Coupling modelling and satellite observations to constrain subglacial melt rates and hydrology

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4D Antarctica

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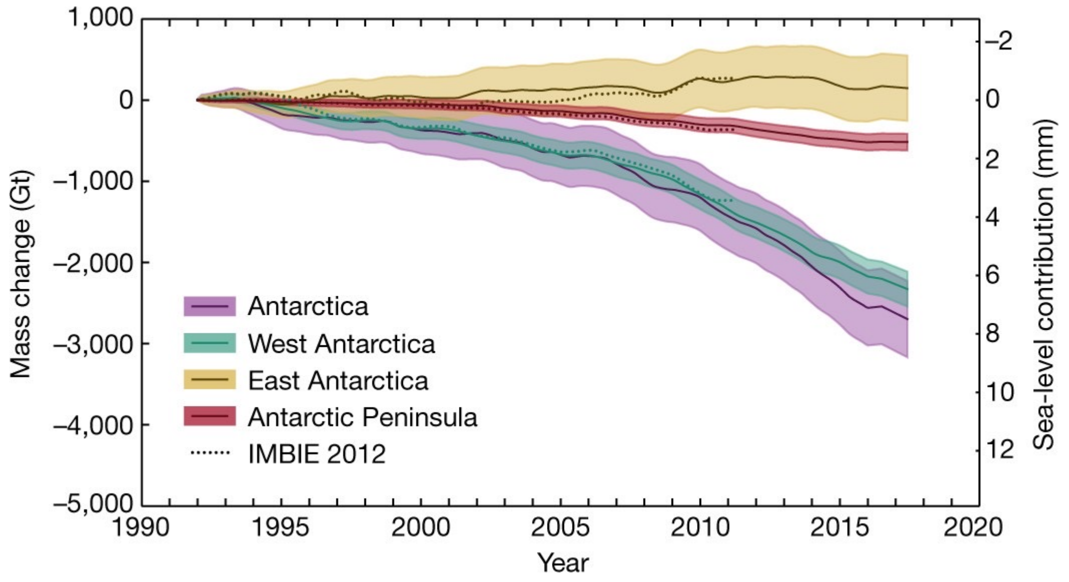
Introduction

- The rate of mass loss from the Antarctic Ice Sheet is increasing.
- Projections of future mass loss from the Antarctic Ice Sheet are highly uncertain.

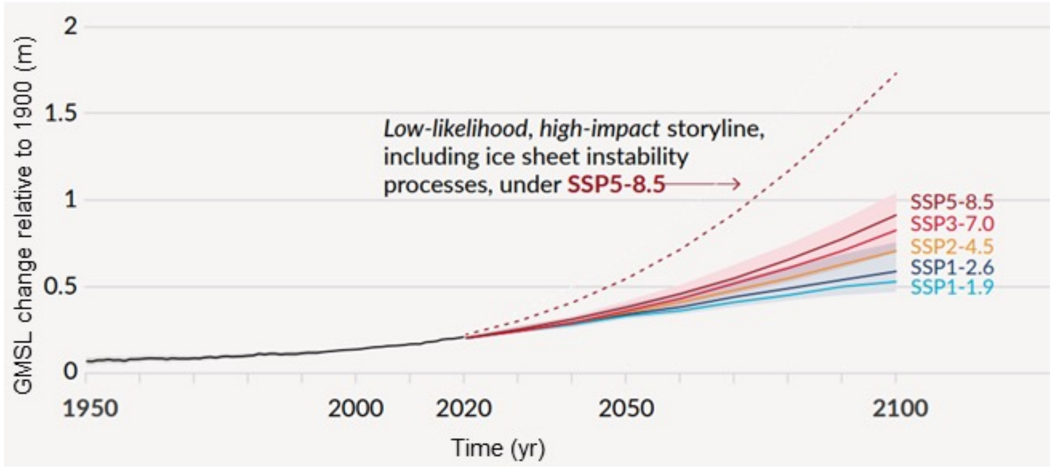
- Implications for global mean sea-level rise.
- Threatens coastal communities and infrastructure.

- To reduce uncertainty in projections we need to improve our understanding of complex ice-sheet processes.
- One such process is ice-sheet subglacial hydrology.

Observed mass loss from the Antarctic Ice Sheet (IMBIE)



Projections of future sea-level rise: IPCC AR6 WG1 SPM (2021)

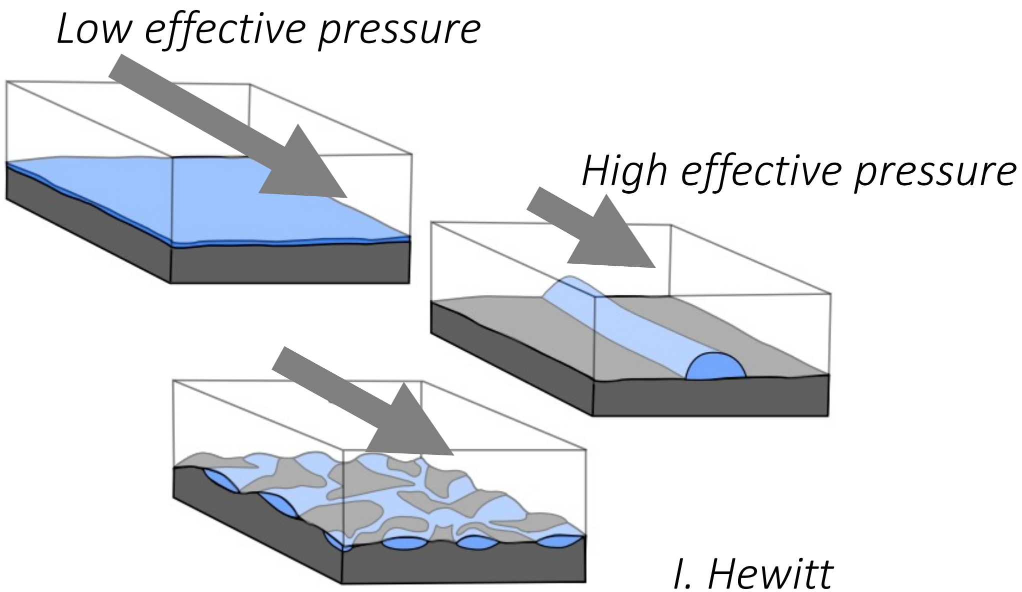


Introduction

- Meltwater forms at the base of the ice sheet due to geothermal heat flux and frictional dissipation.

- Subglacial melting is only a small component of the total ice sheet mass balance (≈3% of surface accumulation) but plays an important role:
  - Lubricates the ice-bed interface allowing faster ice flow.
  - Runoff of freshwater into the ocean, enhances ice-shelf basal melting, influences biological productivity and ocean circulation.

- However, melt rates and hydrology are highly uncertain – there are few observations of the subglacial environment hidden by up to 4 km of ice.



