A Physical Model of Moulin Formation and Evolution

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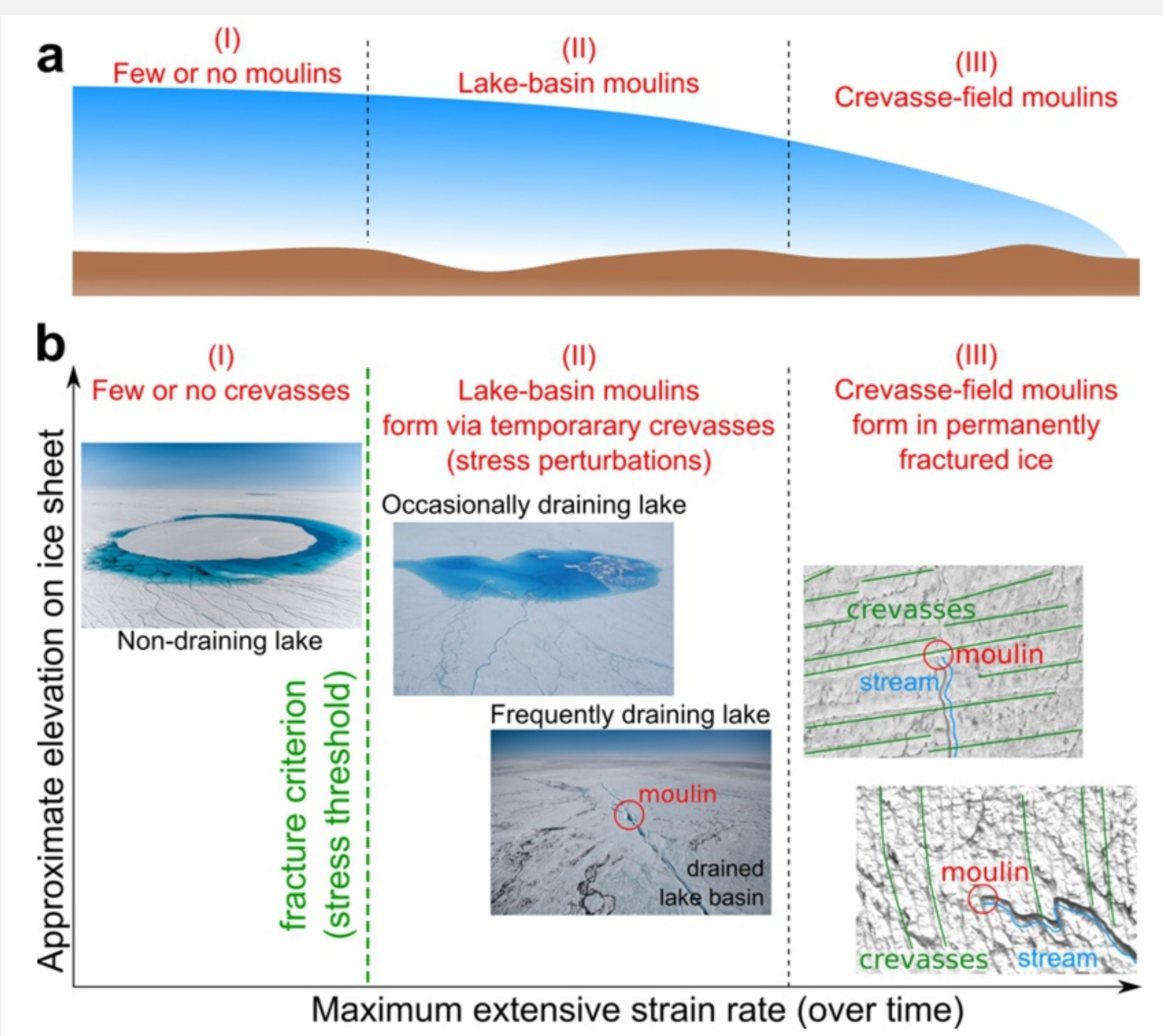
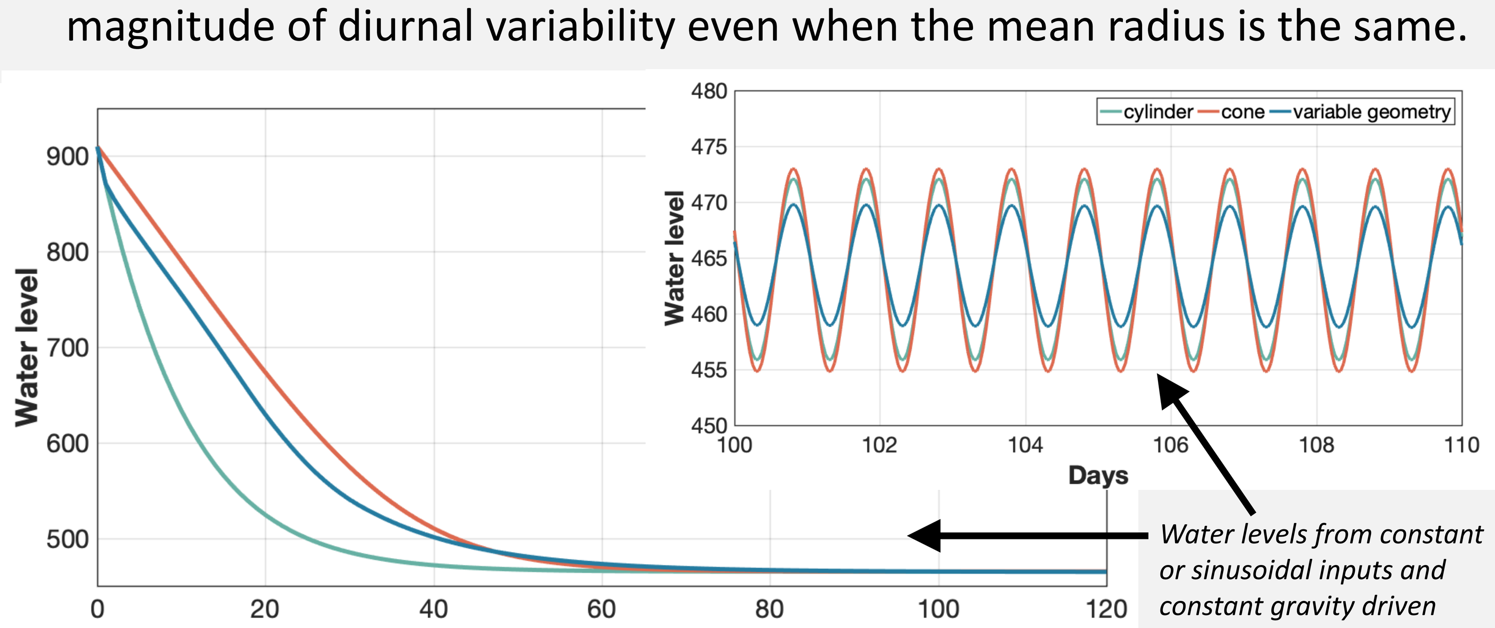
1. Moulin formation & subglacial processes

