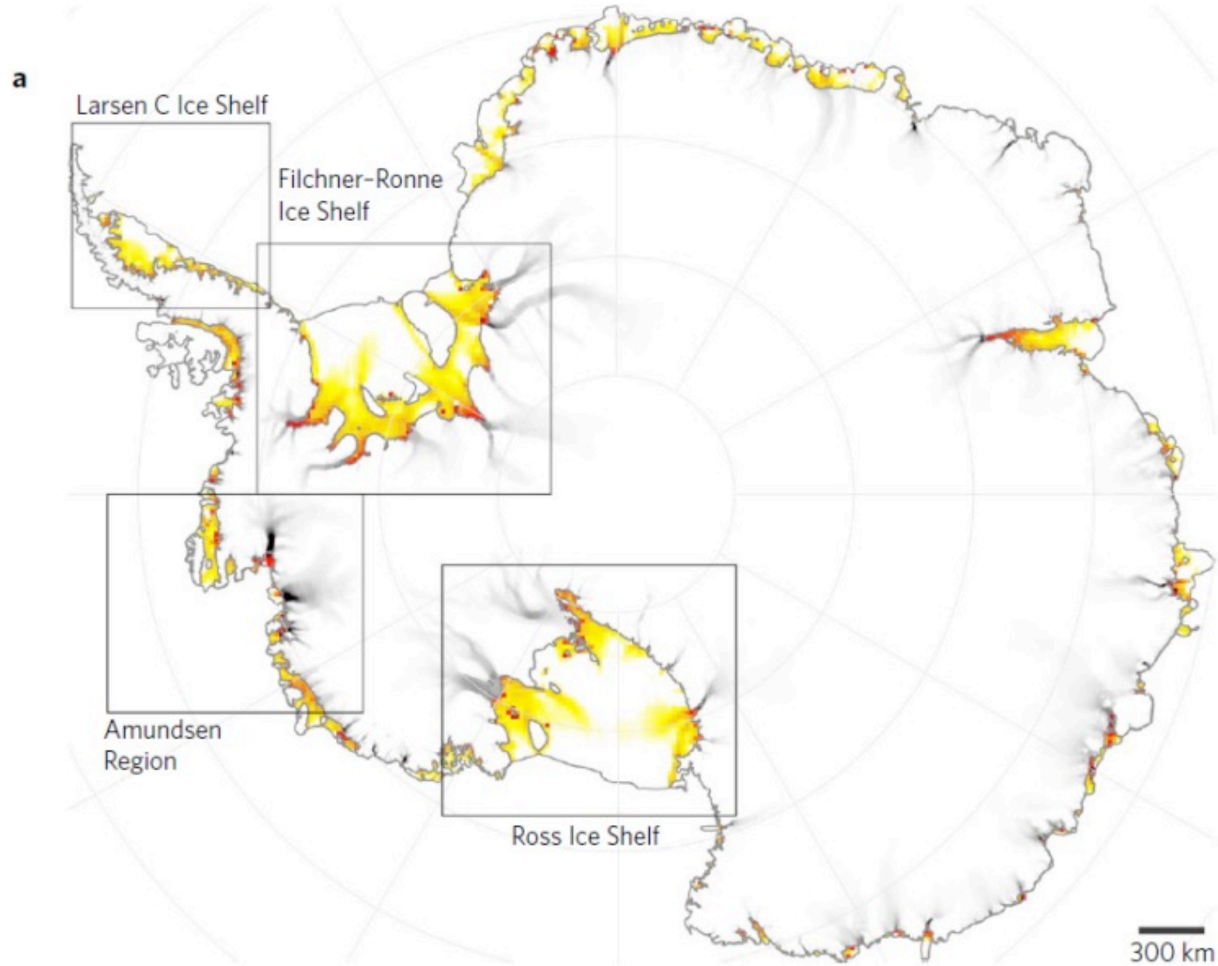
Glaciology
EESCGU4220

Lecture 9: Review + Ice Shelves



Review of SIA practical

Review of first ½ of semester

Ice shelves

SIA practical: surface mass balance

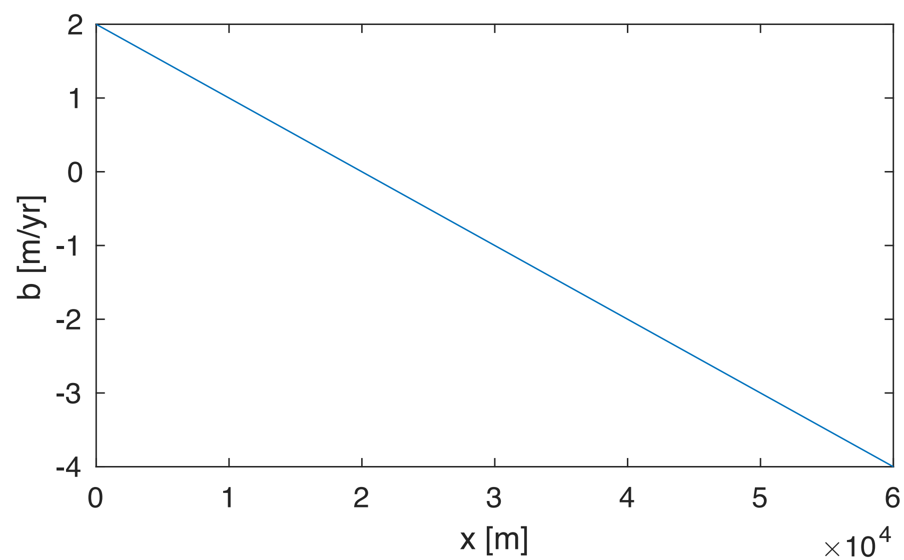
$$\frac{\partial H}{\partial t} + \frac{\partial q}{\partial x} = b_i$$

