Modelling meltwater delivery to the ice-bed interface through fractures at the margin of the Greenland Ice Sheet

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Rationale

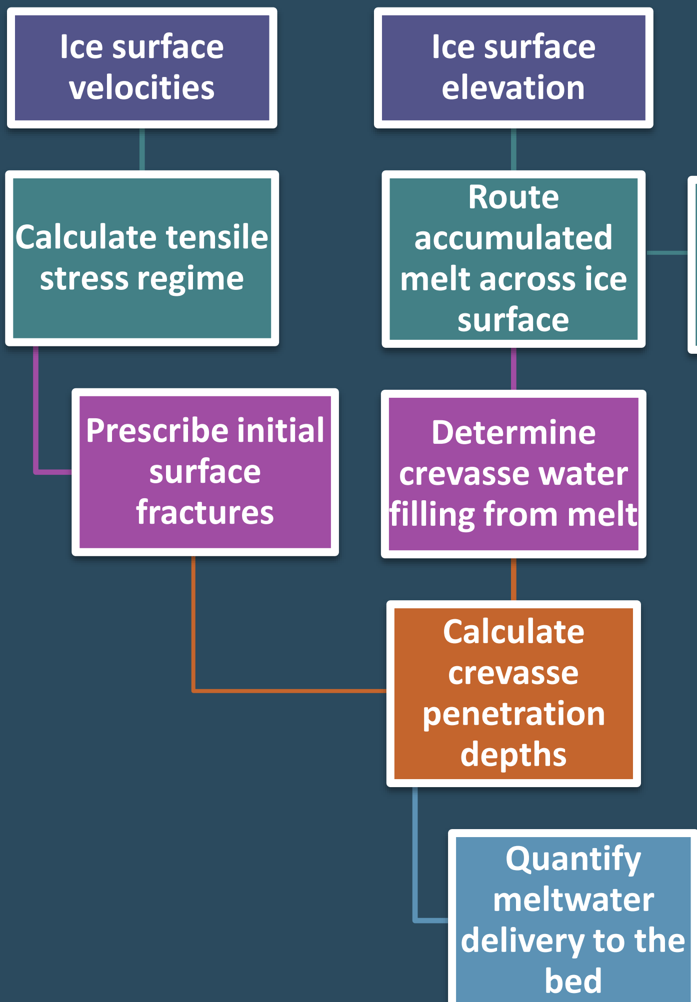
- Meltwater-driven fracture believed to be a key mechanism contributing to glacier dynamic response (Alley et al, 2005; Das et al, 2008).

- Recent data suggest a trend in rising air temperatures and melt rates across much of the Greenland Ice Sheet (Box et al, 2010) twinned with increased mass loss.

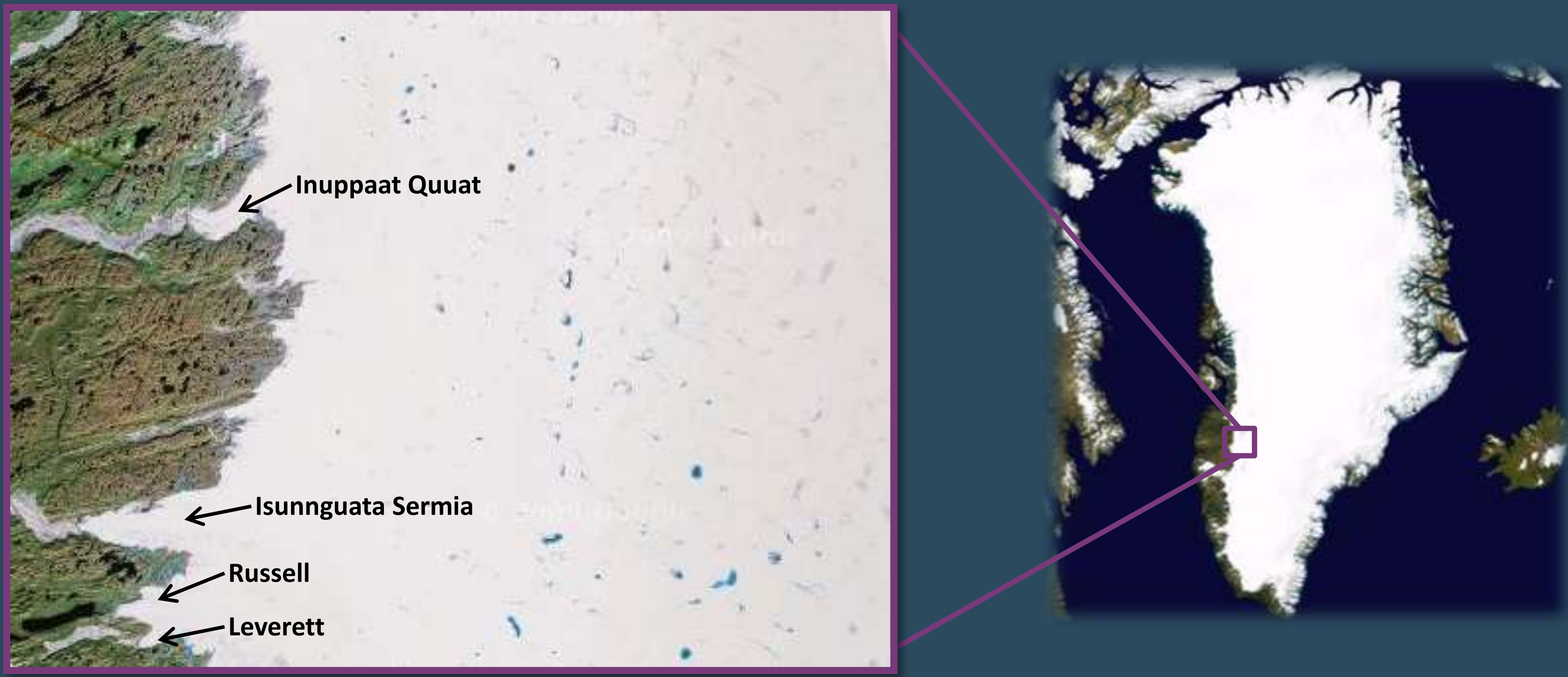
- Thus, **it is timely that transfer of meltwater to the ice-bed interface is modelled** such that models of hydrology and dynamics may be better coupled.

