On the relation between ice thickness changes and glacier speed-up

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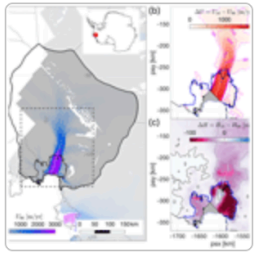
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Research article

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Drivers of Pine Island Glacier speed-up between 1996 and 2016



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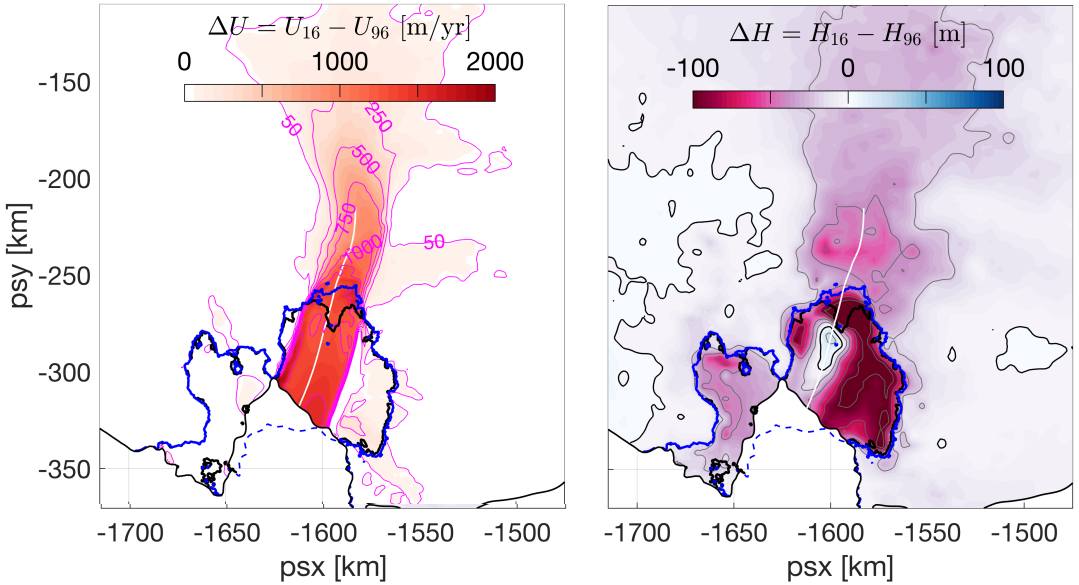
Tipping Points in Antarctic Climate Components

Motivation

Measured changes in surface speed (ΔU) and ice thickness (ΔH) hold important information about poorly constrained physical parameters.

For example, the relationship between ΔU and ΔH for grounded ice critically depends on the (uncertain) rheology of the underlying bedrock and sediments.

We used observations of ΔU and ΔH for Pine Island Glacier between 1996 and 2016 (Fig. on the right) to gain insights into the basal properties of the glacier.



Measured changes in ice surface speed (left) and ice thickness (right) of Pine Island Glacier between 1996 and 2016.

Theoretical relationship between ΔU and ΔH

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A linearized relationship between infinitesimal changes in surface speed (δU) and ice thickness (or surface elevation, δS) can be expressed in terms of the transfer function $\mathcal{T}_{US}$:

$\delta U = \mathcal{T}_{US}\, \delta S$

An analytical expression for $\mathcal{T}_{US}$ was derived by *Gudmundsson [2008]* for SSA flow and a non-linear viscous sliding law

$$\boldsymbol{\tau}_\mathrm{b} = C^{-1/m} \|\boldsymbol{U}_\mathrm{b}\|^{\frac{1}{m}-1} \boldsymbol{U}_\mathrm{b}.$$

The amplitude of the transfer function $|\mathcal{T}_{US}|$ depends on the sliding exponent *m* in a non-linear way:

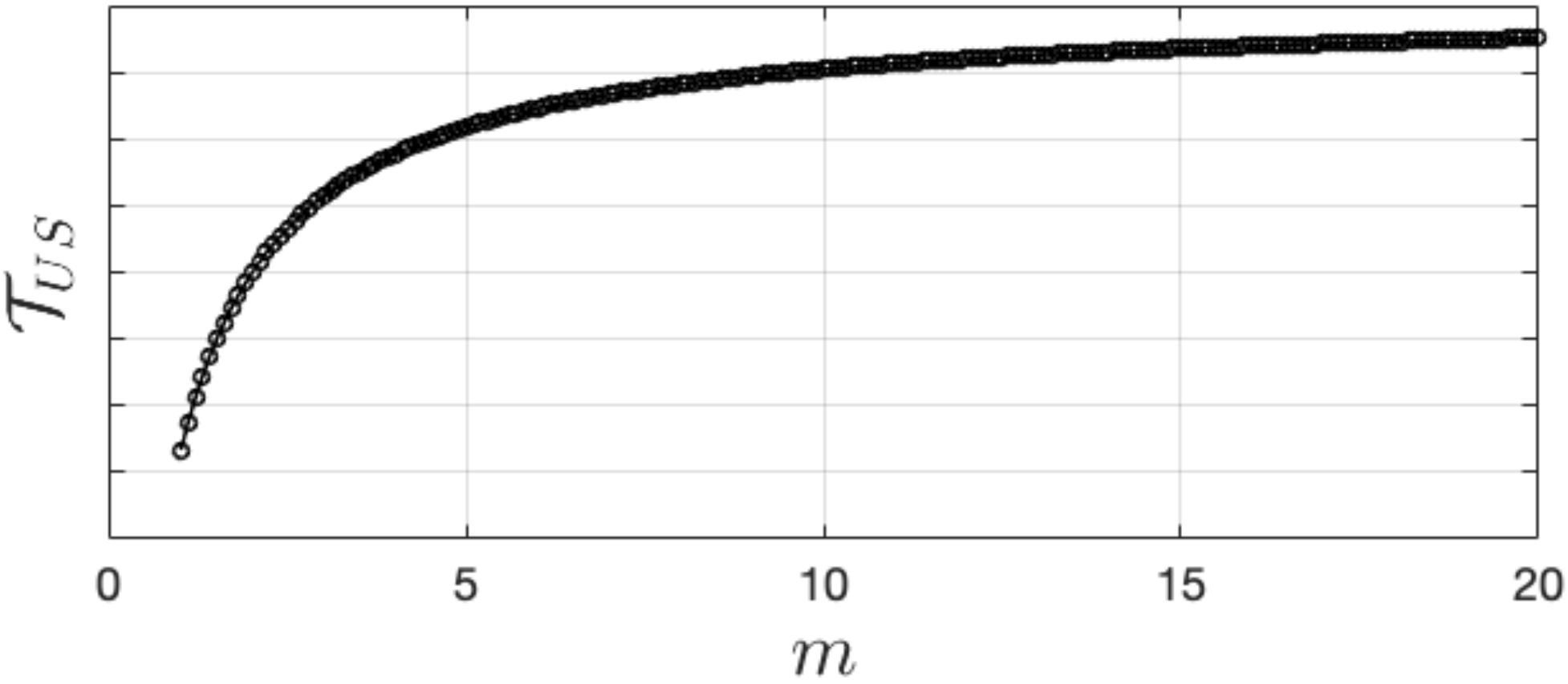
$$\delta U \equiv \left| \mathscr{T}_\mathrm{US}\left(m\right) \right| \delta S = \frac{f_1 m}{m + f_2} \delta S\,.$$

where f_1 and f_2 depend on the geometry of the system.

Gudmundsson, G. H.: Analytical solutions for the surface response to small amplitude perturbations in boundary data in the shallow-ice-stream approximation, The Cryosphere, 2, 77–93, https://doi.org/10.5194/tc-2-77-2008, 2008

Theoretical relationship between ΔU and ΔH

Transfer theory therefore implies that the velocity response to a given perturbation in ice thickness increases with values of the sliding exponent *m*:



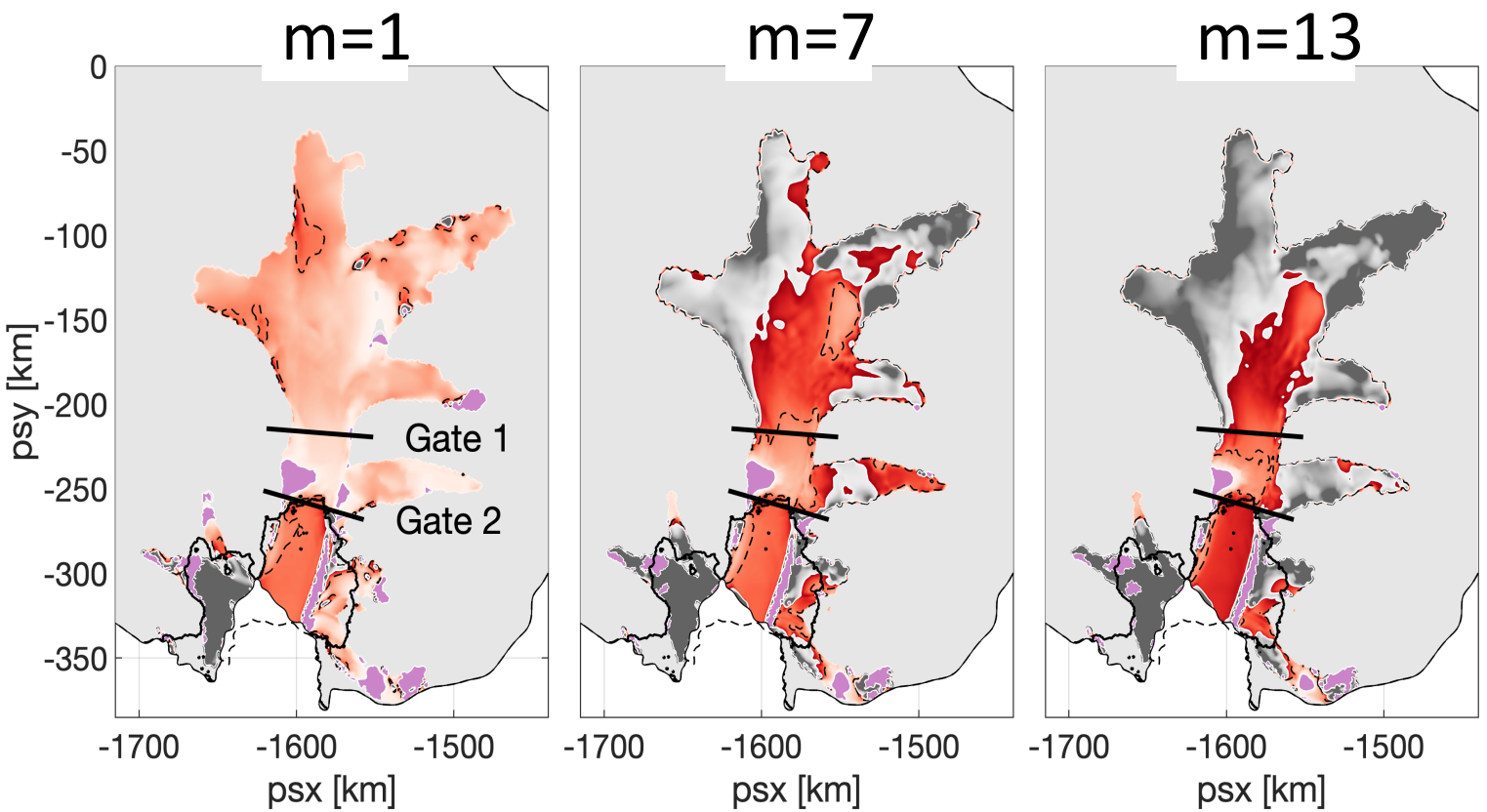
The value of the horizontal asymptote ($m \to \infty$), and the slope of the curve are determined by f_1 and f_2.

Relationship between ΔU and ΔH in an SSA model

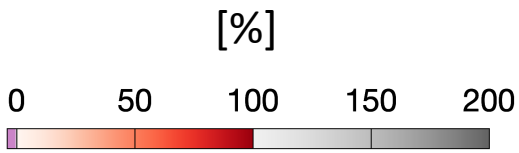
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For realistic systems, the relationship between ΔU and ΔH can be explored with an SSA ice flow model.

We used the ice flow model Úa [Gudmundsson 2020] to simulate the velocity response of Pine Island Glacier to an identical (measured) perturbation in ice thickness, but for different values of *m* (see Fig. below)



The simulated changes in surface speed are expressed as a percentage of the measured change in surface speed.

