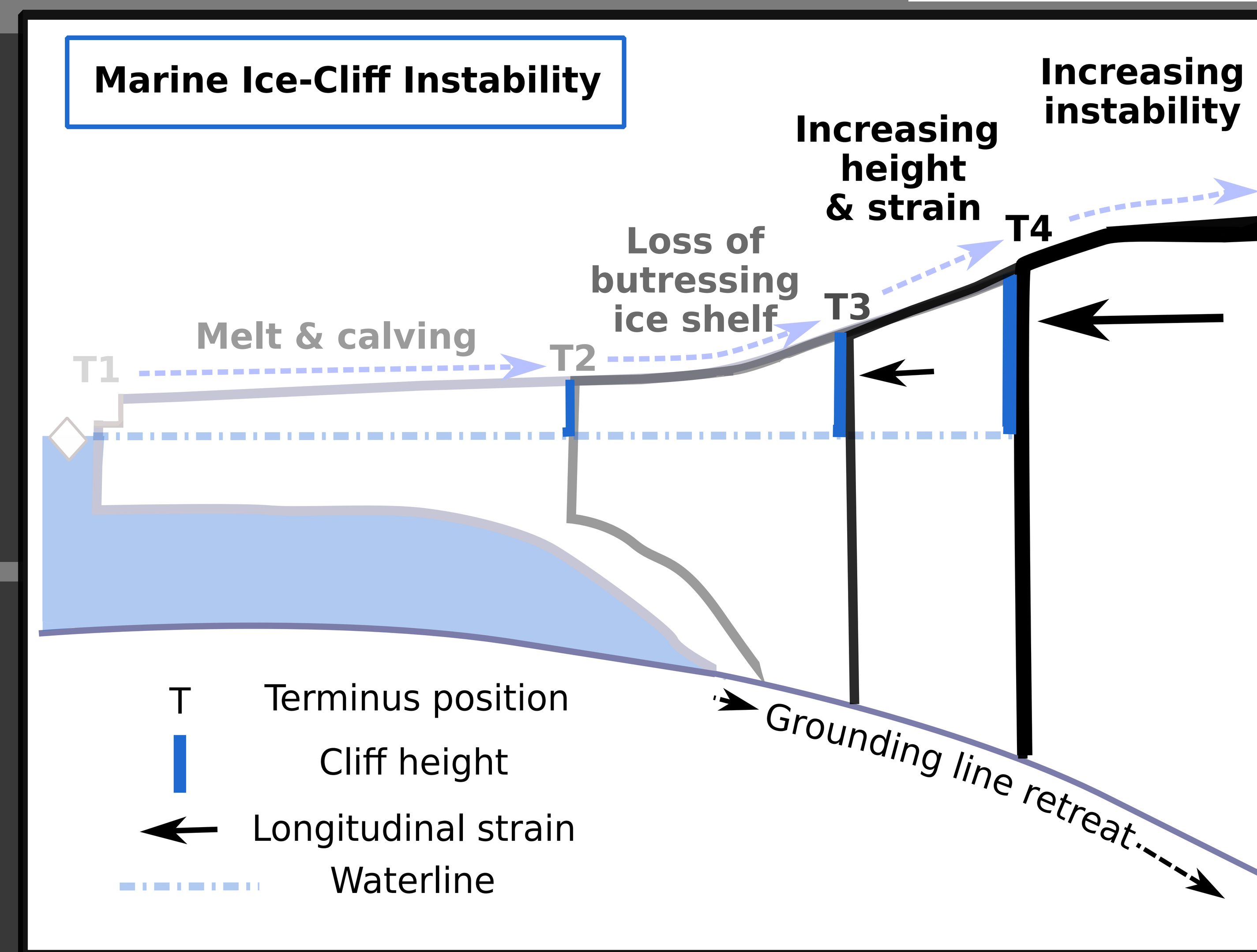
Background

Marine Ice-Cliff Instability (MICI) is a mechanism through which marine-based ice sheets may undergo rapid collapse. The finite strength of ice limits ice cliff height, and MICI could initiate when calving cliffs of sufficient height are exposed. If situated over a retrograde slope, retreat will accelerate as increasingly tall and unstable cliffs are formed. MICI will invoke ice front behaviours beyond the current range of observations; therefore, large uncertainties remain in the rate of future ice loss from vulnerable locations (e.g., Thwaites Glacier).