Research aim

“To produce a predictive modelling routine for the delivery of supraglacial meltwater to the ice-bed interface”

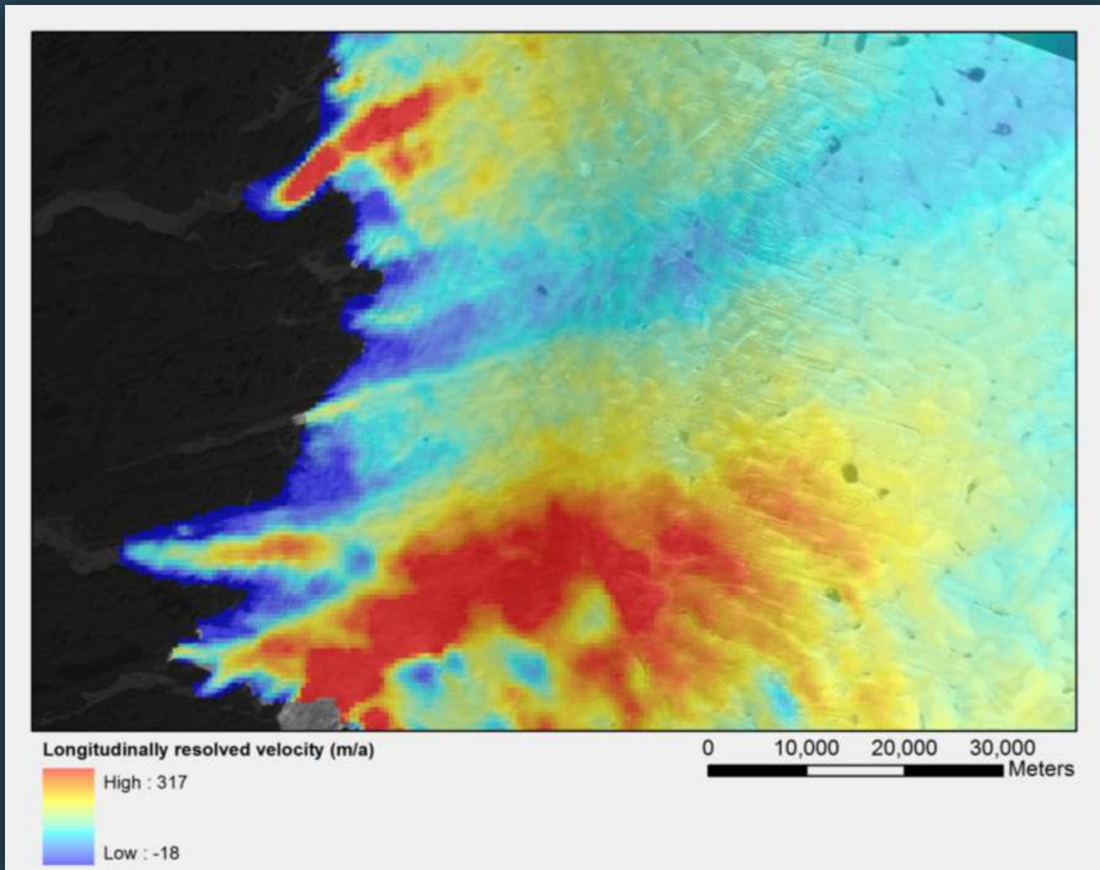


Study site



- We focus on a land-terminating region of the SW Greenland Ice Sheet around 67°N, which encompasses an ice-covered area of around c.8300 km^2. The region extends to 1750 m a.s.l. and around 100 km inland of the ice margin.

Methods: Ice surface velocity → stress



- Study used ice surface velocities from a multi-year composite InSAR dataset (Joughin et al, 2010).
- Velocities resolved into longitudinal and transverse components and subsequently used to derive xx, yy and shear component ice surface strain rates.
- Strain rates converted to stresses following the constitutive relation (Nye, 1957), where *B* is a viscosity parameter, and *n* is 3:

$$\sigma'_{ij} = B\,\dot{\varepsilon}^{(1-n)/n}\,\dot{\varepsilon}_{ij}$$

Ice surface tensile stress regime

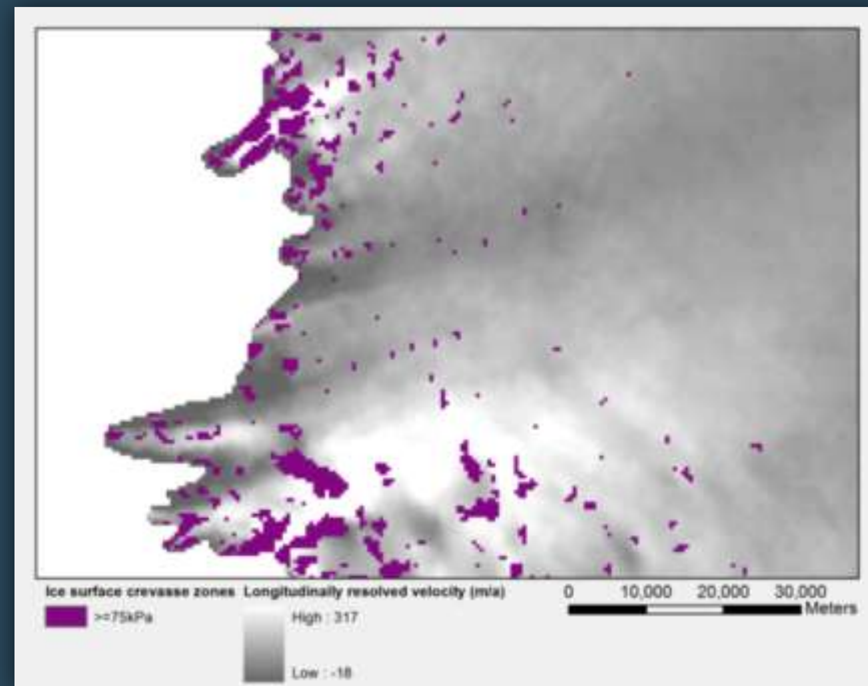
- Surface tensile stresses, σ_t, were determined from principal stresses, σ_1 and σ_3, using the Von Mises criteria for failure of ductile materials after Vaughan (1993):