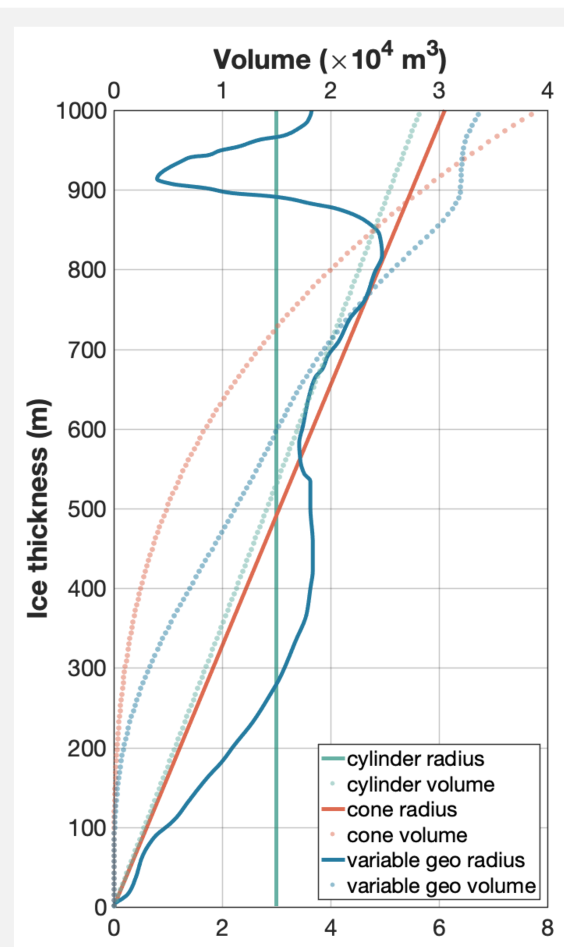
- In many cases, nearly all supraglacial melt is routed englacially via moulins and crevasses.
- Crevasse and moulin formation is dependent on persistent (crevasses) or transient (moulin initiation) stresses which result in surface-to-bed hydrofracture (e.g., Hoffman et al., 2018; Christoffersen et al., 2018).
- Understanding the conditions, including both the transient stress state and the surface runoff flux, needed to form and maintain a moulin are an important component to developing a stochastic model for englacial connections.
- **Constraints on moulin formation and density are valuable for understanding the behavior of both future and past ice sheets, including the interpretation of geomorphological features.**