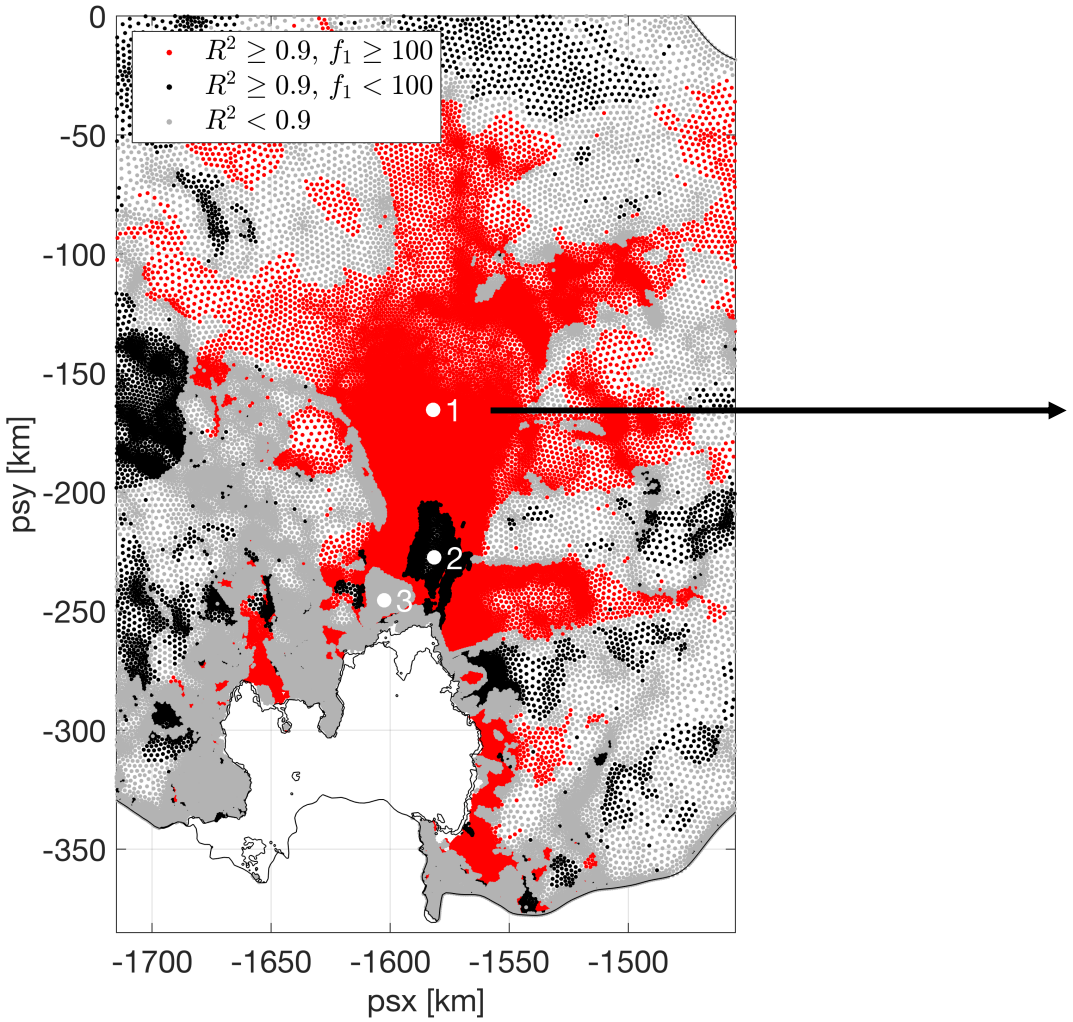


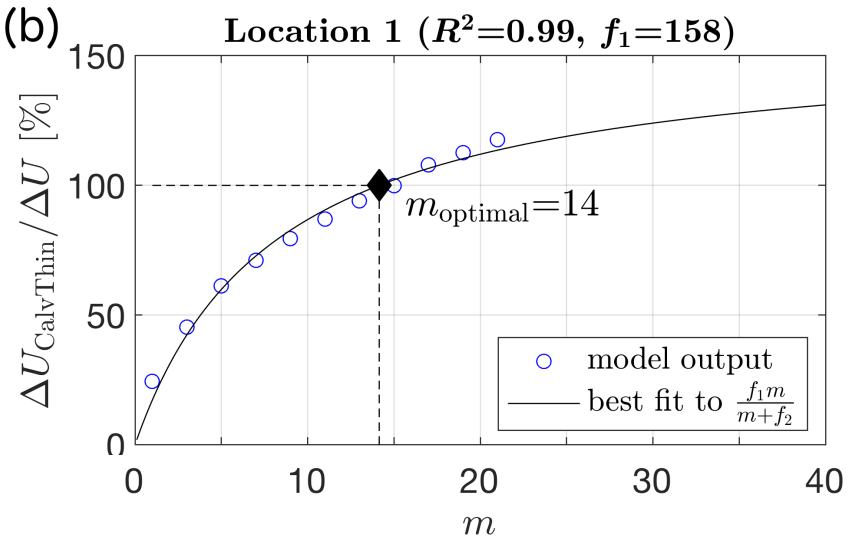
Gudmundsson, G. H.: GHilmarG/UaSource: Ua2019b (Version v2019b), Zenodo, https://doi.org/10.5281/zenodo.3706623, 2020.

Relationship between ΔU and ΔH in an SSA model

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For large parts of the glacier (red areas in Fig below), the expected non-linear dependency on *m* of the velocity response is recovered.