$$\sigma_t^2 = \sigma_1^2 + \sigma_3^2 - \sigma_1 \sigma_3$$

where:

$$\sigma_1 = \sigma_{\max} = \tfrac{1}{2}(\sigma_x + \sigma_y) + \sqrt{[\tfrac{1}{2}(\sigma_x - \sigma_y)]^2 + \tau^2{}_{xy}}$$

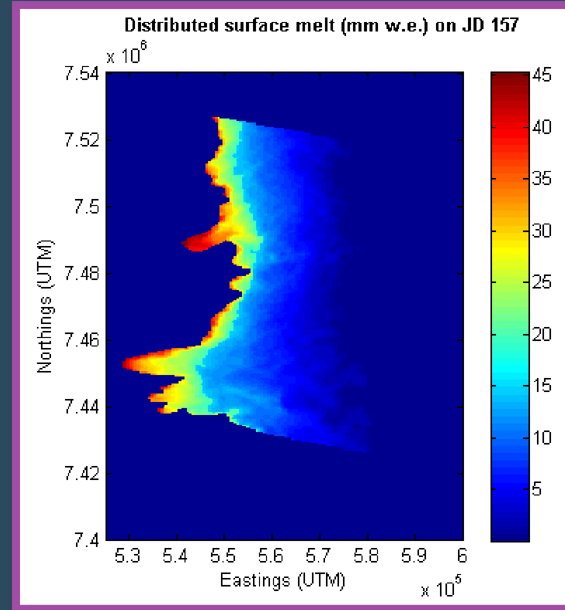
$$\sigma_3 = \sigma_{\min} = \tfrac{1}{2}(\sigma_x + \sigma_y) - \sqrt{[\tfrac{1}{2}(\sigma_x - \sigma_y)]^2 + \tau^2{}_{xy}}$$

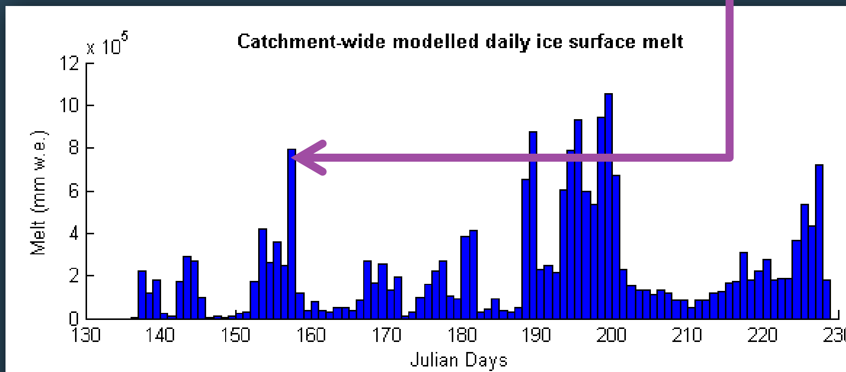


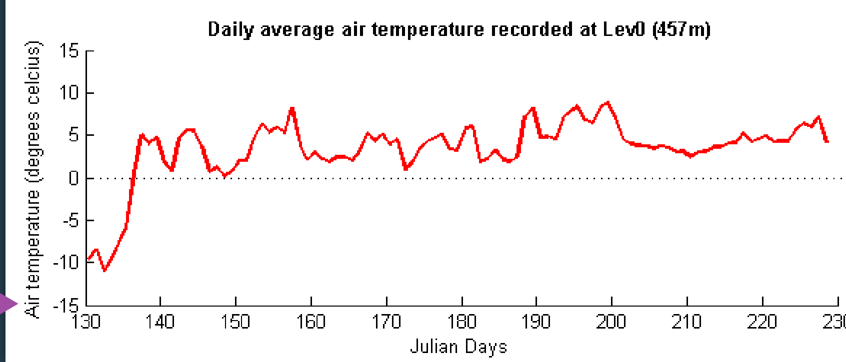
- Areas of initial surface crevassing were prescribed where the calculated tensile stress exceeds the tensile strength of the ice (determined from crevasse locations on imagery).