$$q = \frac{2A}{n+2}(\rho g \alpha)^n H^{n+2}$$

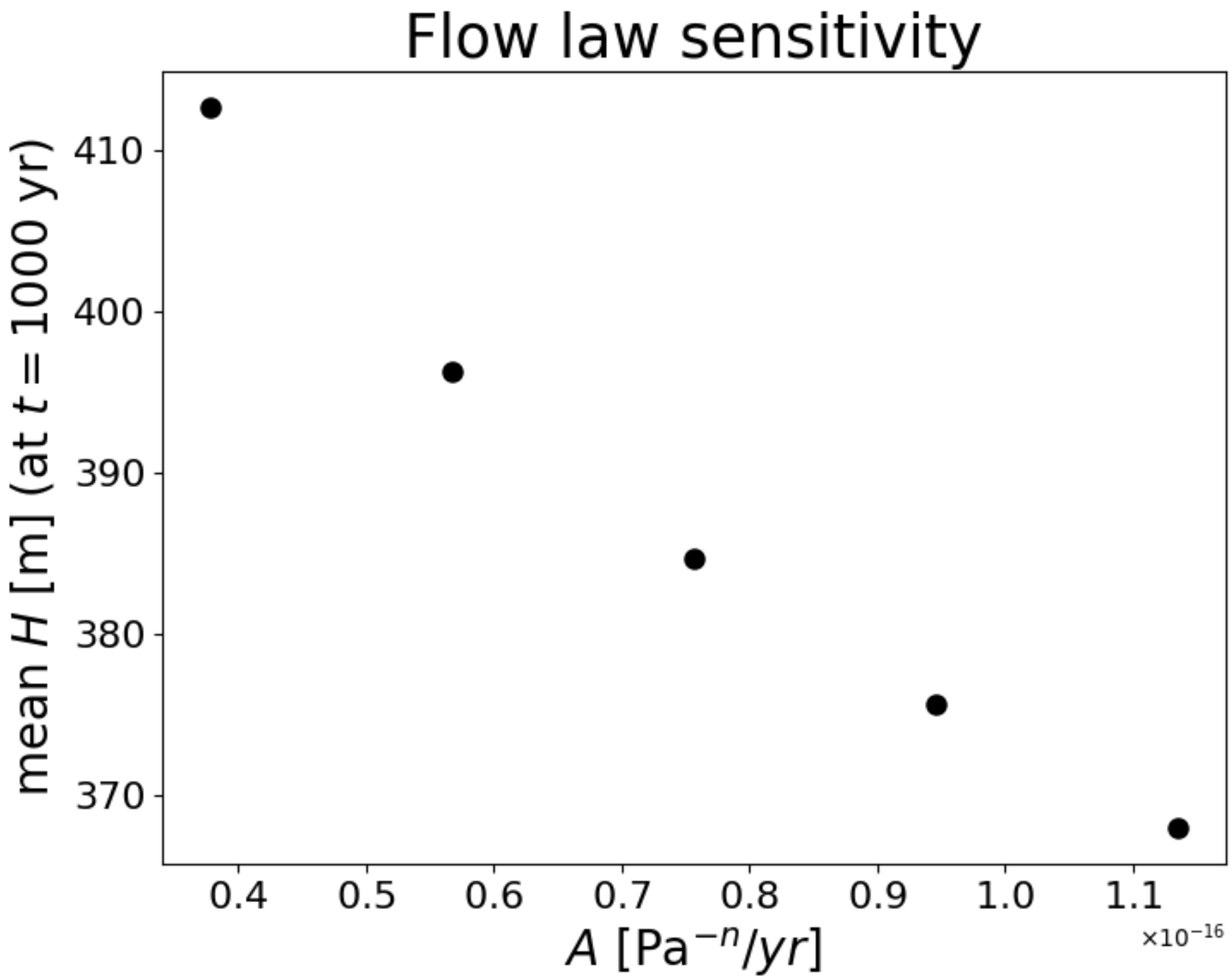
$$q(0) = 0$$

ELx = X/3

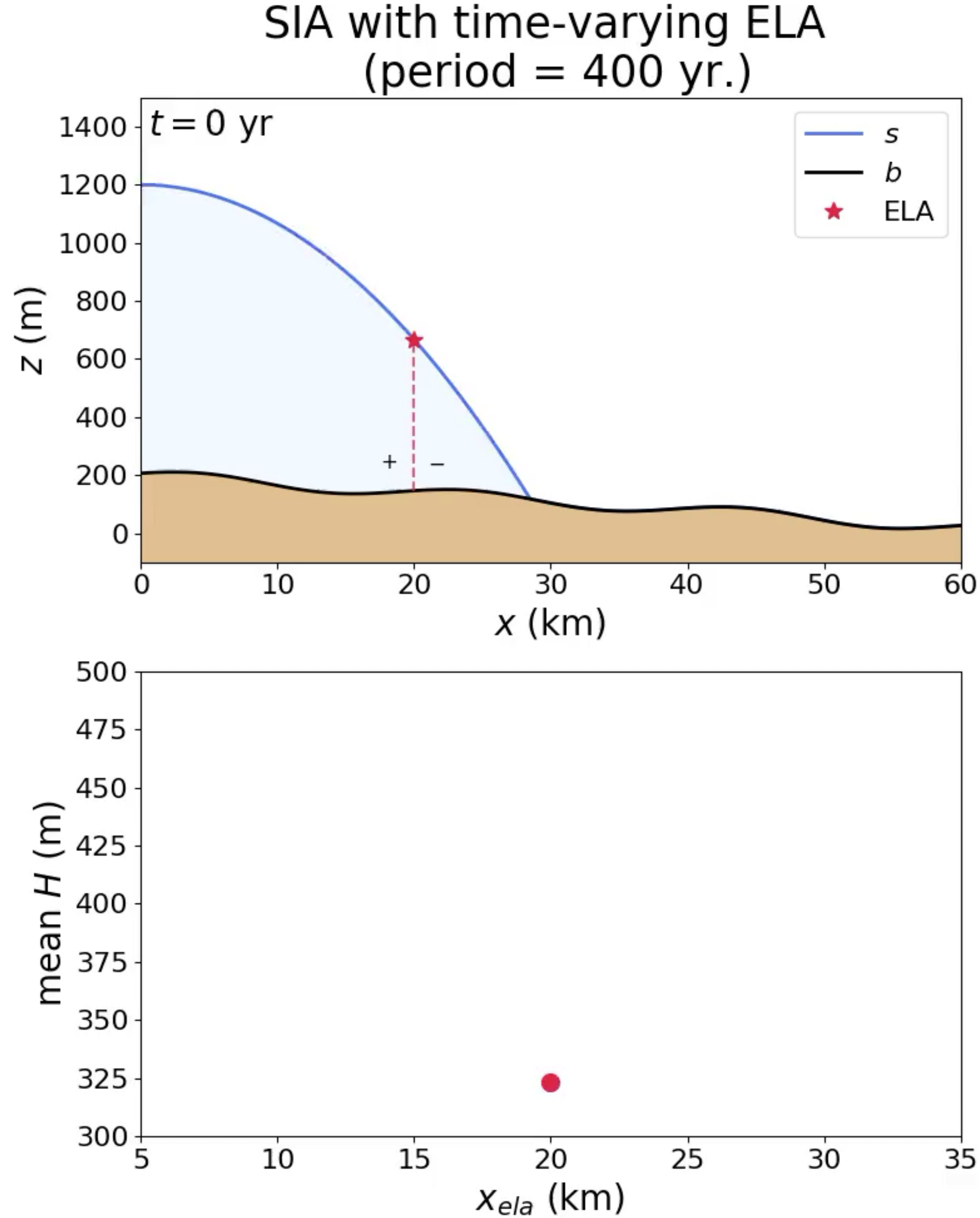
$b = 10^{-4}(X/3 - x)$



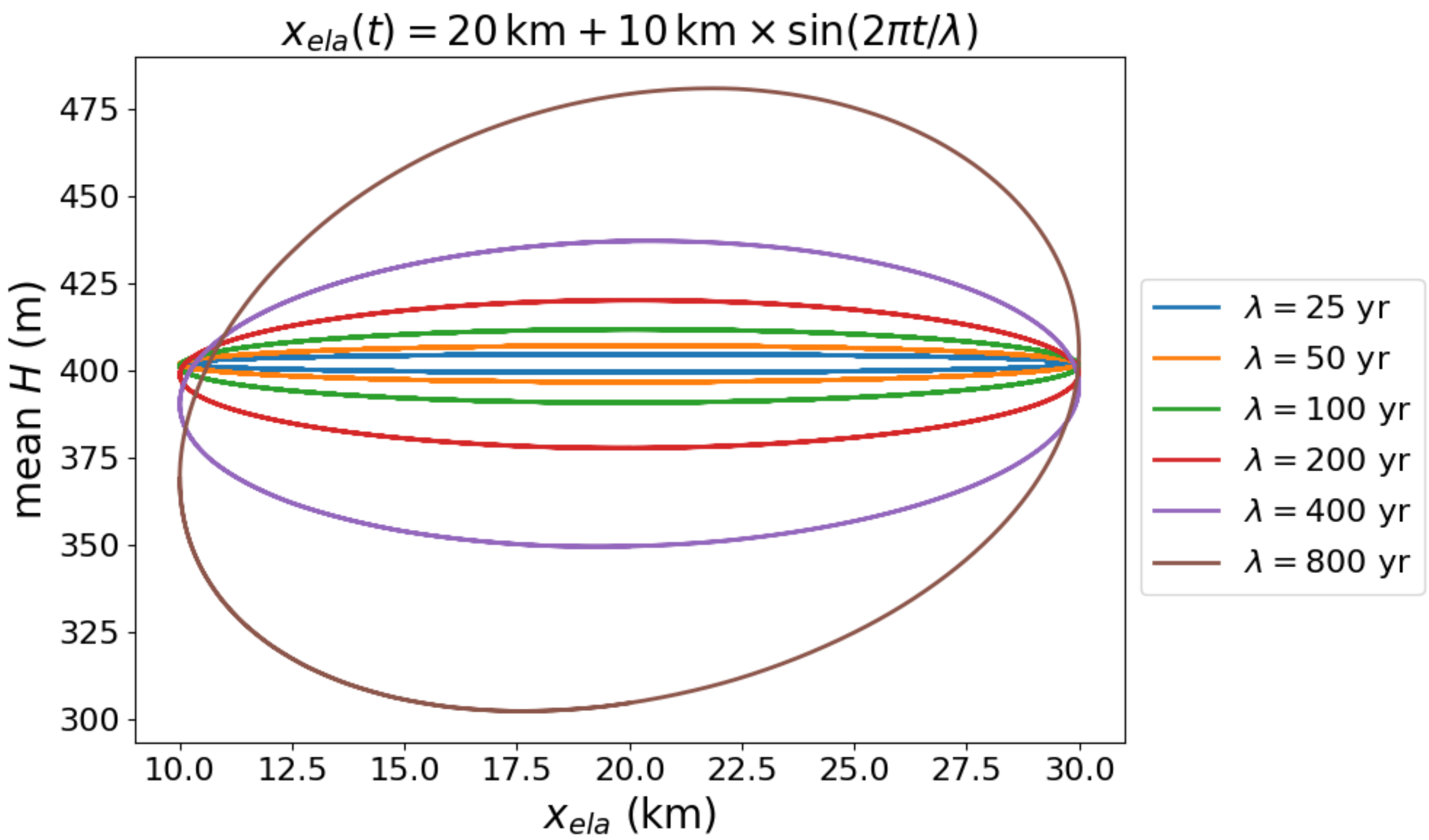
SIA practical: parameter sensitivity