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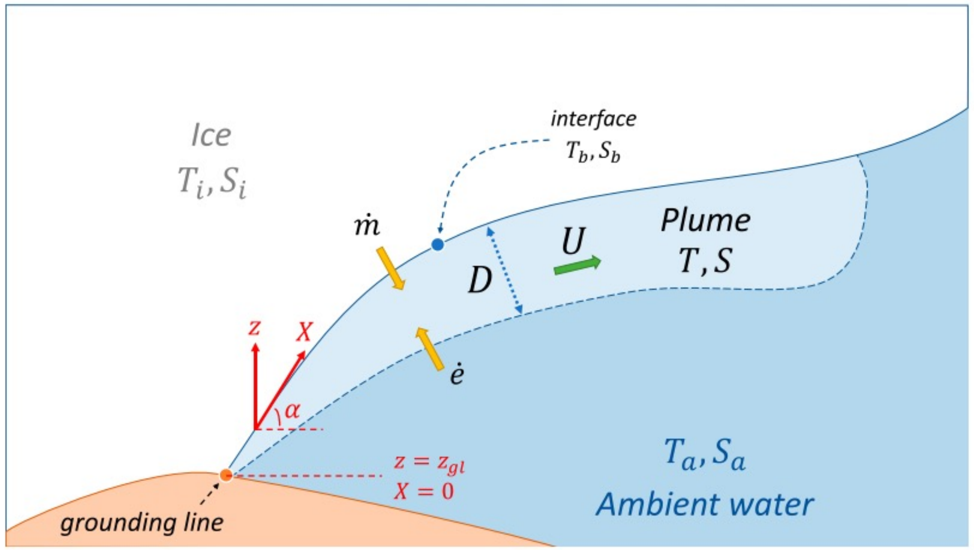


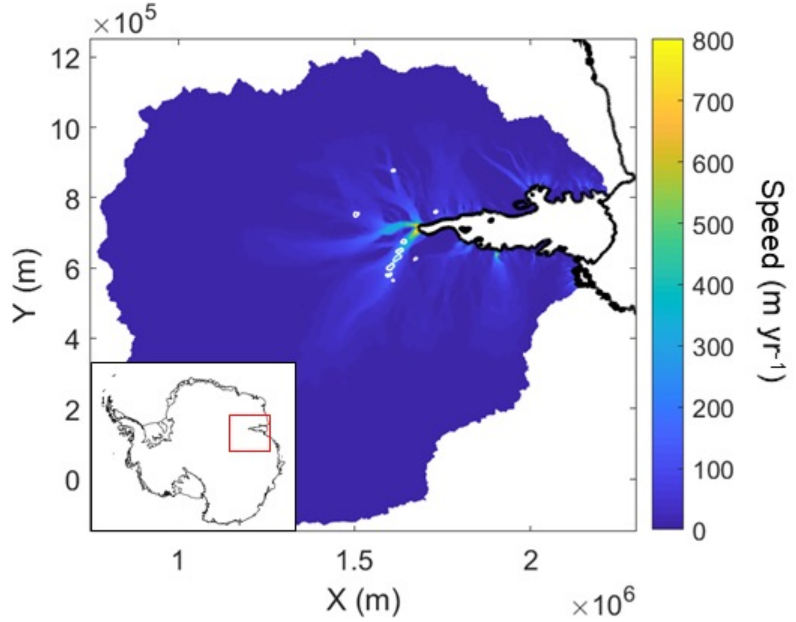
Lazeroms et al., (2019)

Introduction

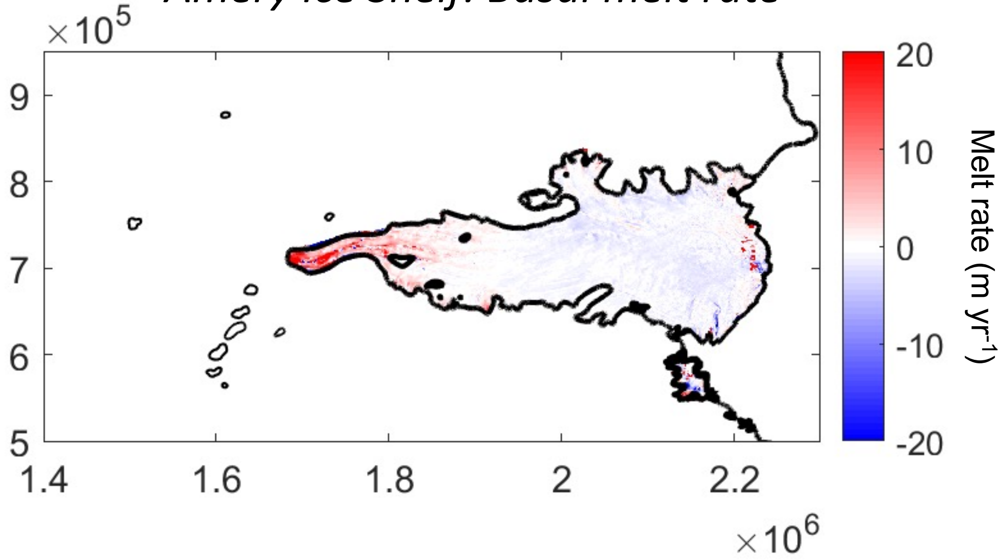
- Study area: Amery Ice Shelf Catchment
  - Region of East Antarctica
  - Area of 1.3 x10^6 km^2
  - Third largest ice shelf.
  - Considered to be relatively stable

- Use satellite observations of active subglacial lakes and ice-shelf basal melting to constrain model of subglacial hydrology.

Amery catchment: Ice surface speed



Amery Ice Shelf: Basal melt rate



Modelling subglacial melt rates

$$M = \frac{\boxed{GHF} + \boxed{\tau_b u_b} + \boxed{k_i \theta_b}}{L_i \rho_i}$$

$M =$ Melt rate, $GHF =$ Geothermal Heat Flux,
$\tau_b =$ basal shear stress, $u_b =$ basal speed,
$k_i =$ thermal conductivity, $\theta_b =$ basal temperature gradient,
$L_i =$ Latent heat of fusion, $\rho_i =$ density of ice

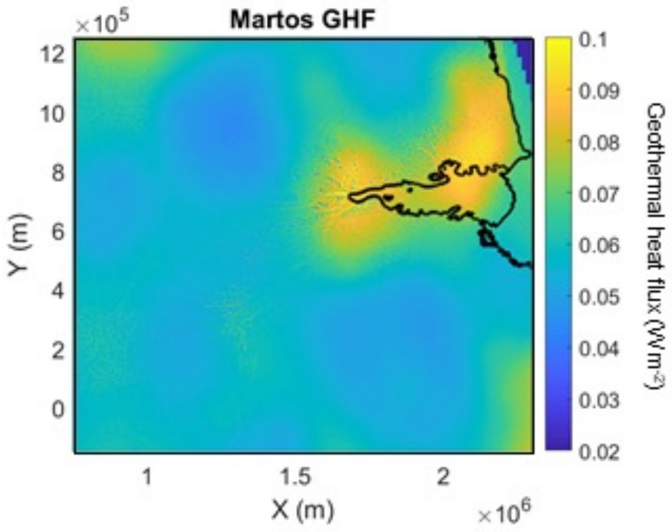
Geothermal heat flux

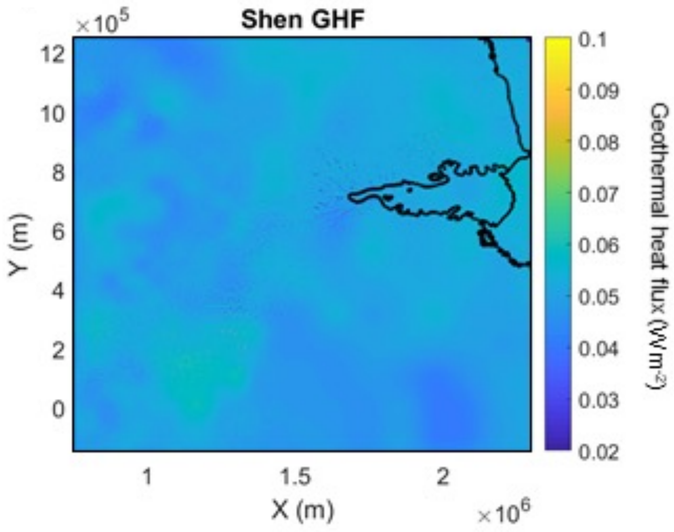
Basal frictional dissipation (next slide)