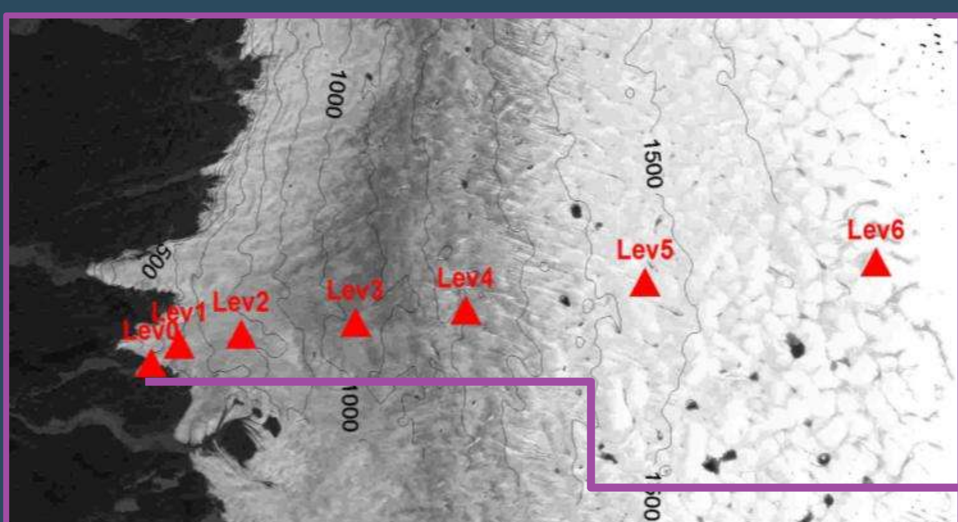
Melt modelling

- Air temperature and snow depth recorded during 2009 along transect, Lev0-6, of Leverett (457-1716 m)
  - air temperature lapse rate: 5.5 °C/km
  - accumulation gradient: 0.26 m w.e./km
- Melt generated using <u>simple degree day</u> approach using degree day factors calibrated against UDG-measured melt.
  - ice: 7.79 mm w.e. d^{-1} °C
  - snow: 5.81 mm w.e. d^{-1} °C

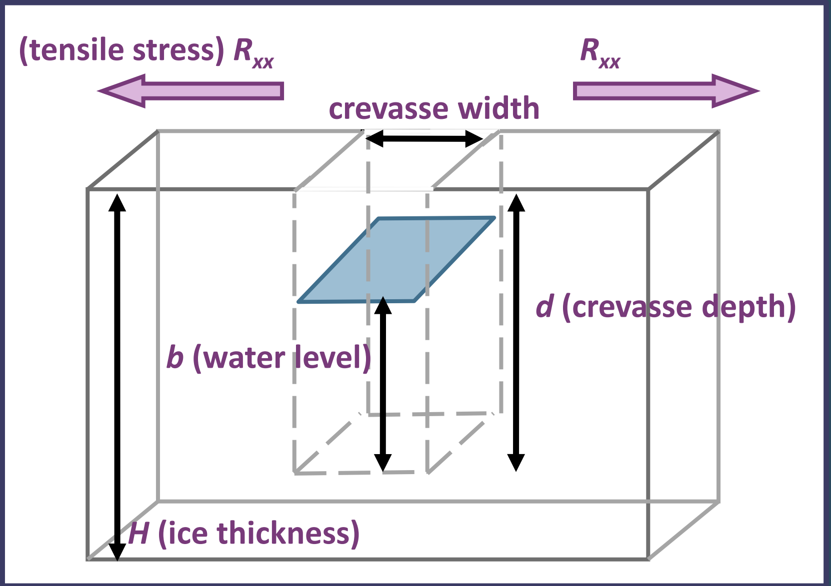








Supraglacial meltwater routing



- Melt used to weight flow accumulation across the ice surface DEM (credit: Palmer et al, in review, ESPL) based upon single flow direction (D8) algorithm.

- Where intersecting cells of tensile stress > tensile strength, and thus containing initial surface crevassing, melt accumulation ratio transferred to the downstream cell is reset to zero.

- Accumulated melt values used to determine crevasse water filling levels, adjusted for prescribed crevasse width.

Crevasse depth calculation

- Water level in the crevasse, *b*, and tensile stress, R_{xx}, used as inputs to model of <u>fracture propagation of single water-filled crevasses</u>, after Van der Veen (2007):

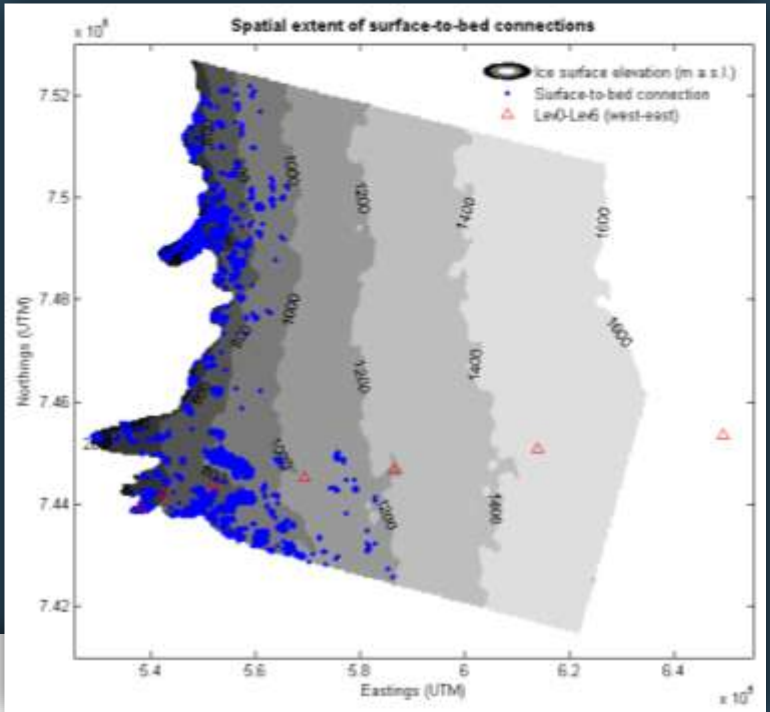
$$K_I = 1.12 R_{xx}\sqrt{\pi d} - 0.683\rho_i g d^{1.5} + 0.683\rho_w g b^{1.5}$$