SIA practical: Transient evolution



SIA practical: Transient evolution



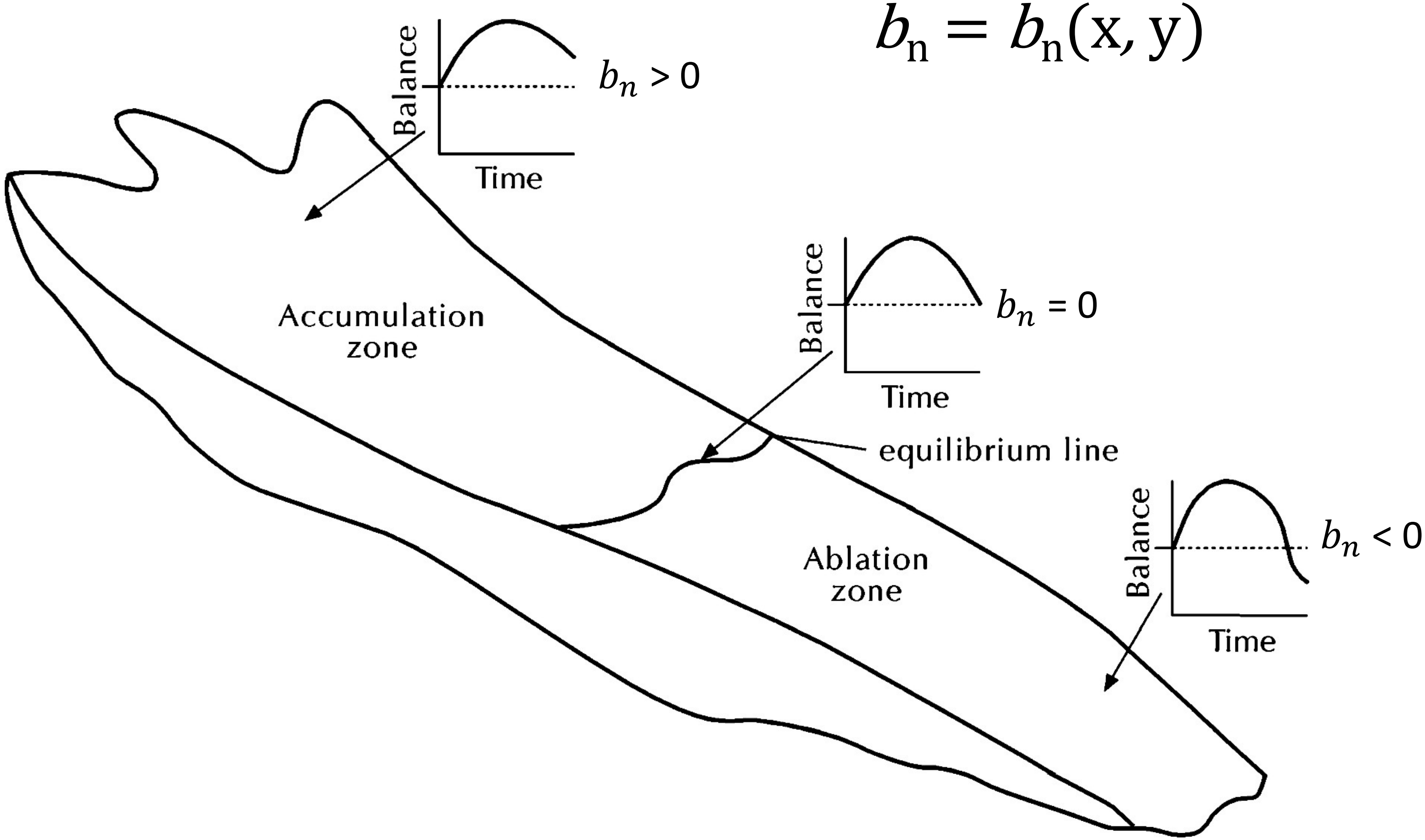
Review of first half of semester

- Surface mass balance
  - Accumulation zone processes
  - Surface energy balance
  - Basal melting