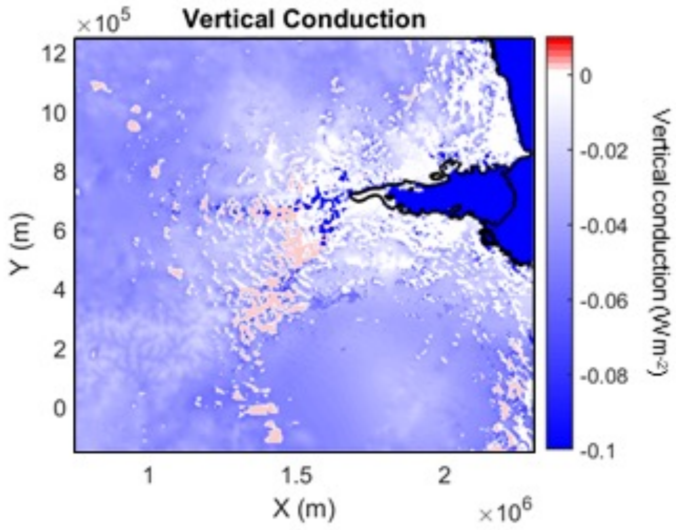
Vertical conduction

Martos et al., (2017) - magnetic
Shen et al., (2020) - seismic

Englacial temperature profile:
Van Liefferinge & Pattyn (2013)







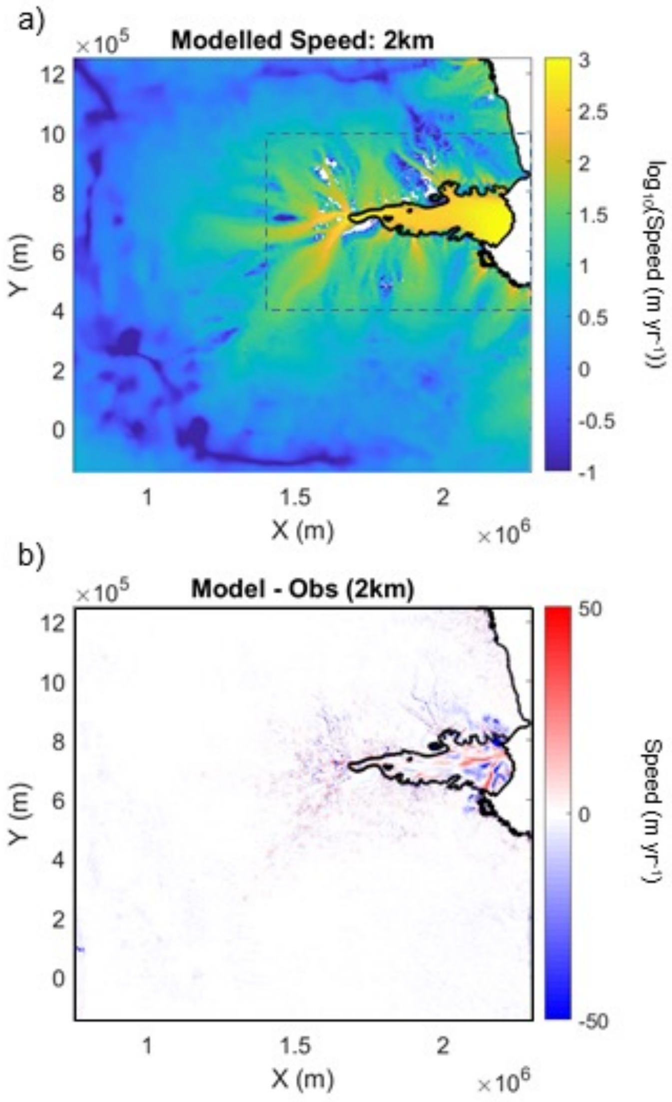
Modelling subglacial melt rates: Frictional Dissipation

- We use an ice-sheet model inversion to calculate basal frictional dissipation.
    - STREAMICE: Higher-order ice flow model

- Given observations of:
    - Bedrock topography
    - Ice thickness
    - Ice surface velocity

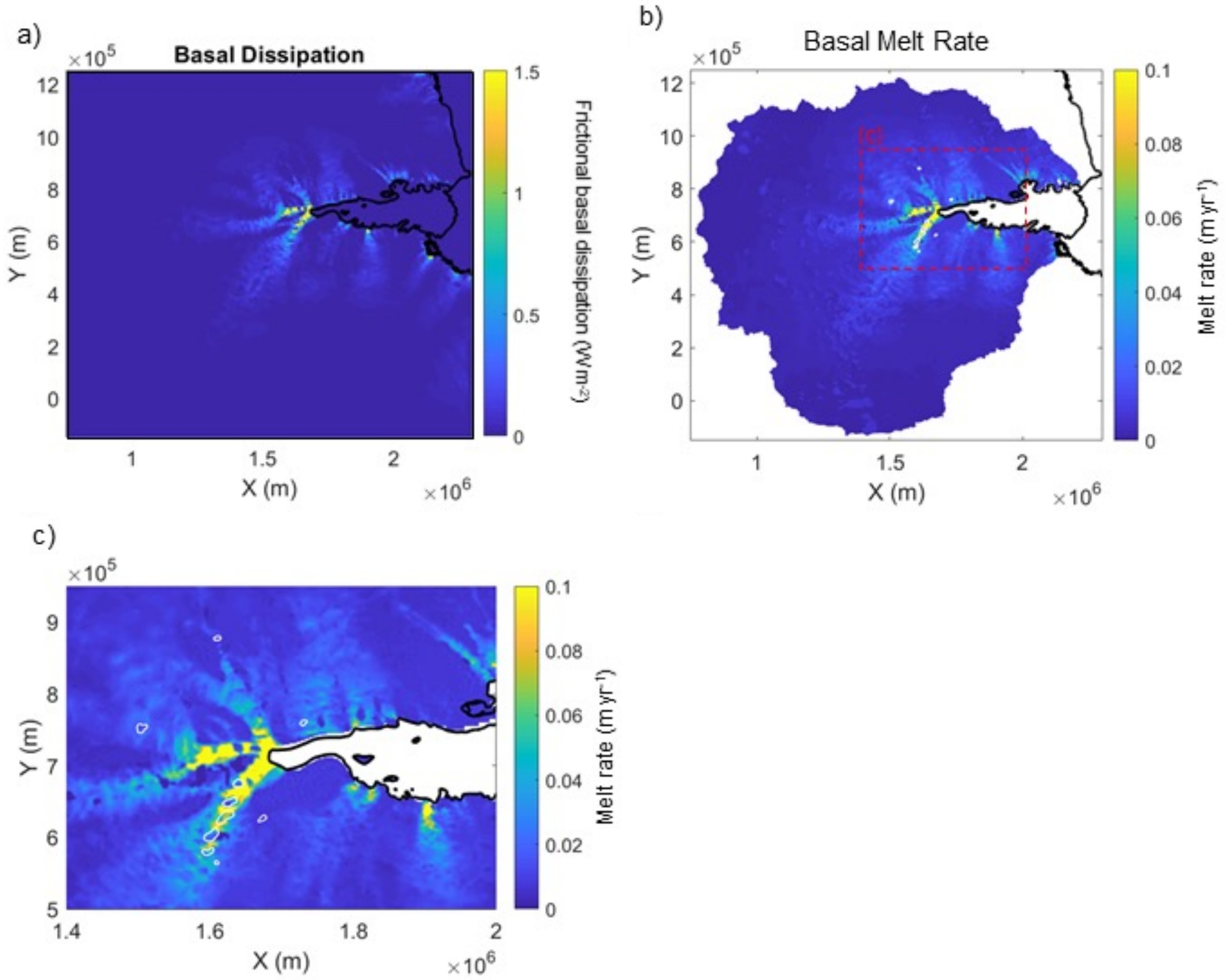
- Infer:
    - Ice viscosity (constrained by englacial temperature)
    - Basal friction