2. Does moulin geometry matter?

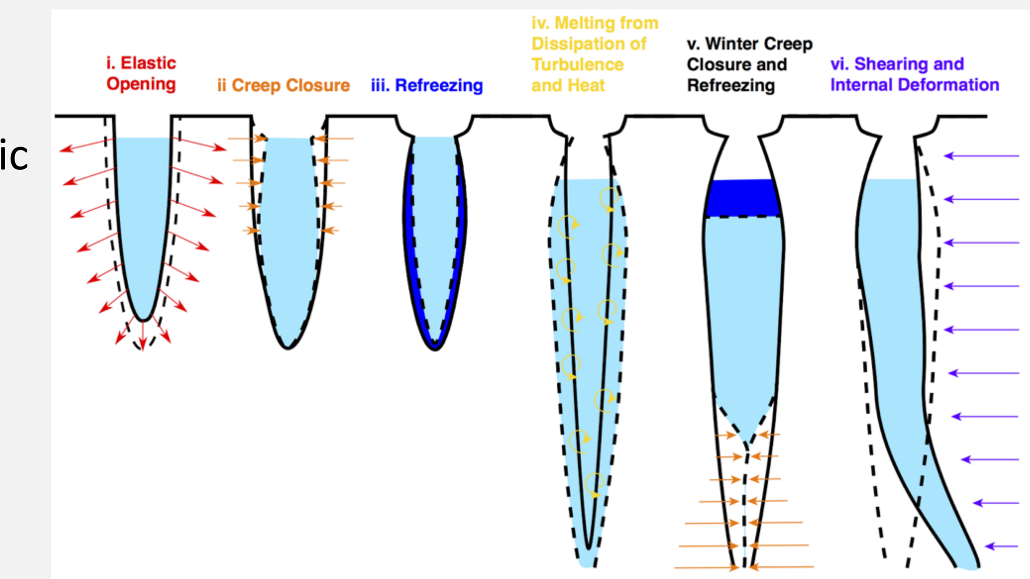
- Moulin may reasonably compose ~10% of the englacial-subglacial hydrologic system and are likely larger than subglacial conduits.
- Moulin shape can alter the equilibrium response time and modify the magnitude of diurnal variability even when the mean radius is the same.