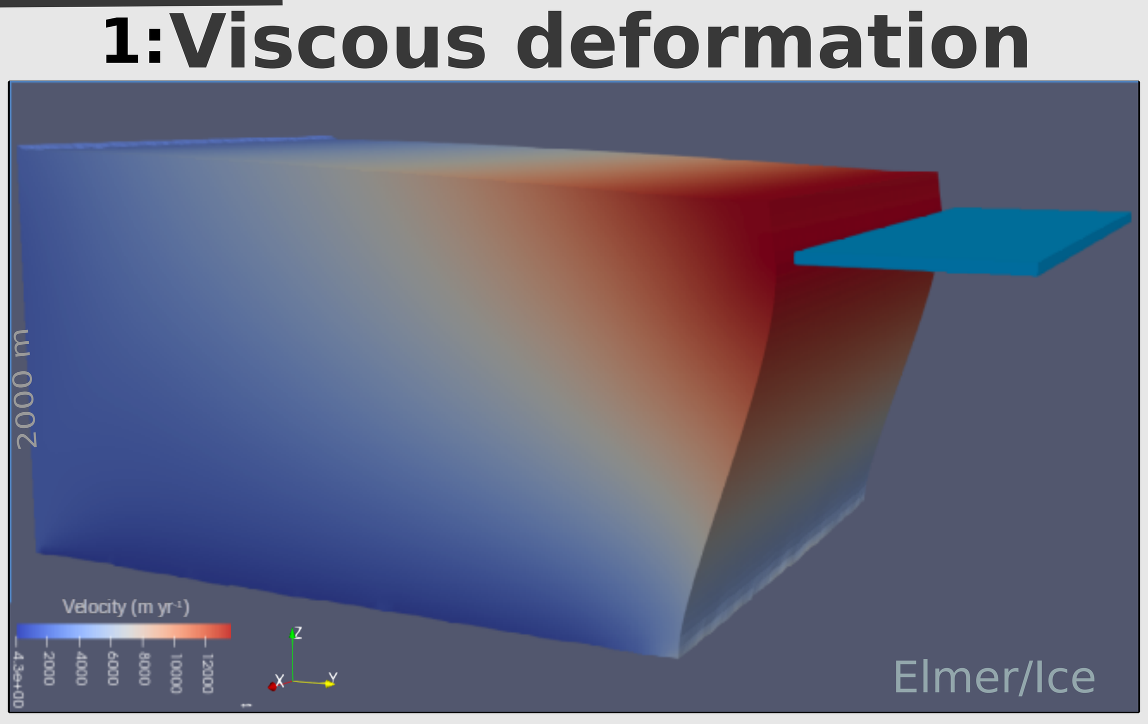
Objectives & Approach

We use three high-fidelity glacier models to shed light on the mechanics of MICI and provide the basis for a physically-based MICI calving rate law.

Our model suite includes the full-Stokes continuum model, ELMER/Ice, and two versions of the Helsinki Discrete Element Model (HiDEM): the standard brittle-elastic implementation (HiDEM-be) and an intermediate, brittle visco-elastic implementation (HiDEM-ve).