Average misfit = -0.63 m yr^{-1}



Results: Subglacial melt rate

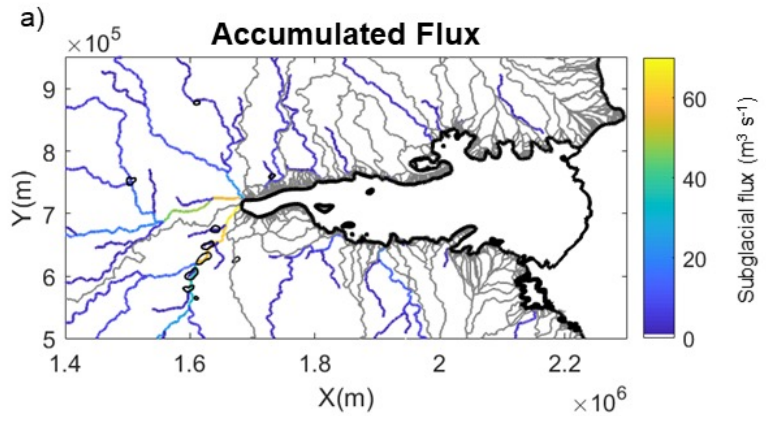
- Total melt rate: 6.5 Gt yr^{-1}
    - 8% of mass loss from ice-shelf melting and iceberg calving.
- Spatial pattern of melting is dominated by basal frictional dissipation – high melt rates beneath fast-flowing ice streams (> 0.1 m yr^{-1}).
- Total melt rate is 48% larger than previous estimates (Van Liefferinge & Pattyn, 2013).
- We are able to more accurately resolve high melt rates beneath ice streams using our higher-order ice-flow model.



Uncertainty in melt rate

- Source for total melting is 50:50 split between GHF and basal dissipation.
  - But contributions vary spatially.

- We use a subglacial routing approximation to assess the contribution to meltwater flux along drainage pathways.
  a) Drainage pathways connect observed subglacial lakes
  b) GHF is main meltwater source in slow-flowing upstream regions.
  c) Different GHF estimates lead to ±7% difference in total melt rate.
    - In places difference is up to 30%



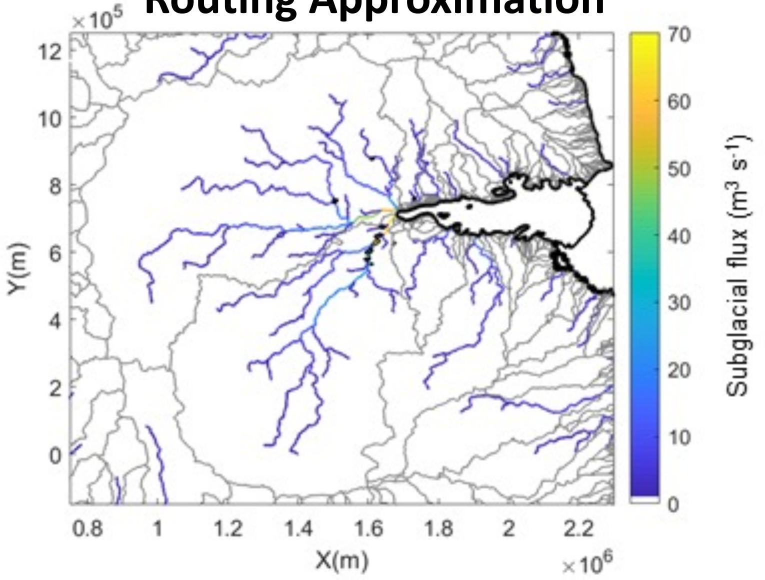
Subglacial hydrology

- Subglacial routing approximation shows likely pathways for drainage, but it is not physically realistic.

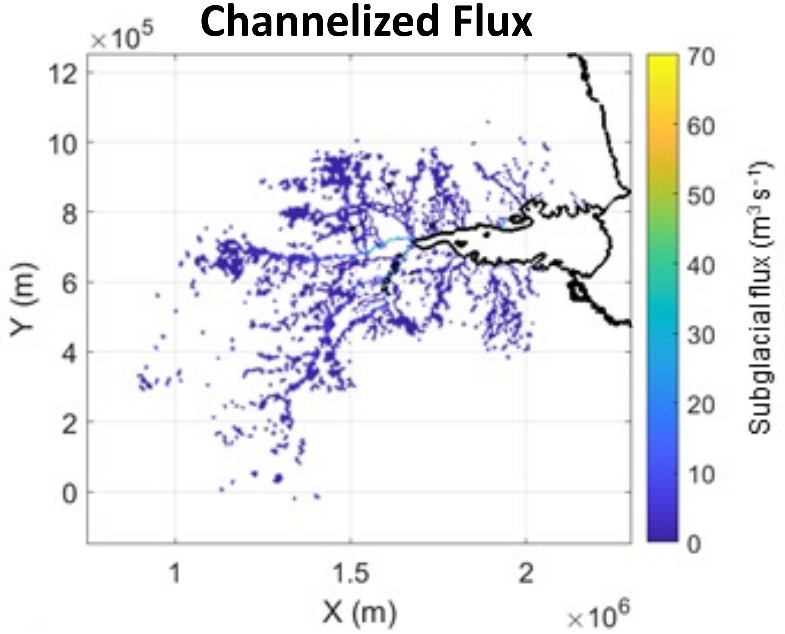
- To model subglacial hydrology we use the GlaDS model:
    - Simulates flow through both distributed sheet and channelized network.
    - Channels are able to grow and shrink depending on subglacial flux.

- We perform two sets of simulations varying the channel conductivity parameter (high or low).