- Ice flow
  - Rheology
  - Stress balance
  - SIA model
  - Basal motion
  - Ice divides
  - Grounding lines

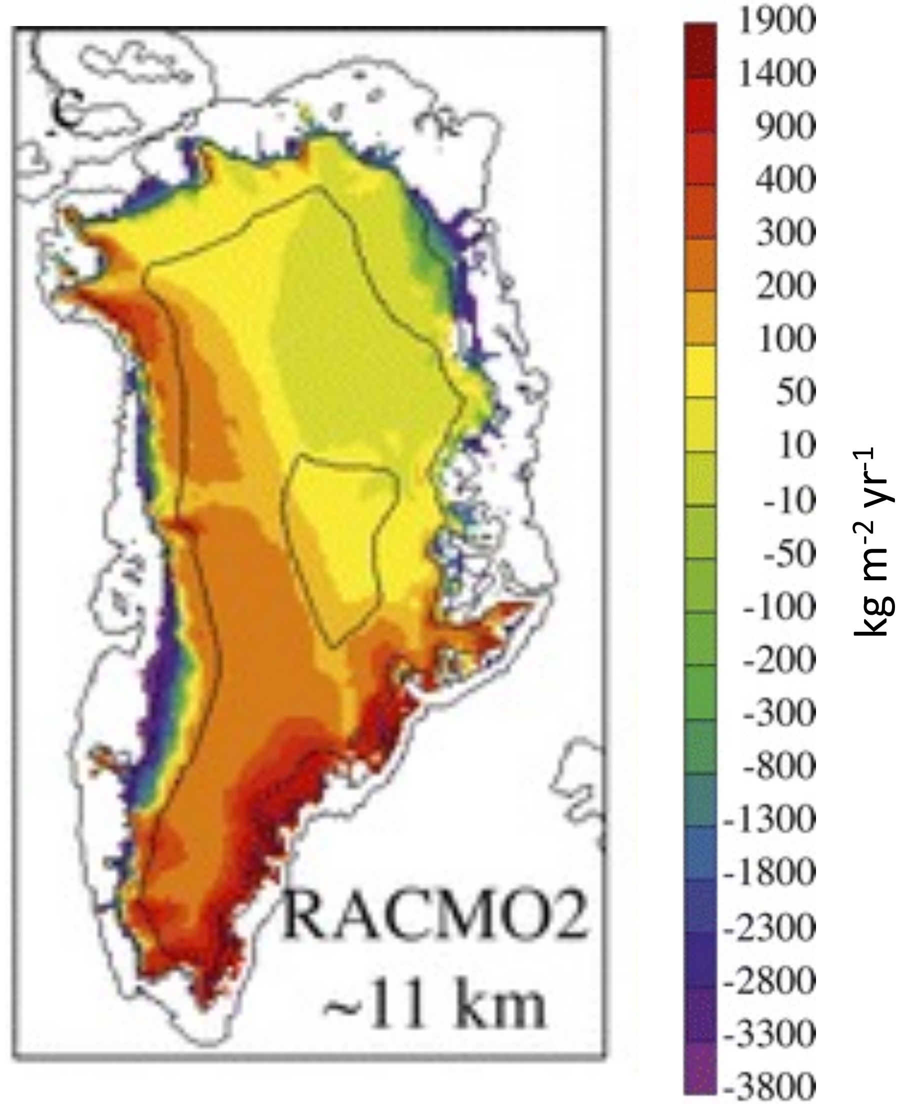
Spatially-varying net specific balance

$$b_n = b_n(x, y)$$



Cuffey and Paterson (2010)

Long-term SMB of Greenland

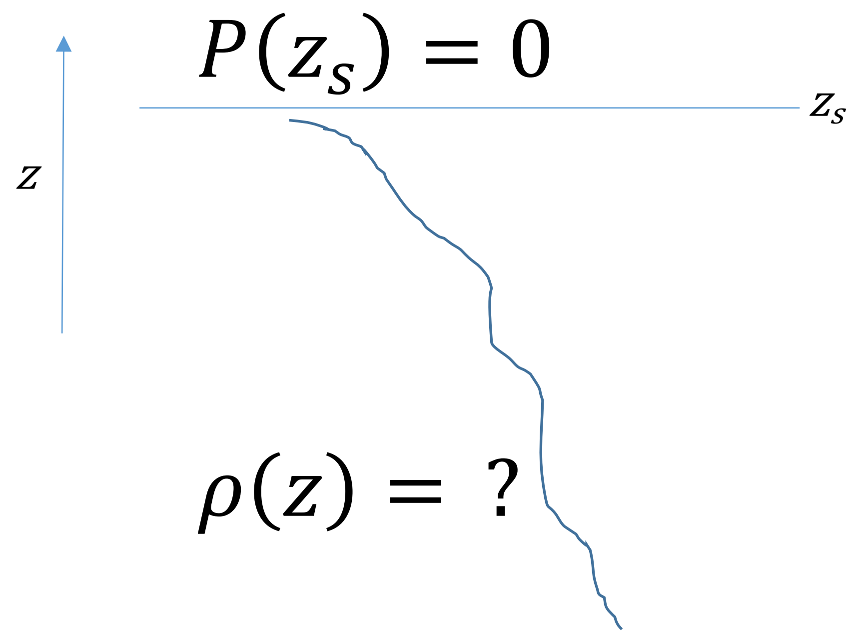


Vizcaíno et al. (2014)