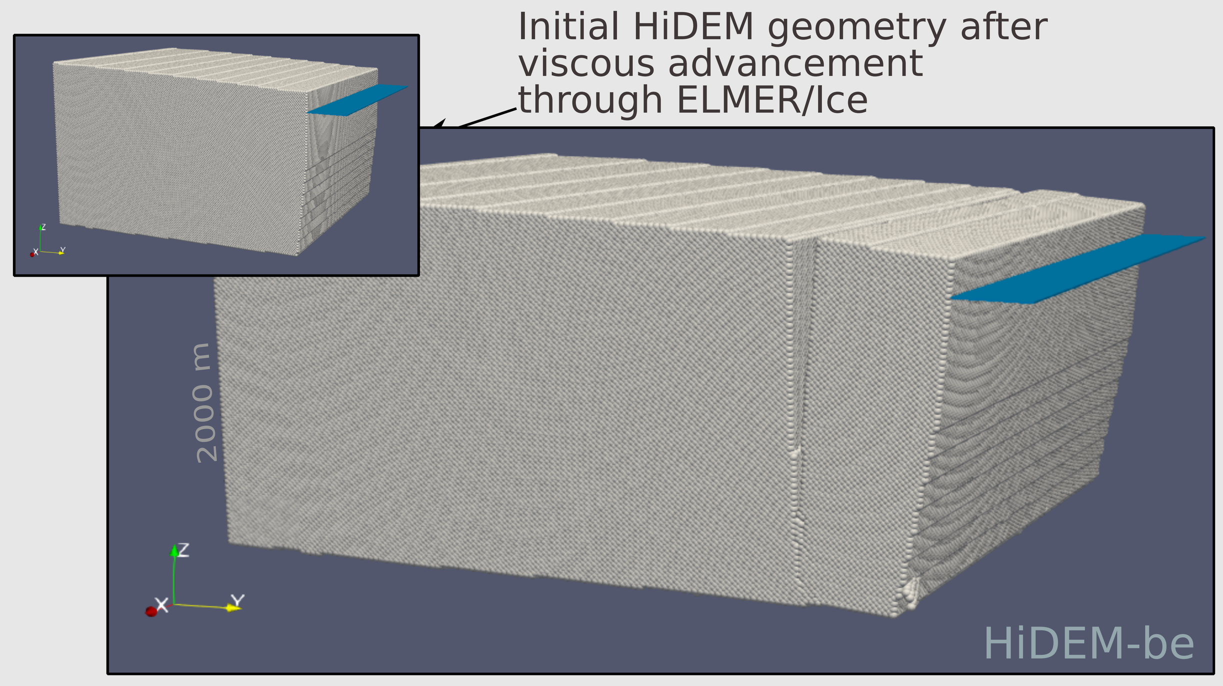
Results

1: Viscous deformation



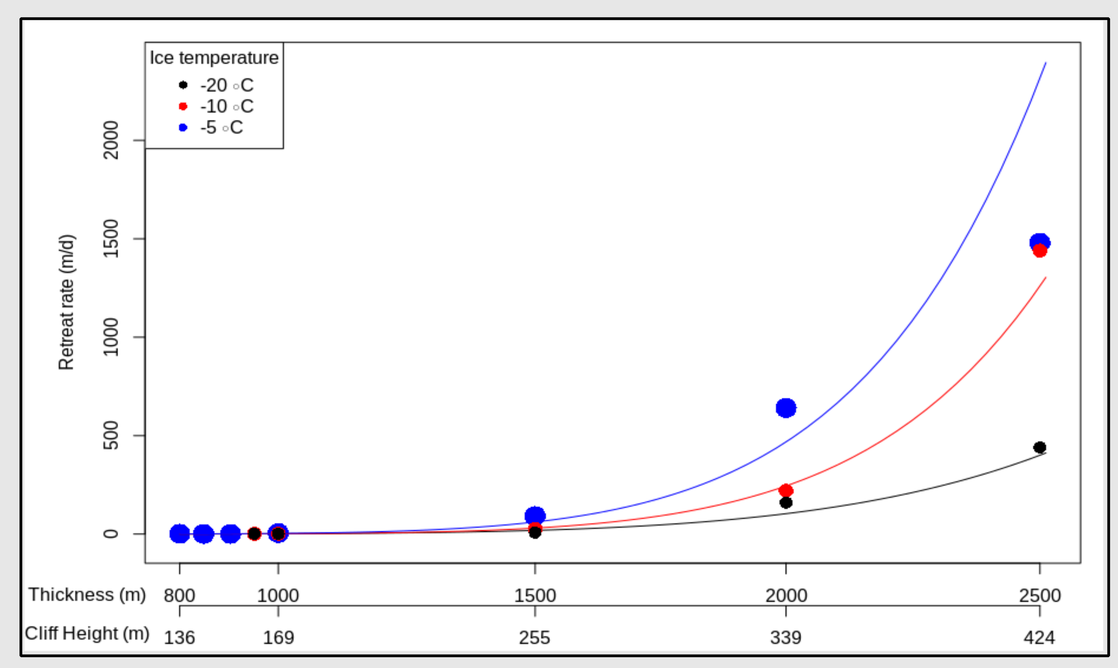
The progression of deformation is consistent with previous modelling studies (Hanson and Hook, 2003). Thinning occurs via cliff advance & surface lowering, and bulging is observed at the waterline where stress concentrates.