Routing Approximation



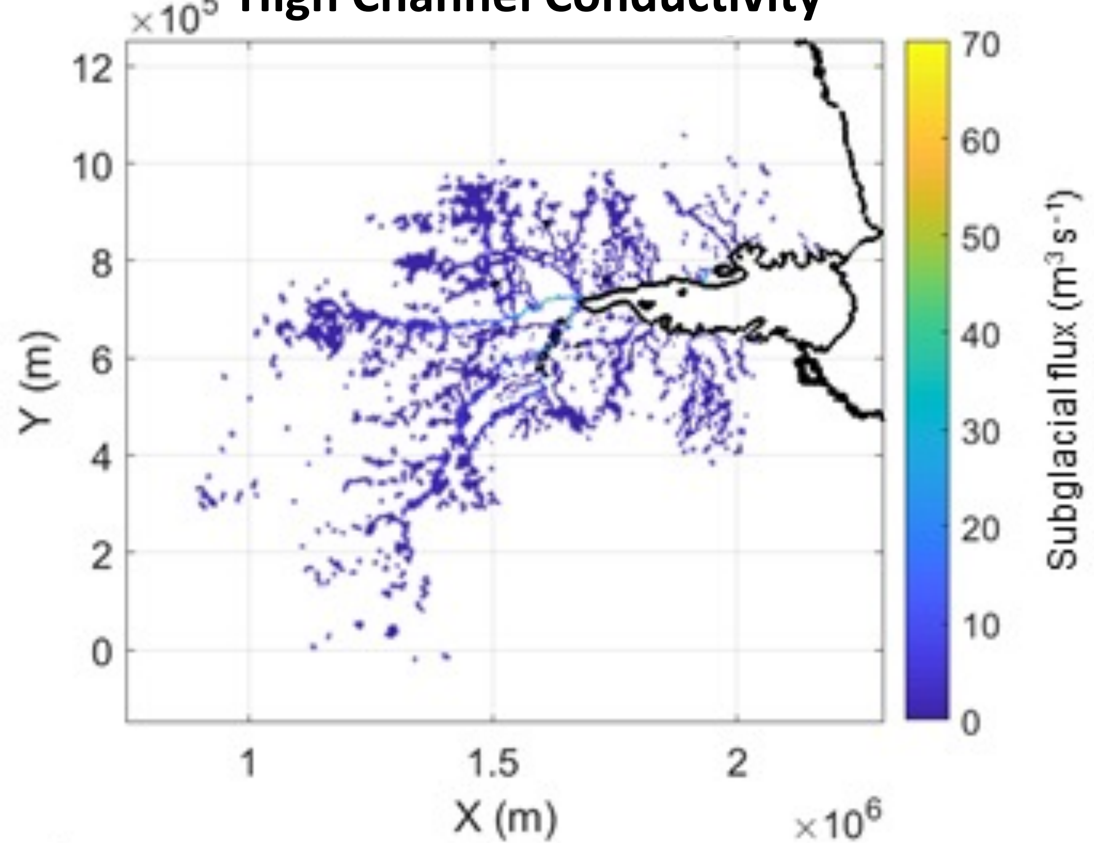
Two component model: Channelized Flux



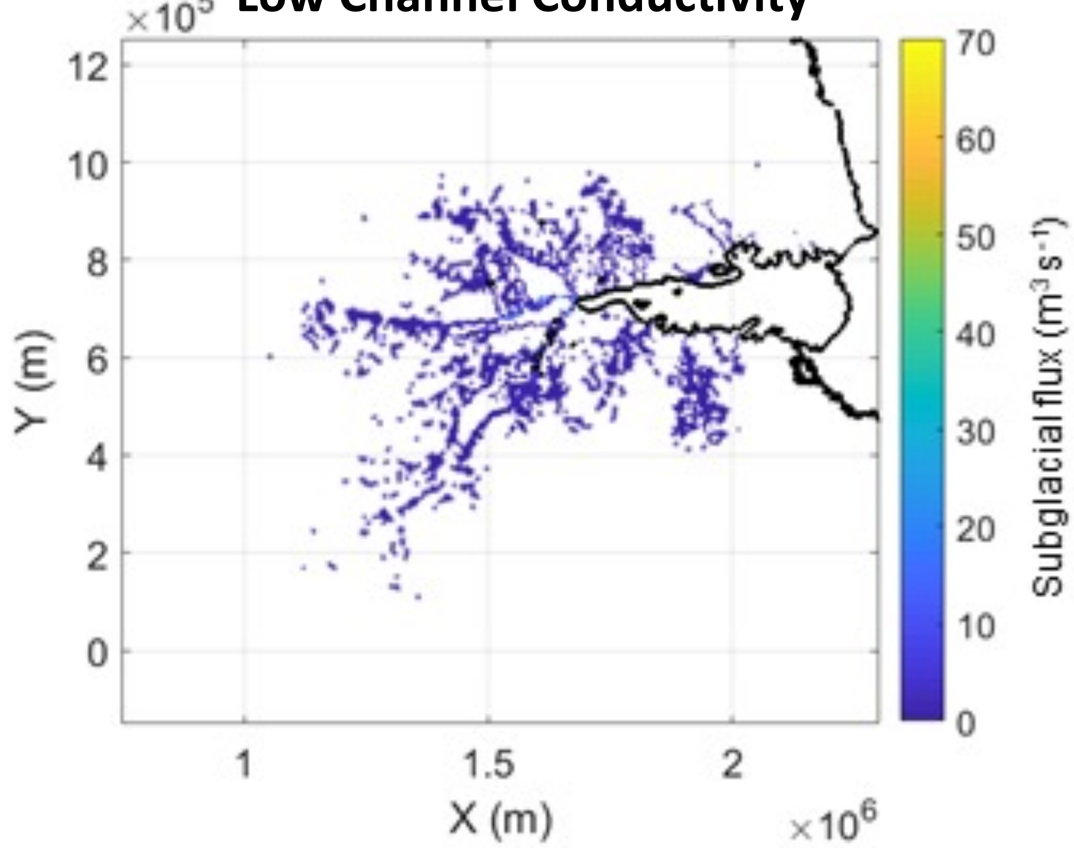
Results: Subglacial hydrology

Channelized Subglacial Flux

High Channel Conductivity



Low Channel Conductivity

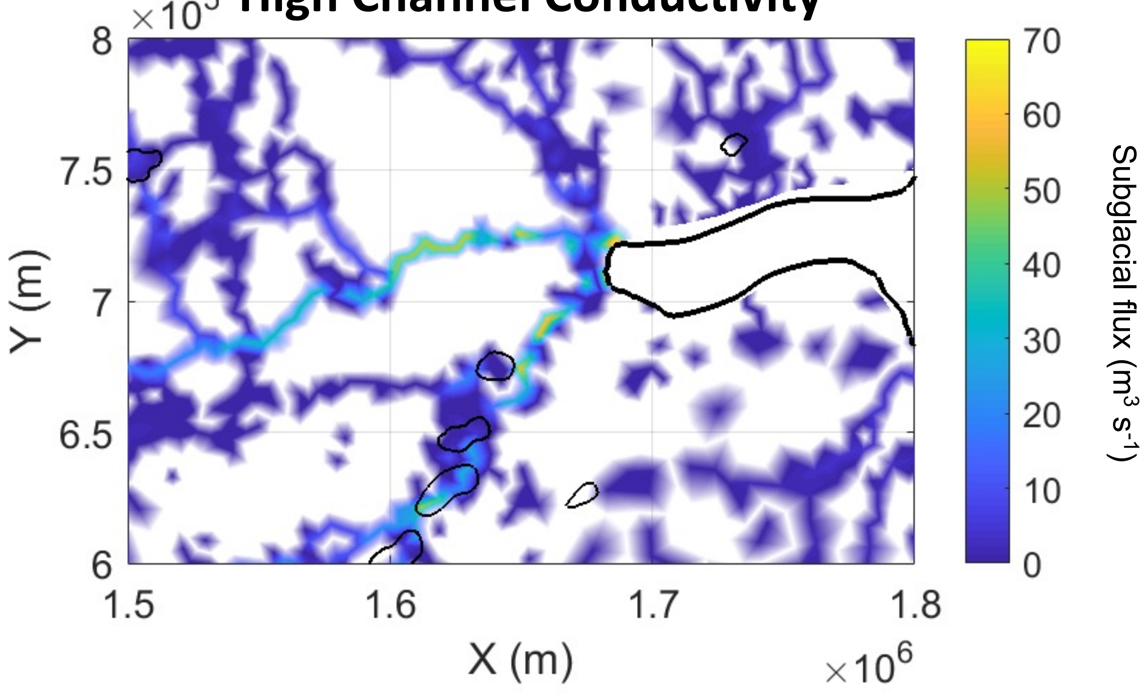


With high channel conductivity, subglacial flux is higher (max 70 vs 40 m^3 s^{-1}) and channels are more extensive