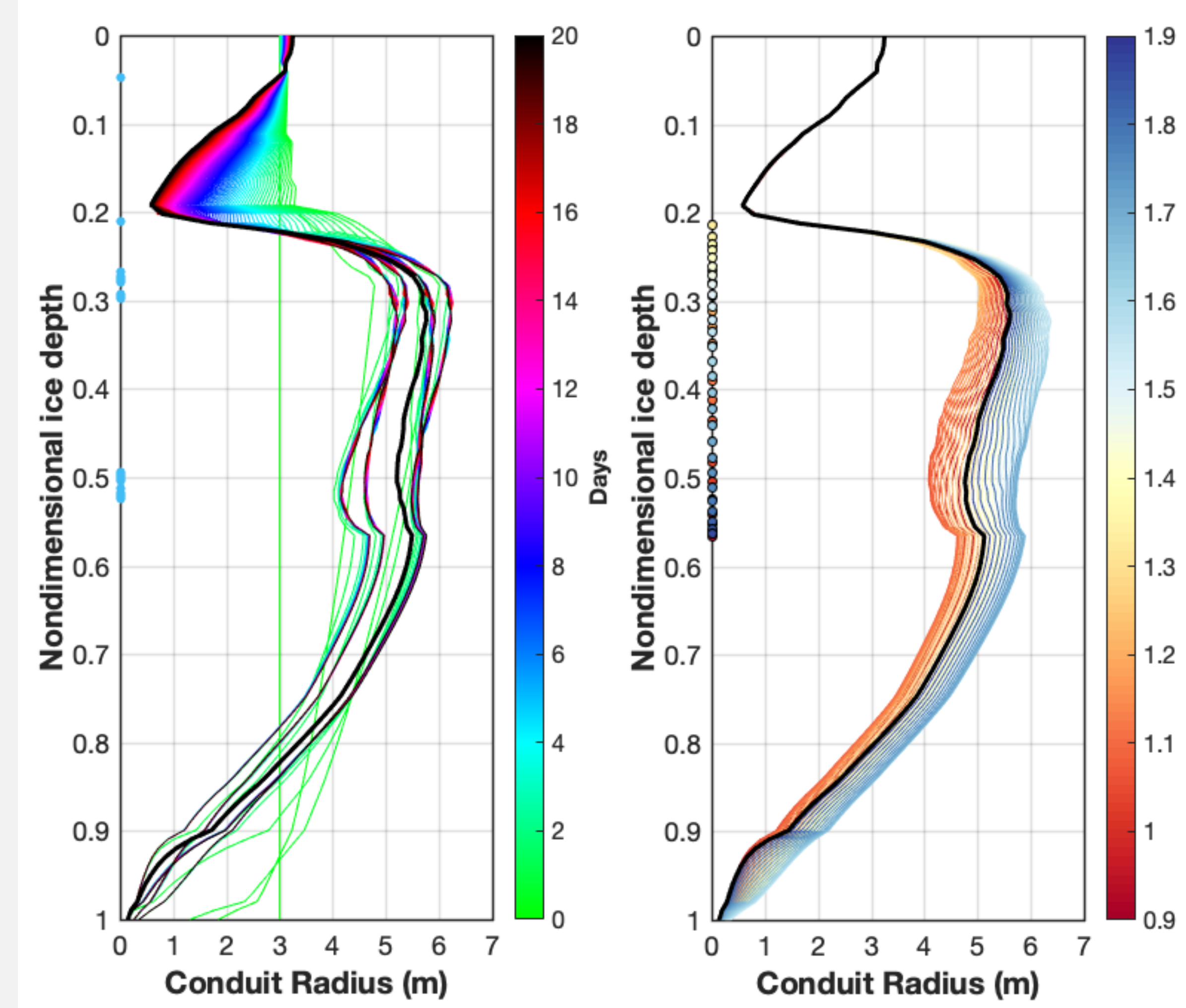
3. Developing moulin geometry

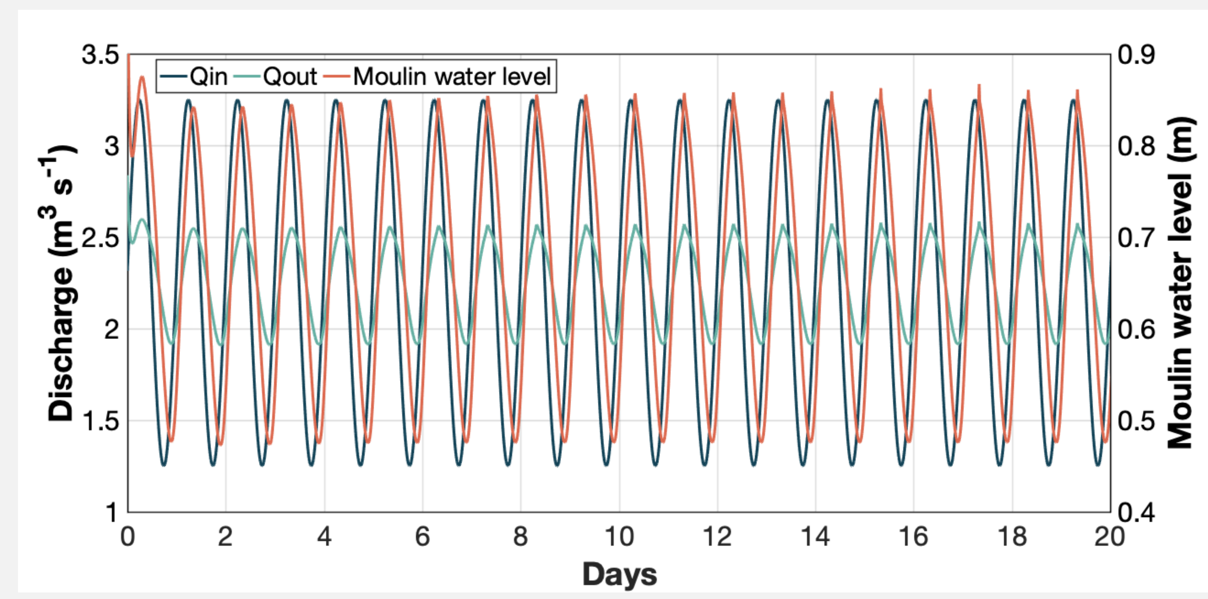
- Moulins persist over months or years when elastic opening and melting due to the dissipation of turbulent and heat energy are equivalent or exceed creep closure and refreezing.
- Geometries become more complex over time, potentially impacting the discharge-pressure relationship in individual moulins.