2: Brittle failure following viscous deformation



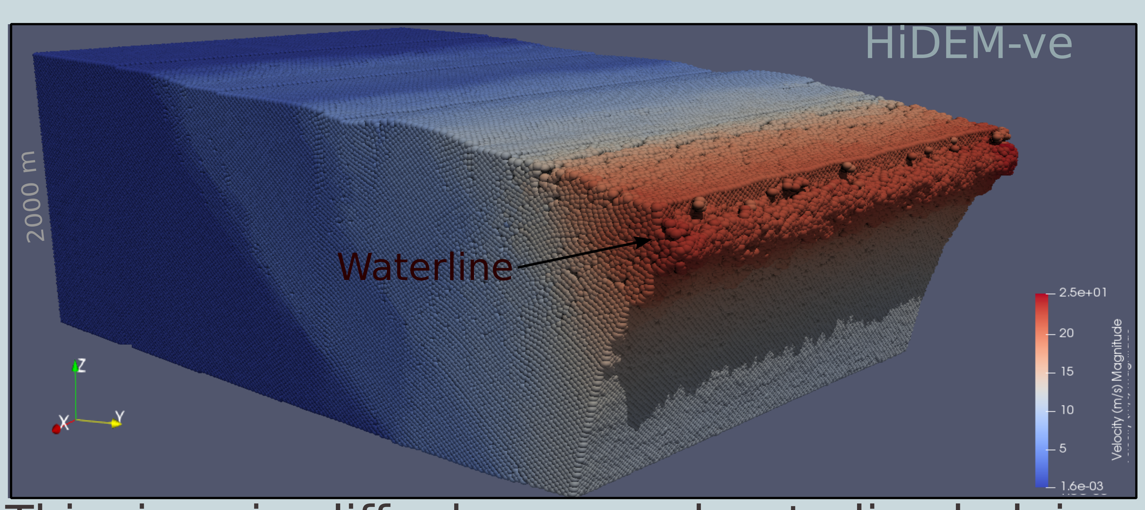
Surface crevassing results from tensile stresses imposed by the developed overhang, causing full-thickness calving of the terminus.

3: Retreat rates

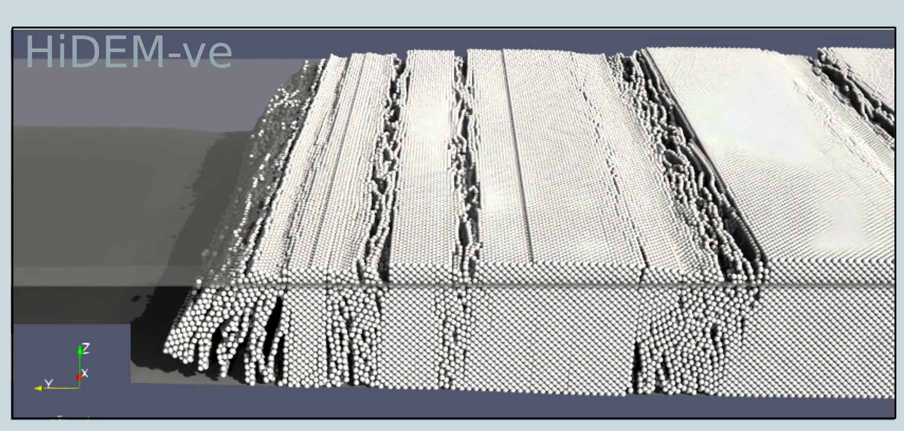


Retreat rates, derived with the consideration of viscous deformation and brittle failure, follow a power-law relationship with cliff height. Retreat rates quicken with warmer ice temperatures.