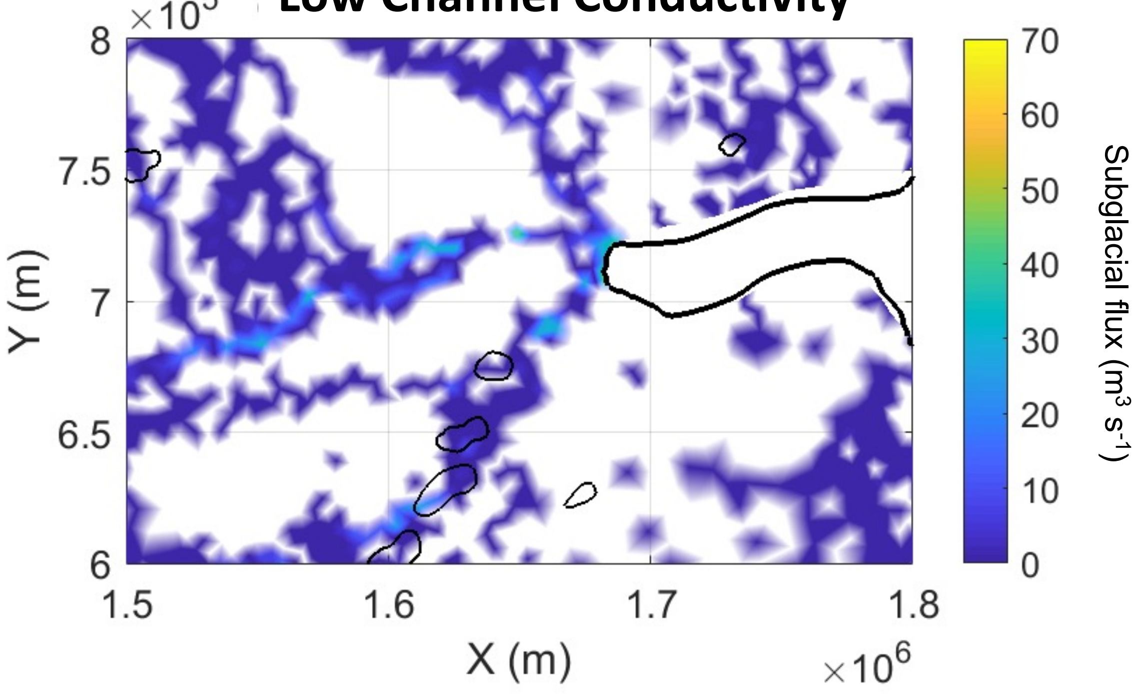
Results: Subglacial hydrology

Channelized Subglacial Flux

High Channel Conductivity



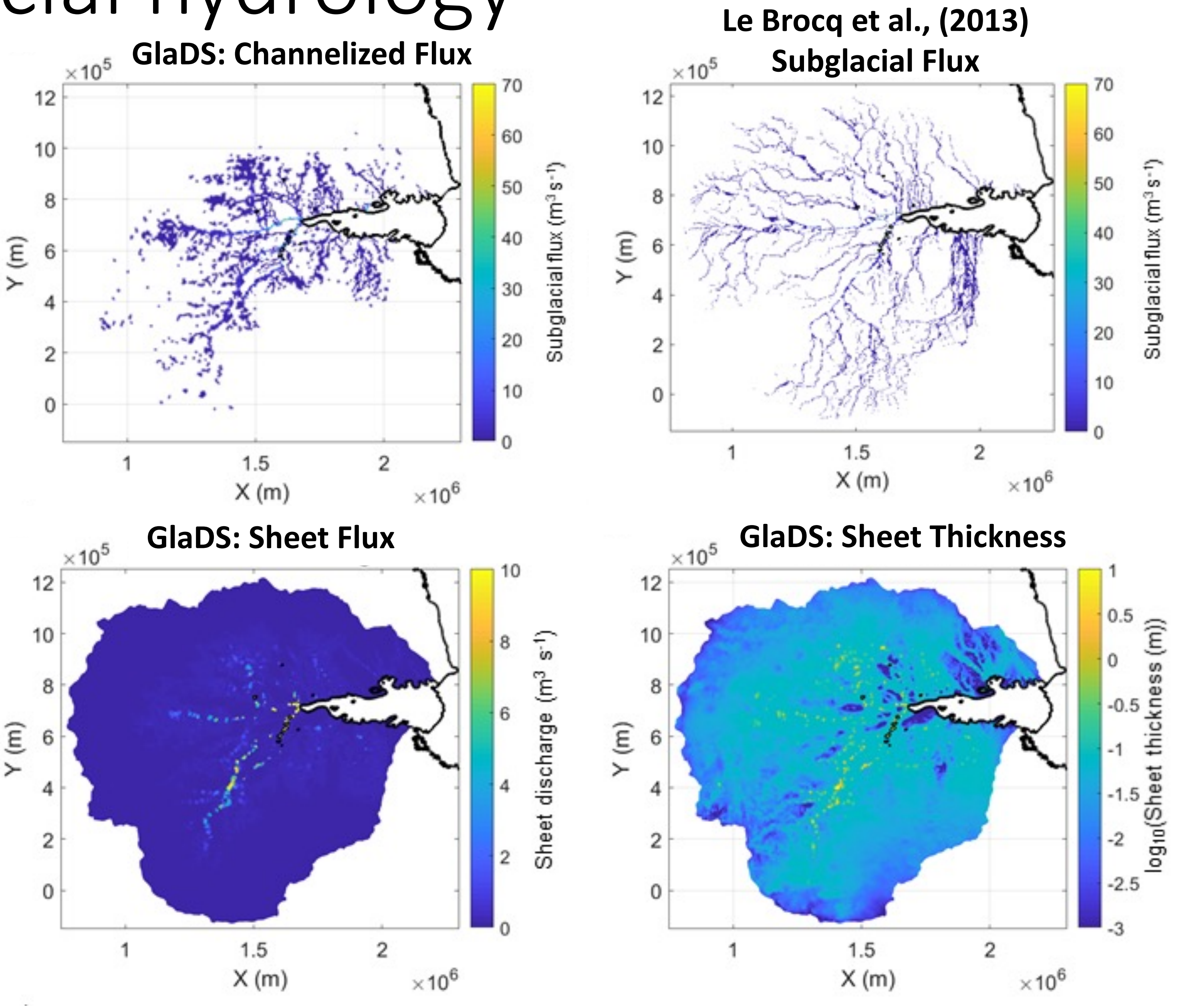
Low Channel Conductivity



With high channel conductivity, subglacial flux is higher (max 70 vs 40 $m^3 s^{-1}$) and channels are more extensive