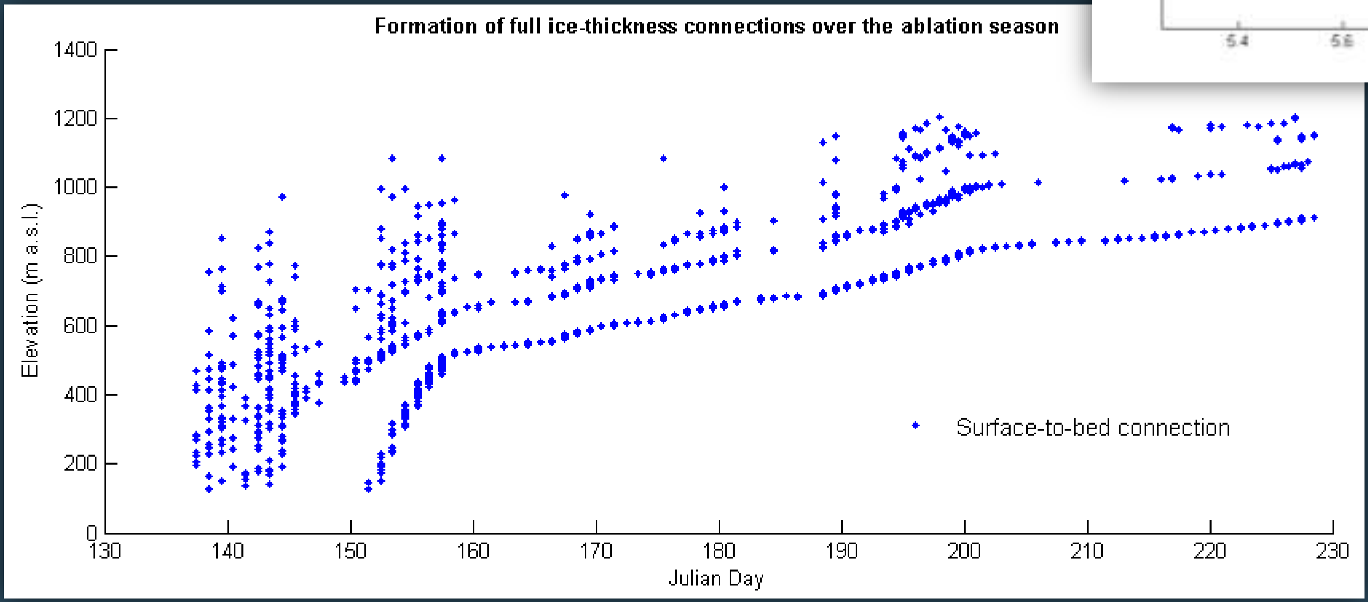
- Equation is solved for depth when the net stress intensity factor, K_I, equals a prescribed fracture toughness.

- When crevasse depth equals the ice thickness meltwater is delivered daily to the ice-bed interface.

Results: predictions with initial parameters

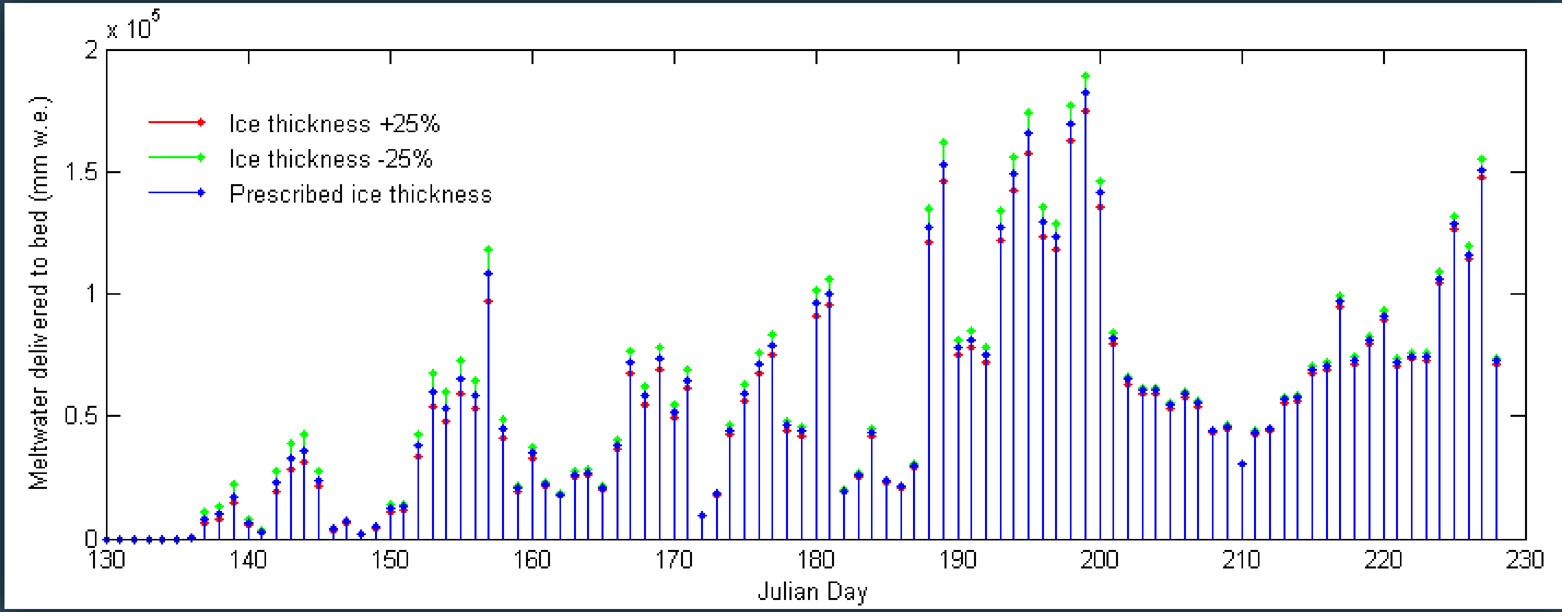
- 1210 surface-to-bed connections delivering 26% of ice surface-generated meltwater to the bed were predicted during the initial parameter run, where:
  - fracture toughness: 150 kPa $m^{1/2}$
  - tensile strength: 75 kPa
  - crevasse width: 1 m