Overburden pressure

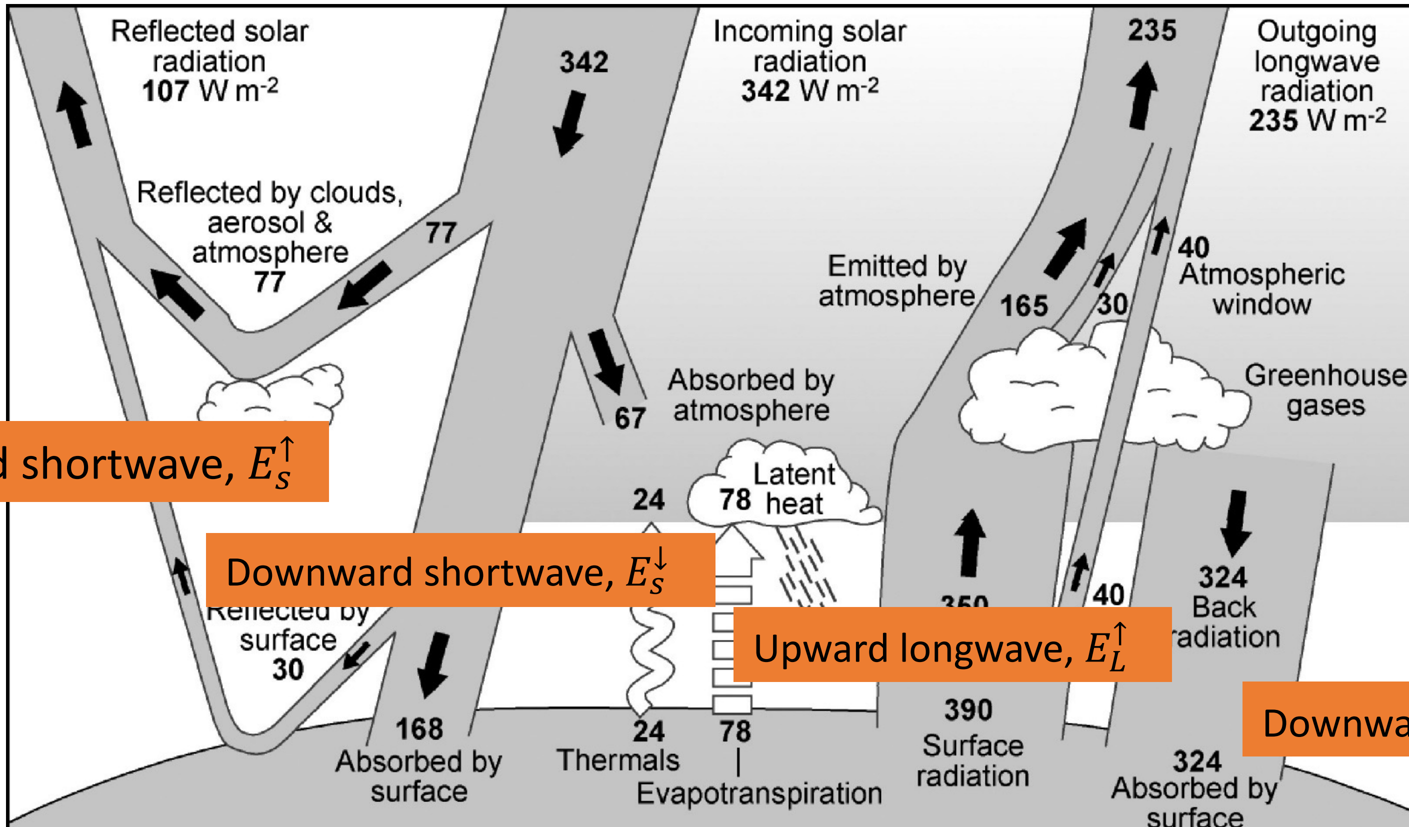
We want an equation for how pressure P varies with depth.

$$\frac{dP}{dz} = \rho(z)g$$



Surface energy balance

$$E_N = E_S^{\downarrow} + E_S^{\uparrow} + E_L^{\downarrow} + E_L^{\uparrow} + E_H + E_E$$



Upward shortwave, $E_S^{\uparrow}$

Downward shortwave, $E_S^{\downarrow}$

Upward longwave, $E_L^{\uparrow}$

Downward longwave,

Stress, strain, rheology, mass balance

$$\dot{\boldsymbol{\epsilon}} = \begin{bmatrix} \dot{\boldsymbol{\epsilon}}_{xx} & \dot{\boldsymbol{\epsilon}}_{xy} & \dot{\boldsymbol{\epsilon}}_{xz} \\ \dot{\boldsymbol{\epsilon}}_{yx} & \dot{\boldsymbol{\epsilon}}_{yy} & \dot{\boldsymbol{\epsilon}}_{yz} \\ \dot{\boldsymbol{\epsilon}}_{zx} & \dot{\boldsymbol{\epsilon}}_{zy} & \dot{\boldsymbol{\epsilon}}_{zz} \end{bmatrix}$$

$$\boldsymbol{\sigma} = \begin{bmatrix} \sigma_{xx} & \tau_{xy} & \tau_{xz} \\ \tau_{yx} & \sigma_{yy} & \tau_{yz} \\ \tau_{zx} & \tau_{zy} & \sigma_{zz} \end{bmatrix}$$

$$\dot{\epsilon_{ij}} = \frac{1}{2}\left[\frac{\partial u_j}{\partial x_i} + \frac{\partial u_i}{\partial x_j}\right]$$

$$\boldsymbol{\sigma} = \boldsymbol{\tau} + \boldsymbol{\sigma_m}$$

$$\dot{\epsilon_{ij}} = A\tau_E^{n-1}\tau_{ij} \qquad (i,j = x, y, z)$$

$$\tau_E^2 = \frac{1}{2}\left[\tau_{xx}^2 + \tau_{yy}^2 + \tau_{zz}^2\right] + \tau_{xz}^2 + \tau_{xy}^2 + \tau_{yz}^2$$

$$\frac{\partial \sigma_{xx}}{\partial x} + \frac{\partial \tau_{yx}}{\partial y} + \frac{\partial \tau_{zx}}{\partial z} = 0$$

$$\frac{\partial \tau_{xy}}{\partial x} + \frac{\partial \sigma_{yy}}{\partial y} + \frac{\partial \tau_{zy}}{\partial z} = 0$$

$$\frac{\partial \tau_{xz}}{\partial x} + \frac{\partial \tau_{yz}}{\partial y} + \frac{\partial \sigma_{zz}}{\partial z} = \rho g$$