Results: Subglacial hydrology

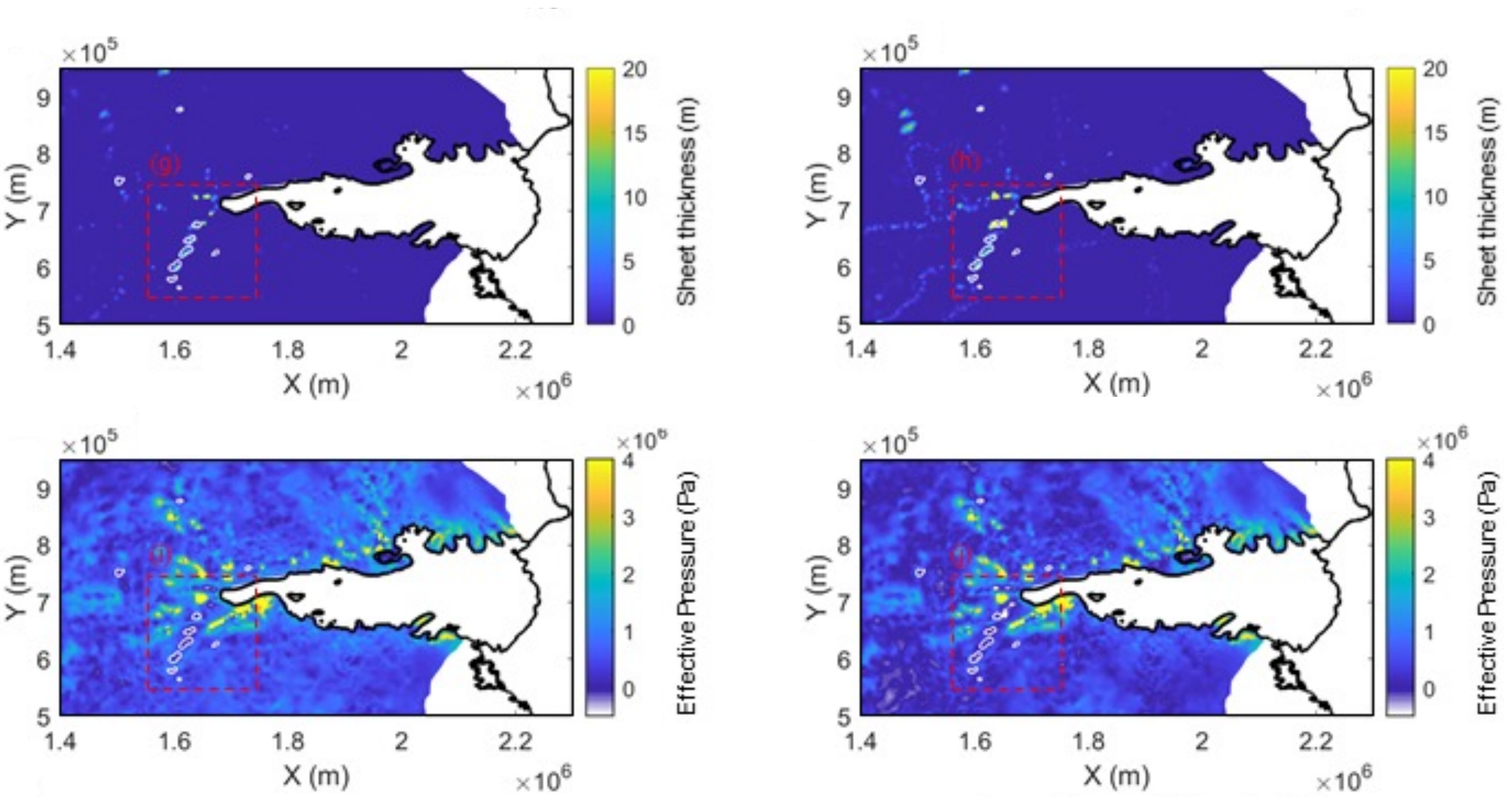
- Compare our result with previous subglacial hydrology modelling from Le Brocq et al., (2013).
- This model does not make the distinction between channelized and distributed drainage.
- Similar structure, although channels don’t extend so far inland. Discharge is approximately half our result.
- GlaDS also simulates the distributed sheet: i.e. flux and thickness (1 – 10 mm).



Results: Subglacial hydrology

- Comparing high and low channel conductivity.
- The observed locations of subglacial lakes coincide with simulated areas of deep subglacial water and low effective pressure.

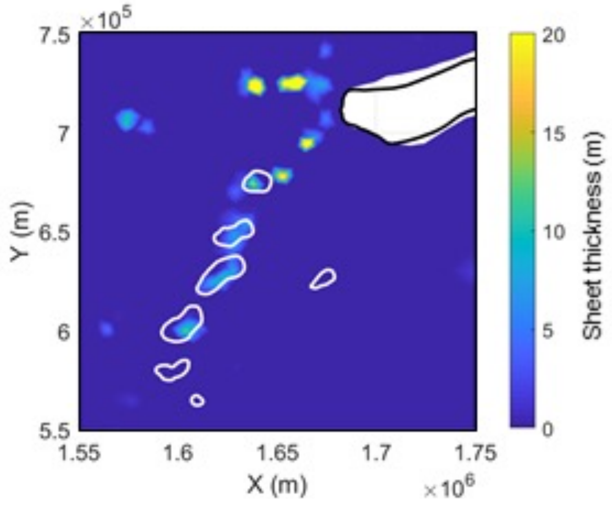
High Channel Conductivity **Low Channel Conductivity**

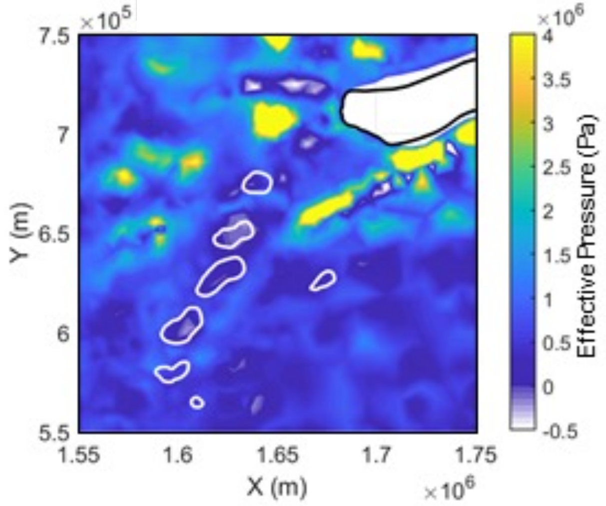


Results: Subglacial hydrology

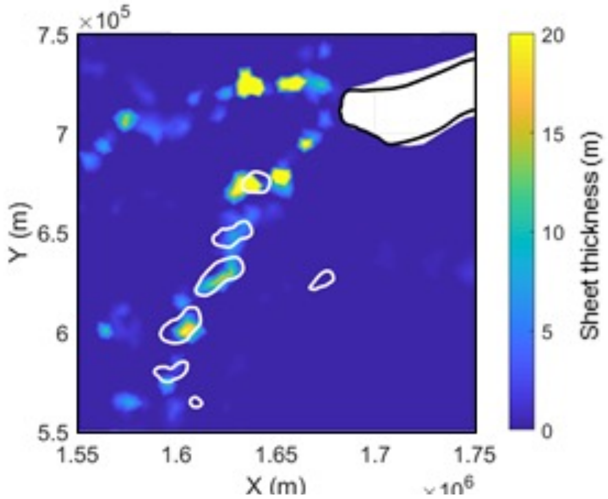
- Comparing high and low channel conductivity.
- The observed locations of subglacial lakes coincide with simulated areas of deep subglacial water and low effective pressure.
- For low channel conductivity additional areas of deep subglacial water are present and areas of low effective pressure exceed subglacial lake boundaries.