Ice thickness associated error

- To investigate model sensitivity to ice thickness we applied errors of +/- 5, 10 and 25%:



Ice thickness tolerance	*Total number of surface-to-bed connections*	*% change from initial run*	*% transfer of surface generated melt to the ice-bed interface*	*% change from initial run*
+/- 5%	1176/1229	-2.8/+1.6	26.0/26.5	-0.2/+0.3
+/- 10%	1159/1242	-4.2/+2.6	25.8/26.7	-0.4/+0.5
+/- 25%	1130/1305	-6.6/+7.9	25.1/27.5	-1.1/+1.3

- Errors of up to +/- 25% result in small changes in connection numbers and less than 2% change in meltwater transfer from surface to bed.

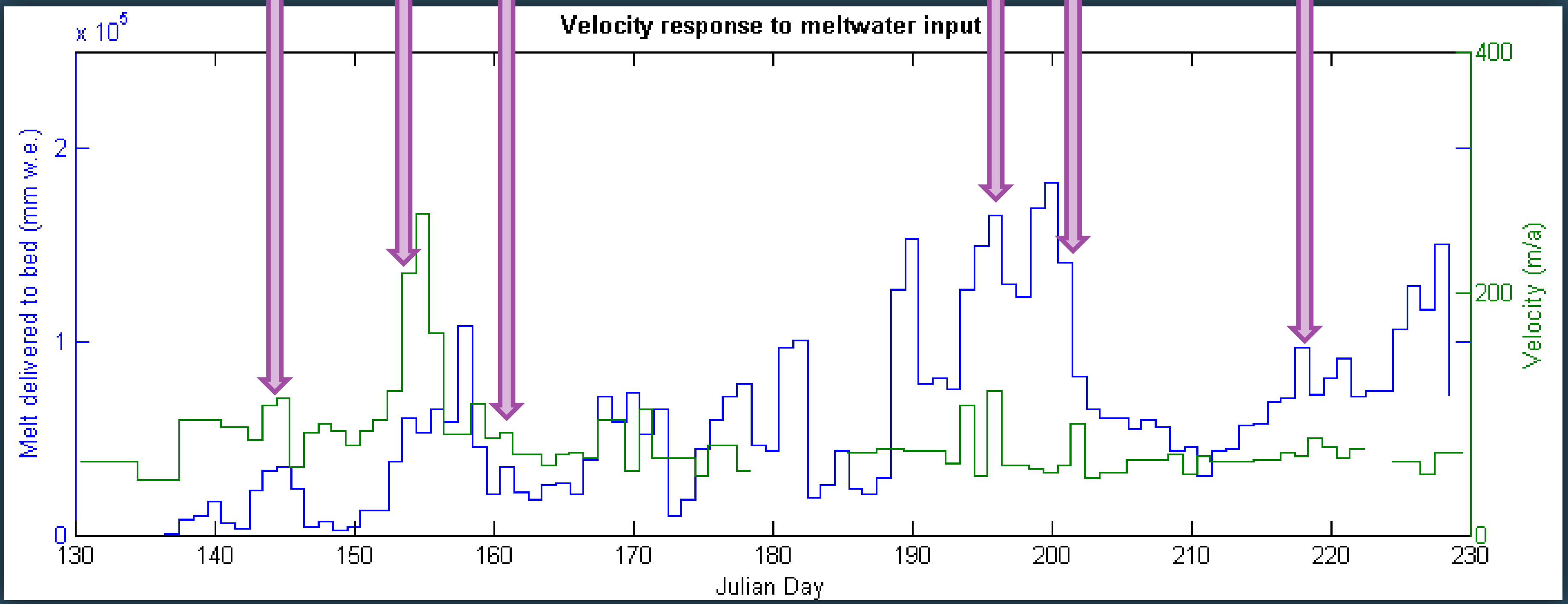
Velocity surveys

Velocity response to melt influx

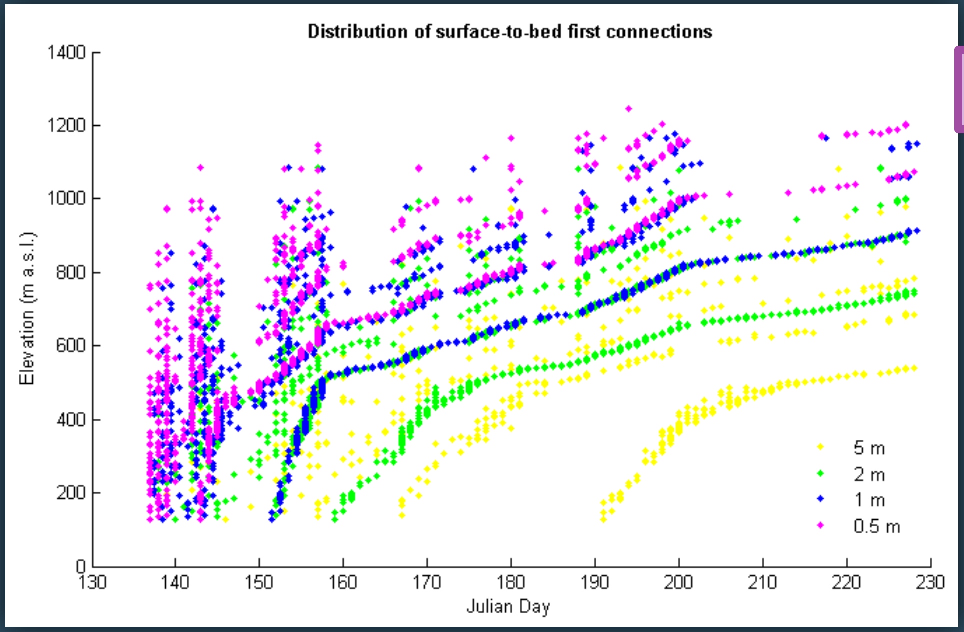
- Ice surface velocities were surveyed daily for stakes on Leverett Glacier during 2009 field season. Peaks in velocity show correspondence with predictions of melt delivery and vary in response to melt input during the early and late season:

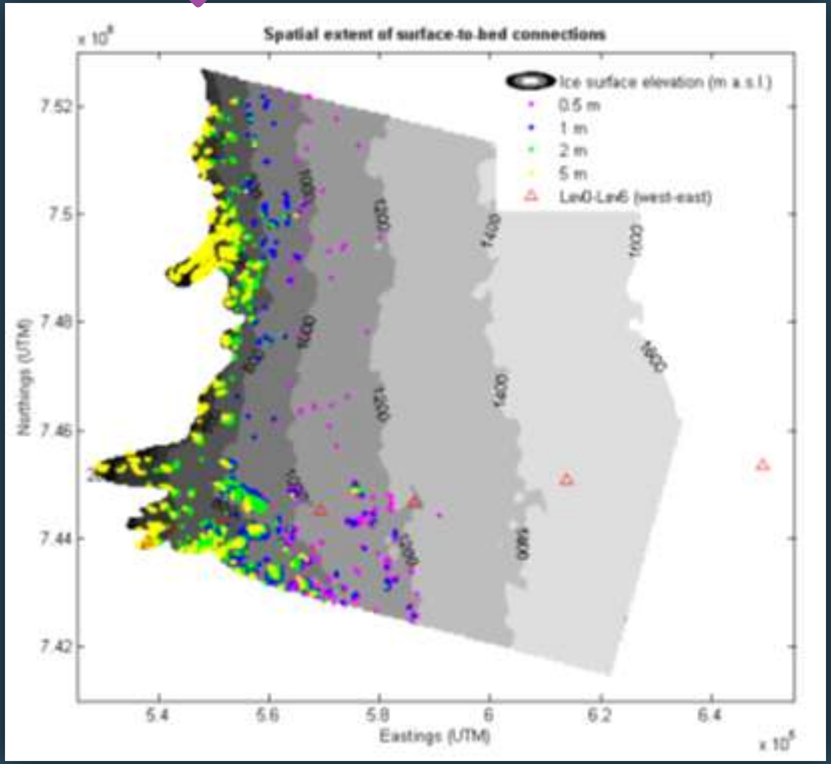
Peaks in melt delivery in the early season coincident with pronounced peaks in velocity (**inefficient drainage system**).

Velocity response in the late season characterised by a much dampened response to greater meltwater input (**efficient drainage system**).