$$\frac{\partial H}{\partial t} + \frac{\partial q}{\partial x} = b_i$$

Ice flux in the Shallow Ice Approximation

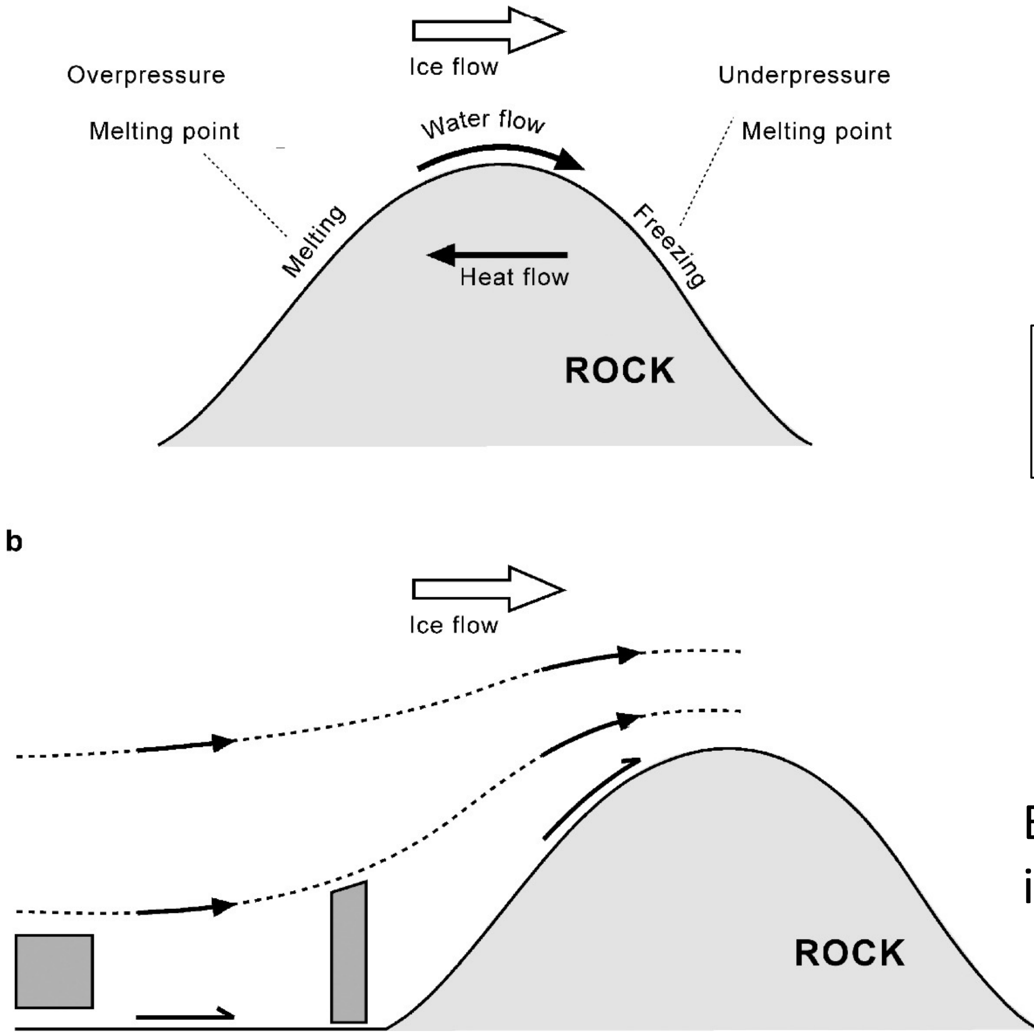
Depth-integrated horizontal velocity per unit width:

$$\hat{u} = 2A(\rho g \alpha H)^n \left(\frac{H}{n+2}\right)$$

Depth-integrated volume-flux per unit width:

$$q = \hat{u}H = \frac{2A}{n+2}(\rho g \alpha)^n H^{n+2}$$

Weertman's theory for hard beds



Two mechanisms:
Regelation &
enhanced creep.

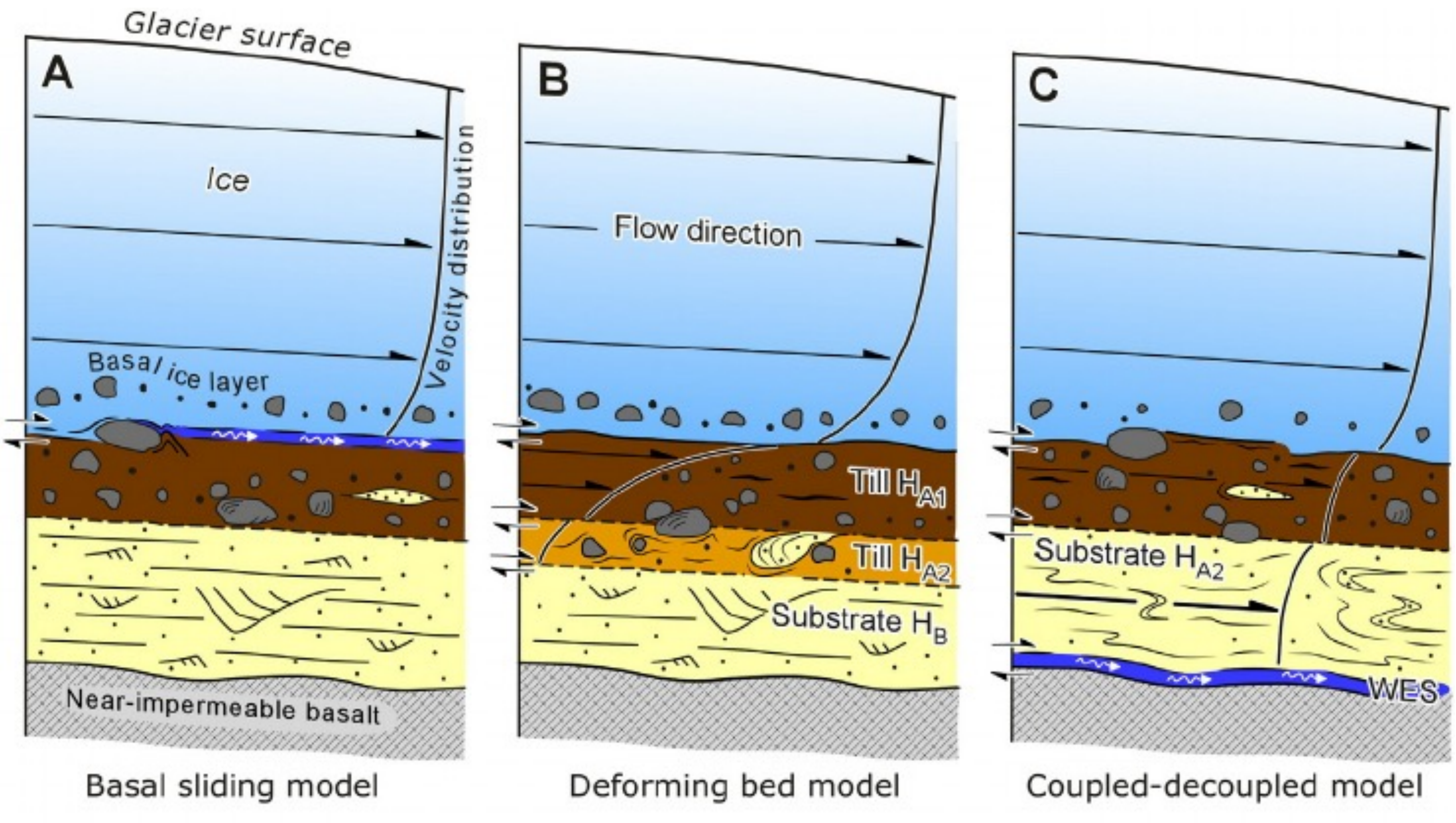
$$\boxed{u_b \propto \left(\frac{\sqrt{\tau_b}}{R}\right)^{n+1}}$$

This is a crude model, but it captures some essence of the processes.