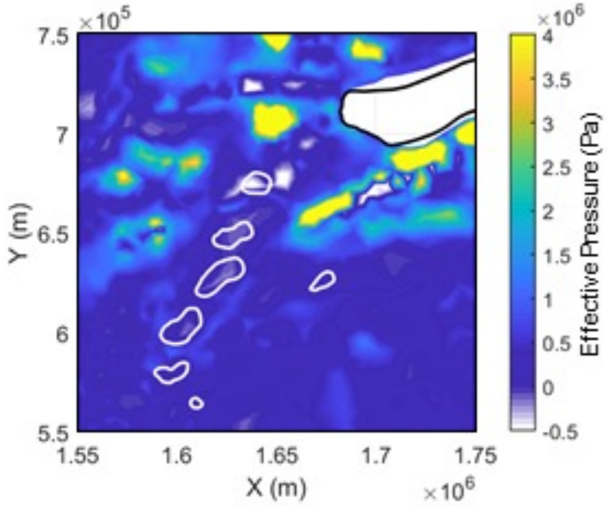
High Channel Conductivity





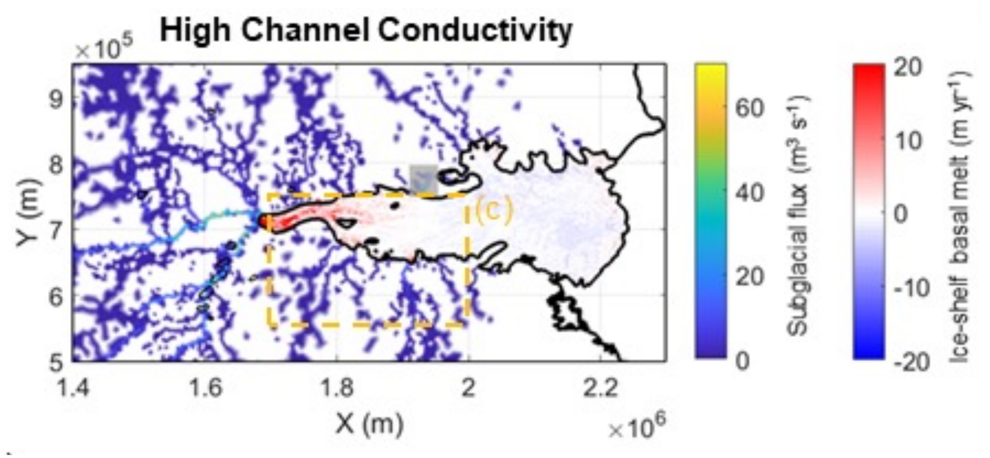
Low Channel Conductivity



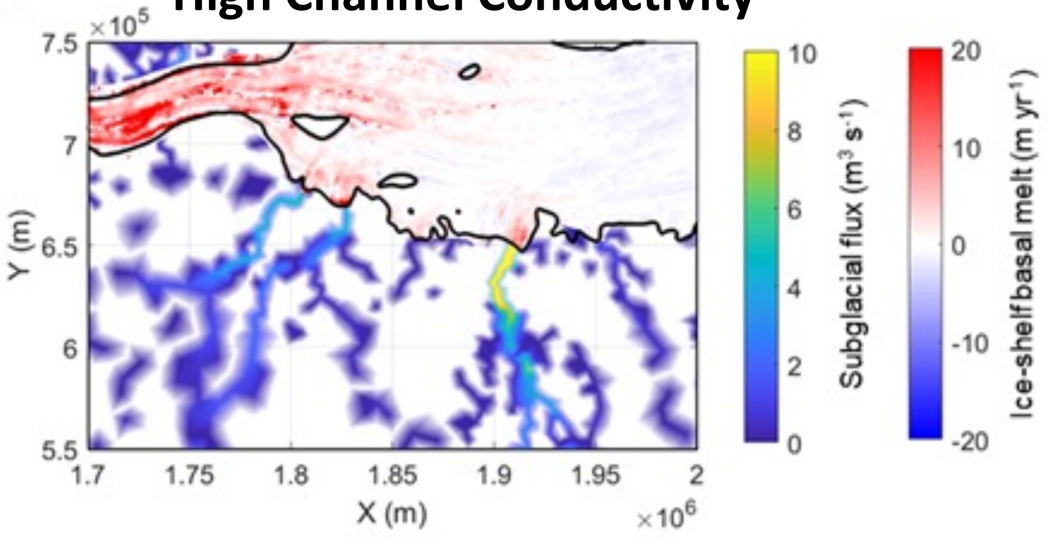


Results: Subglacial hydrology

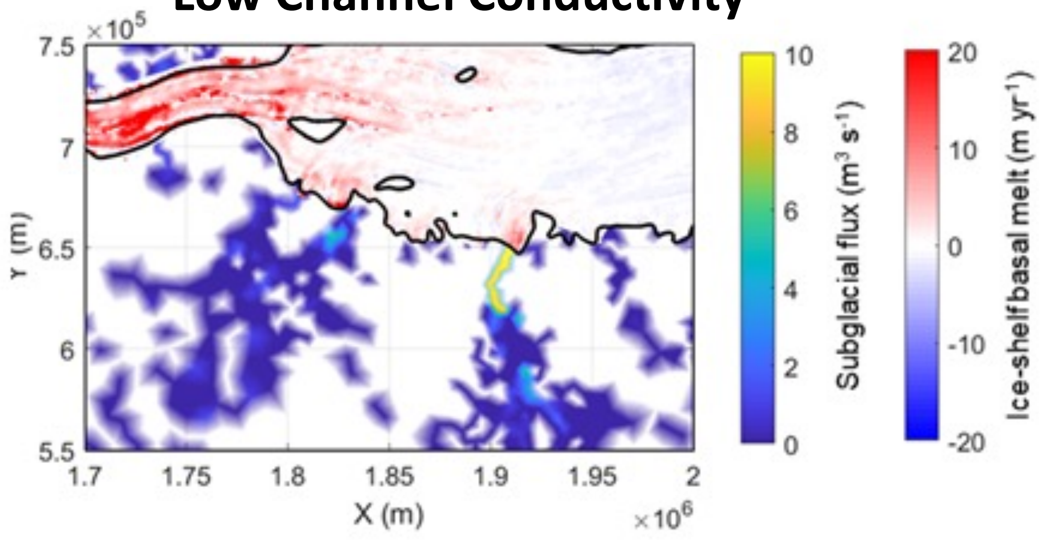
- Comparing channel location and flux with high and low conductivity.
- Channelized discharge for high conductivity coincides with ice-shelf basal melting.
- Channelized flux is significantly reduced for low conductivity



High Channel Conductivity



Low Channel Conductivity



Conclusion

- Total basal melt rate is 6.5 ± 0.5 Gt yr^{-1}, with range due to uncertain GHF.
- 50% more than previous estimates – we resolve high basal frictional dissipation beneath ice streams.

- Using observations from satellite altimetry, we have been able to constrain the subglacial hydrology.
- Coincidence of:
  1. Deep subglacial water and low effective pressure with the locations observed subglacial lakes
  2. Areas of isolated ice-shelf basal melting with channelized discharge

  Both imply high channel conductivity

- Discharge of meltwater provides 15% of freshwater released into the ice-shelf cavity.
- Use of satellite observations to constrain model gives us confidence in subglacial hydrology results.