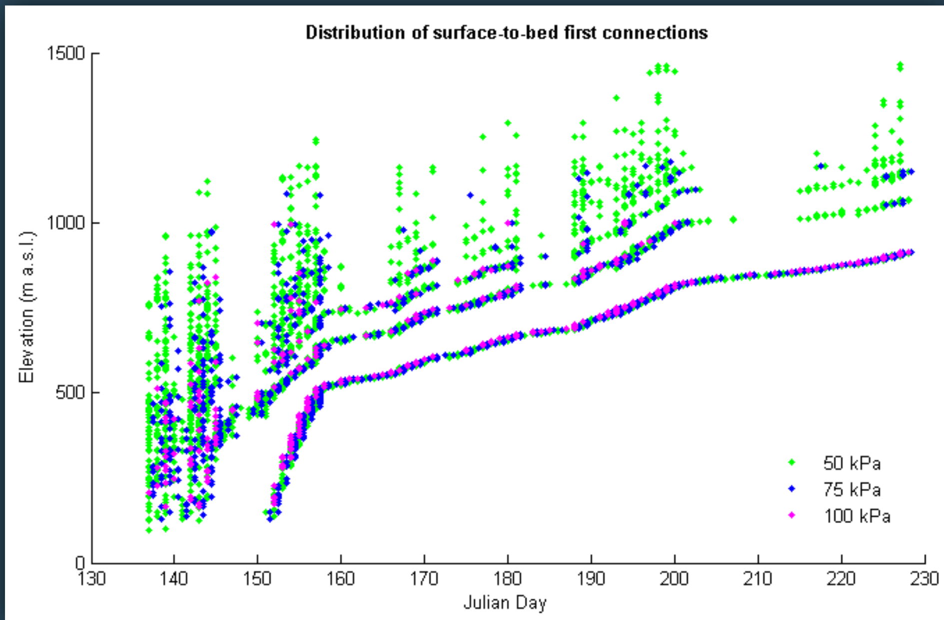
Sensitivity testing: crevasse width

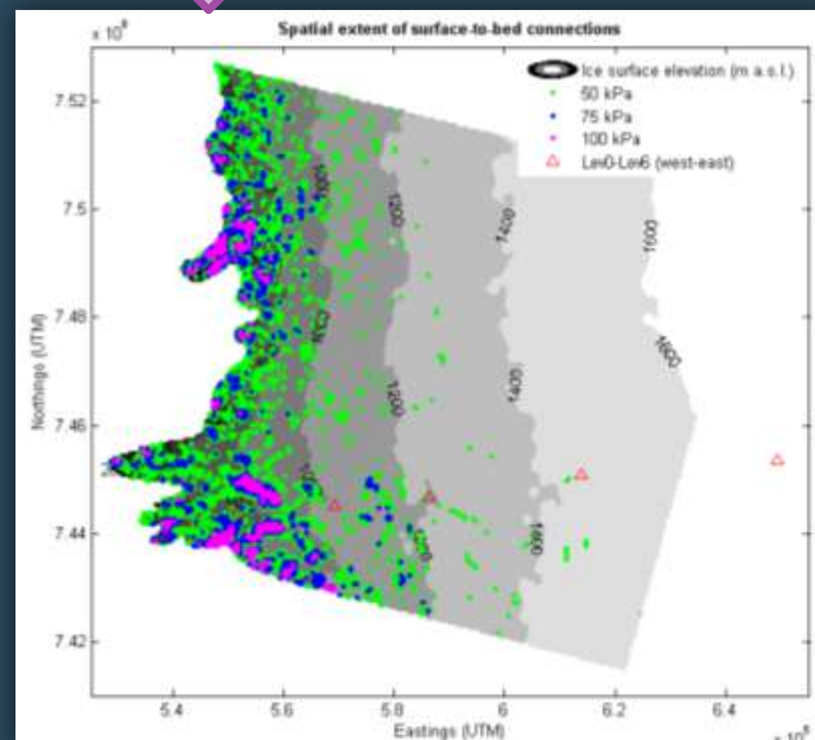




- Wider crevasses take longer to form connections to the bed than narrow crevasses due to the influence of crevasse dimensions on meltwater head.

Sensitivity testing: tensile strength





- Tensile strength is a key control on the distribution of surface-to-bed connections as it determines where initial surface fractures will be present across the catchment.

Sensitivity testing conclusions

I. Fracture toughness has no significant influence on crevasse penetration, and is not an important control on connection numbers or melt delivery.

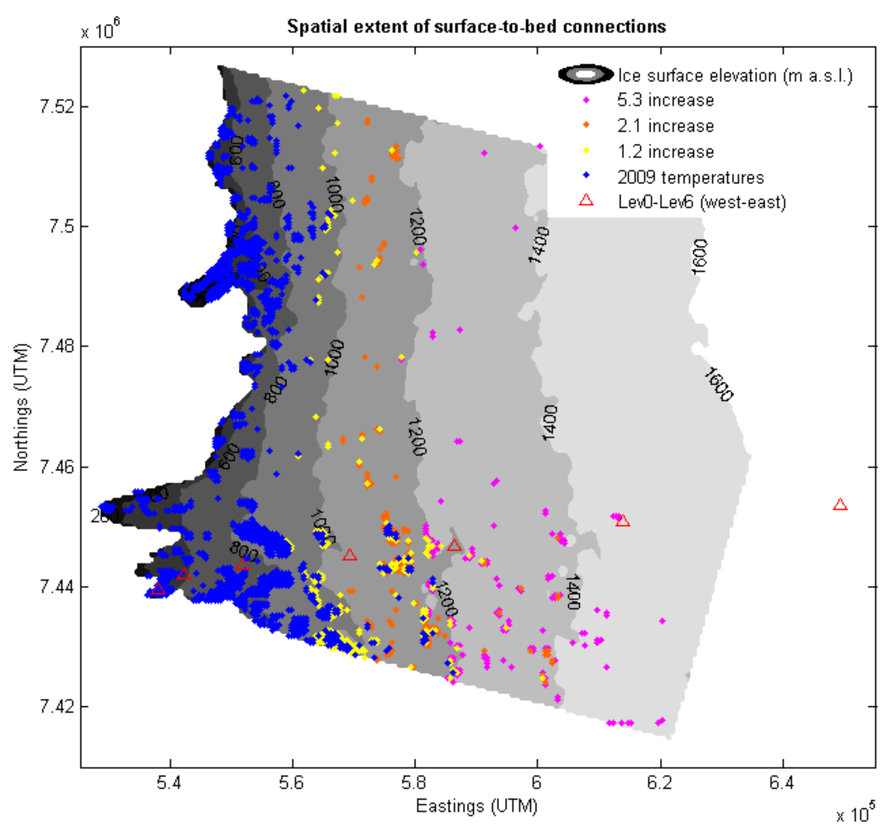
II. Tensile strength is the critical control on both locations of connections and melt delivery to the bed by determining initial surface fracture distribution.

III. Crevasse width has a significant effect on (a) the number of surface-to-bed connections formed (but less so on % surface melt transferred to the bed); and (b), the timing of surface-to-bed connections (wide crevasse = later connection)

Model run	*Total number of surface-to-bed connections*	*% change from initial run*	*% transfer of surface generated melt to the ice-bed interface*	*% change from initial run*
Fracture toughness 400 kPa $m^{1/2}$	1207	-0.3	26.2	0
Tensile strength 50 kPa	3684	+204.5	100	+73.8
Tensile strength 100 kPa	368	-69.6	6.9	-19.3
Crevasse width 0.5 m	1412	+16.7	28.8	+2.6
Crevasse width 2 m	931	-23.1	22.5	-3.7
Crevasse width 5 m	542	-55.2	16.3	-9.9

Future climatic scenarios

- As a preliminary investigation into model response to temperature at the end of the 21st Century, we ran the model for the A1B June, July and August Arctic scenario (IPCC Fourth Assessment Report), keeping all other model parameters static.
- Total melt delivery and the number of connections would be significantly increased, with a larger proportion of surface generated melt stored and drained through supraglacial lakes.



Temperature increase	*Total number of surface-to-bed connections*	*% change from initial run*	*% transfer of surface generated melt to the ice-bed interface*	*% change from initial run*
1.2 °C (minimum)	1402	+15.9	23.0	-3.2
2.1 °C (mean)	1532	+26.6	20.8	-5.4
5.3 °C (maximum)	1664	+37.5	16.3	-19.9

Conclusions

I. Crevasse surface dimensions very important due to control on meltwater head and penetration depth.

II. Model highly sensitive to tensile strength due to control over initial surface fractures. This parameter must be well-constrained for successful implementation of this approach within ice sheet modelling.

III. Future work will include lake storage and drainage simulation which we anticipate will result in a much larger percentage of total surface melt reaching the bed than for moulins alone.

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