Extension of the theory to include cavitation: Iken (1981)

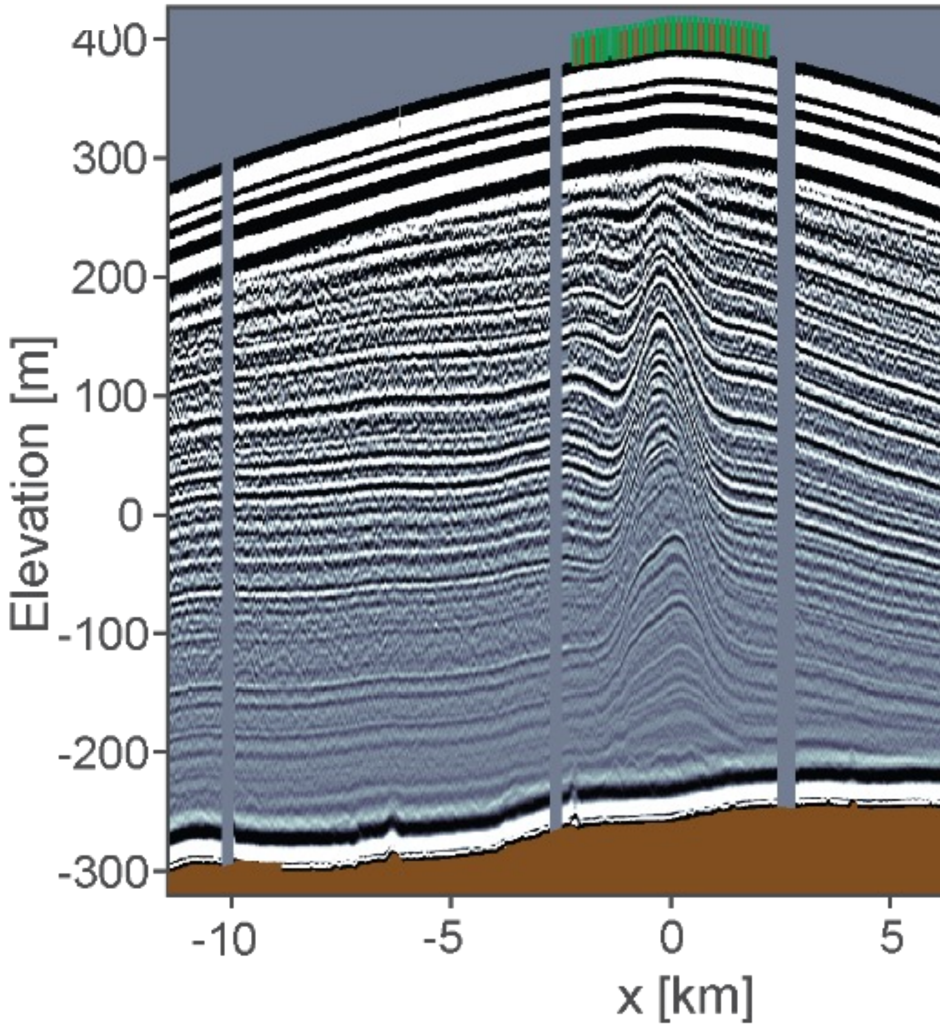
“Soft beds”

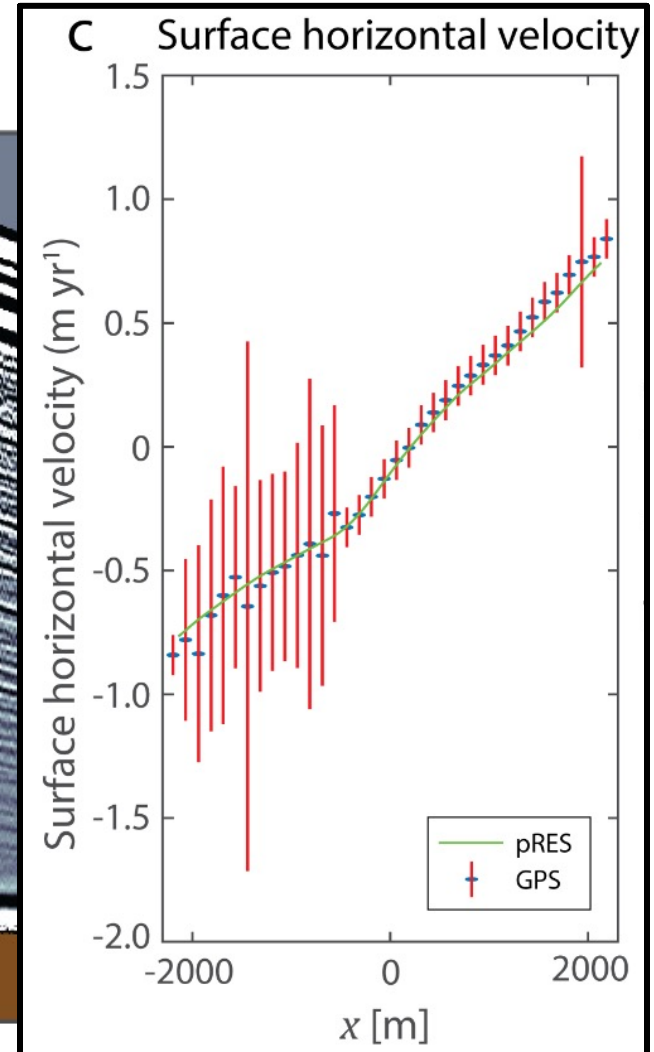
deformable material under the ice.



Modified from Kjær et al. (2006)