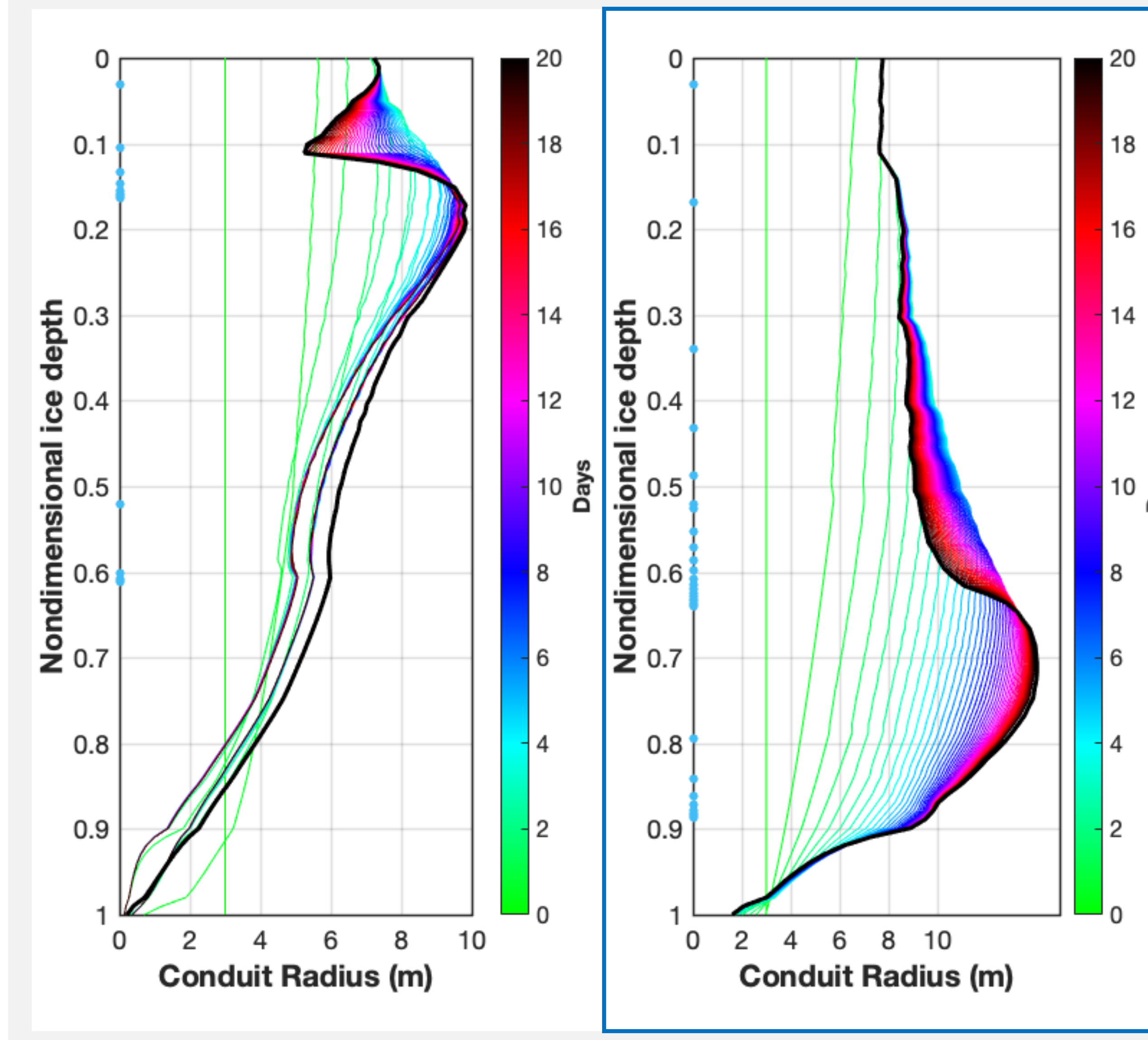
4. Turbulent melting & creep closure

- Creep closure equations are modified from borehole observations from Blinov and Dmitriev (1987) and Salamatin et al (1998) with modifications from Talalay and Hooke (2007).
- Dissipation of turbulent energy and associated ice melting are modified from Spring and Hutter (1981, 1982) and Clarke (2003). Results also include a simplistic, non-conservative treatment of water temperature evolution (see next section).
- Discharge from the moulin is driven by subglacial channel geometry and hydraulic gradient.
- Diurnal variations in melt input result in substantial moulin geometry evolution.