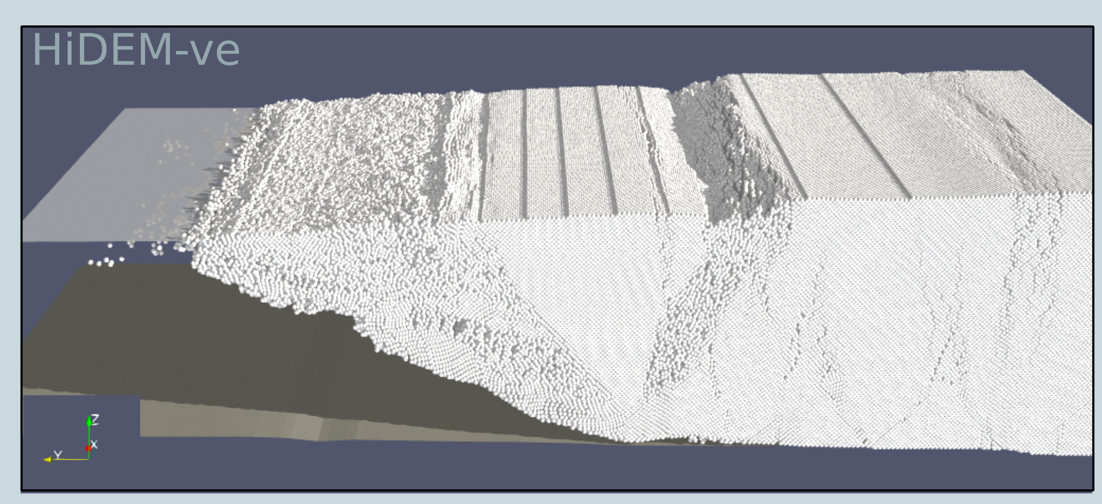
4: Visco-elastic interaction



Thinning via cliff advance and waterline bulging occur in HiDEM-ve simulations. Shear band formation contributes to slumping & buoyant uplift, similar to observations at Helheim Glacier (Parizek et al., 2019).



When sliding is induced, HiDEM-ve simulations show vertical crevassing and calving via block rotation.



As calving fronts become deeper, shear band formation and surface slumping become influential in the MICI-collapse process over a range of basal friction conditions.

5: Further points

- Increasing ice temperature hastens collapse by accelerating overhang development in Elmer/Ice.
- Increasing the waterline to buoyancy while maintaing a static terminus thickness effectively decreases sub-aerial cliff height and elongates a cliff's 'time to failure' (TtF) in HiDEM-be. Basal fractures do not penetrate the full ice thickness, impeding calving via block rotation.
- Increasing the bed friction assigned in Elmer/Ice decreases TtF, as the critical forward lean angle of the overhanging cliff is reached more rapidly.
- The release of kinetic energy, used as a measure of MICI calving amplitude for sliding glaciers in HiDEM-ve, exponentially increases with the thickness of a glacier terminus.
- Test case simulations show that mélange can stymie MICI collapse if sufficient backforce is applied to the calving front.

Key Conclusions & Next Steps

We find that: viscous deformation preconditions a glacier for MICI-collapse by imposing tensile stresses through the development of a cliff overhang; the increase in calving rate with cliff height can be represented by a power-law function; shear band formation is an important process in which unstable ice cliffs deform, becoming an increasingly dominant process with decreasing basal friction and increasing cliff height; and our presented retreat rates are conservative, as they do not consider the role of shear band formation in MICI collapse.

This work will provide the basis for a MICI calving rate law that considers the roles of both viscous and brittle processes as well as conditional time to failure. It will inform forthcoming Thwaites Glacier investigations conducted under the ITGC DOMINOS project. We note that, with ~5 km of further retreat, portions of this glacier's calving front will be at MICI-susceptible ice thicknesses.

References & Resources

Hanson & Hooke. 2003 J Glaciol 49(169):577-586
Parizek et al. 2013 JGR: Earth Surf 118: 638-655
thwaitesglacier.org/projects/DOMINOS
standrewsglaciology.org

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Support

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