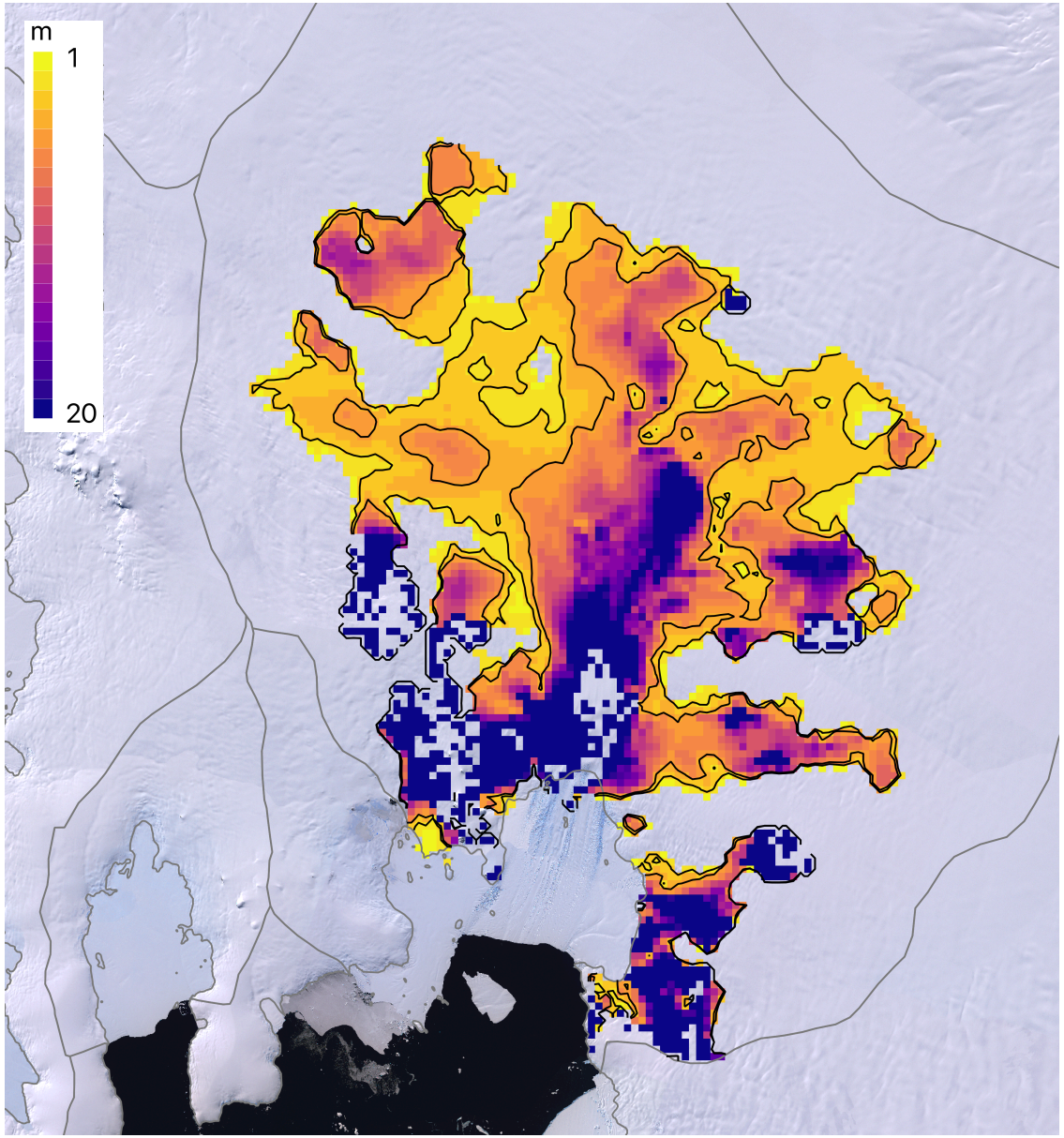




Results: an optimal distribution of *m* beneath Pine Island Glacier

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By requiring an optimal fit between the simulated and observed velocity response, we were able to estimate a spatially heterogeneous distribution of *m* beneath Pine Island Glacier (Fig on the right).



Results: an optimal distribution of *m* beneath Pine Island Glacier

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Key observations:

SSA simulations are only consistent with observed rates of speed-up if

- Plastic (*m*>*5*) bed conditions are assumed beneath most of the fast-flowing tributaries and along the central valley.

- A linear or weakly non-linear rheology exist beneath slow-flowing inter-tributary areas.

Results are consistent with earlier findings, e.g. [Joughin et al. *GRL* 2019] and [Gillet-Chaulet et al. *GRL* 2016].