5. Thermal & elastic considerations

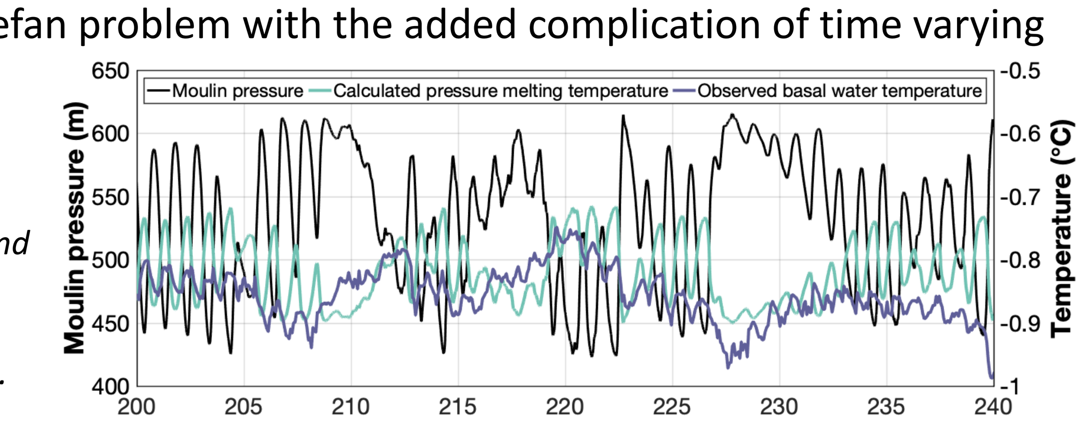


Issue: Realistic ice and meltwater discharge characteristics, but potentially unrealistic geometries and water levels.

Solution: Conservation of heat: explicit representation of ice and water temperatures and an evolving phase boundary.

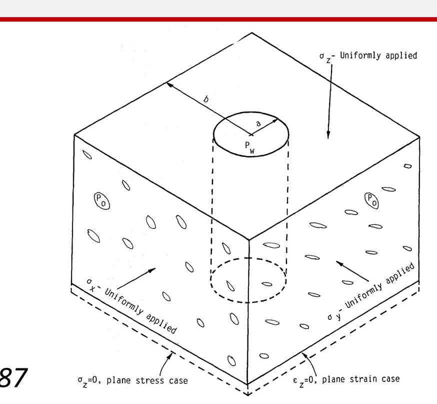
- Warming of the surrounding ice and the evolution of moulin geometry is a classical Stefan problem with the added complication of time varying presence of water.

Moulin pressure and basal water temp. observed in Greenland in 2012.



Solution: Include elastic ice deformation.

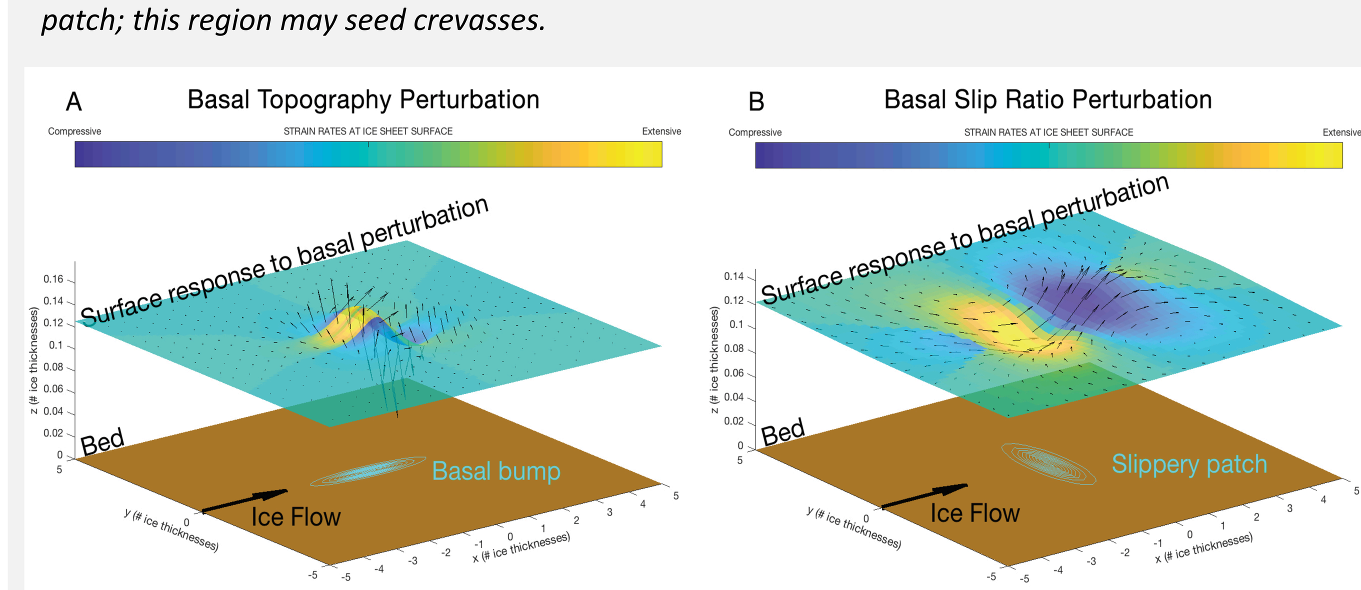
- Crevasse opening and large diurnal swings in water pressure suggest elastic deformation may be an important part of moulin geometry, particularly in stiff ice.

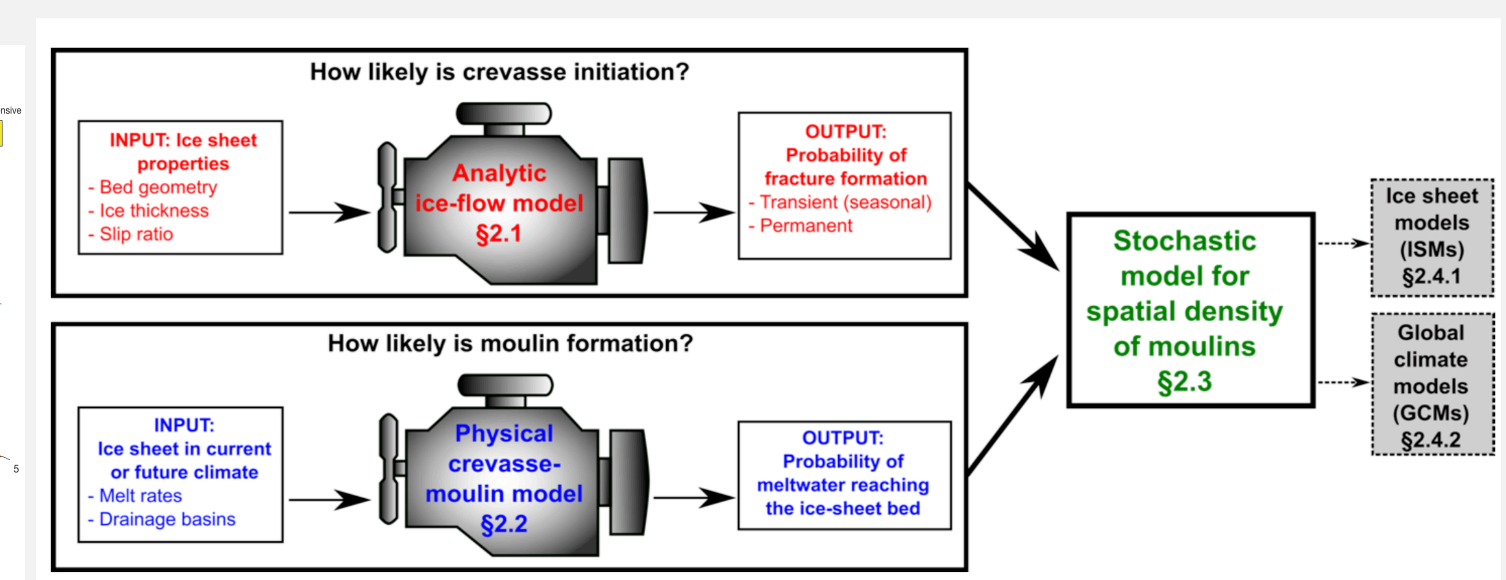


Aadnøy, 1987

6. Linking physics & stochastic behavior

Illustration of the analytic model for the ice-sheet surface response (top surface) to a basal slipperiness perturbation. Ice flow is from left to right. Ice flow is extensive upstream of the slippery patch; this region may seed crevasses.





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