Ice divides



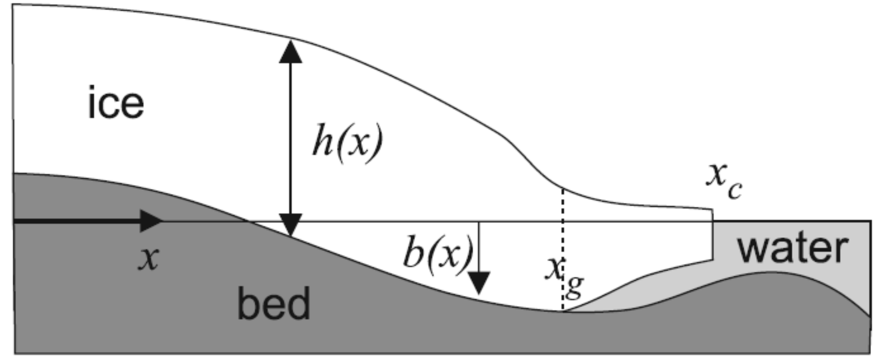


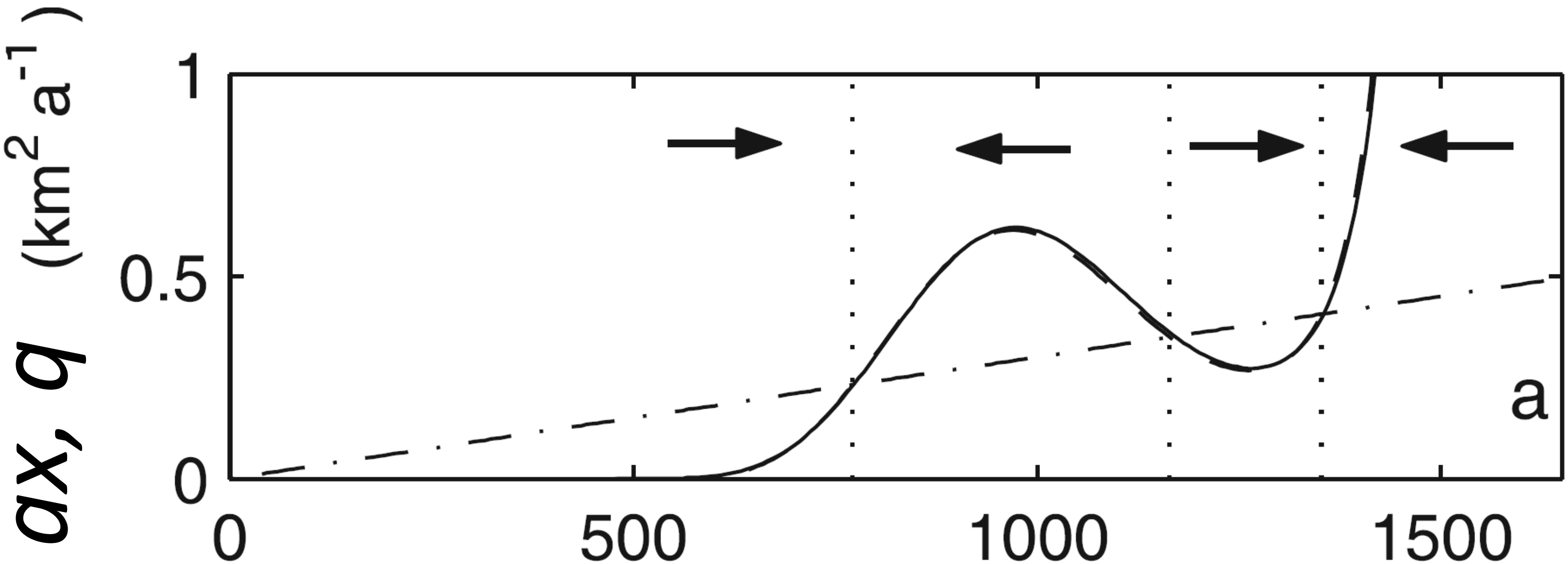
Kingslake et al. (2015)

Schoof's (2007) theory

$$\boxed{q(x_g) \propto h(x_g)^{4.75}}$$

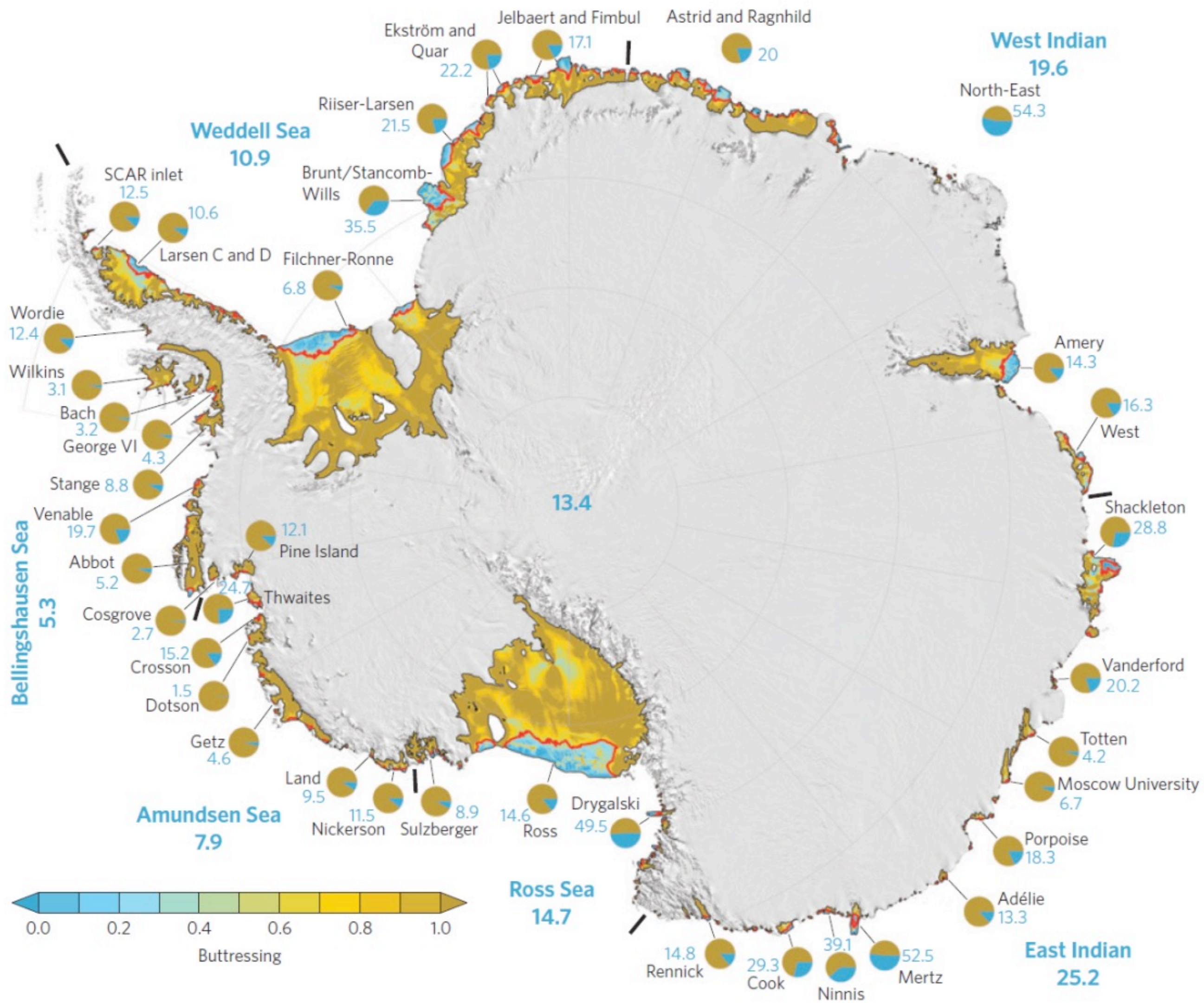
$$\boxed{q = ax}$$





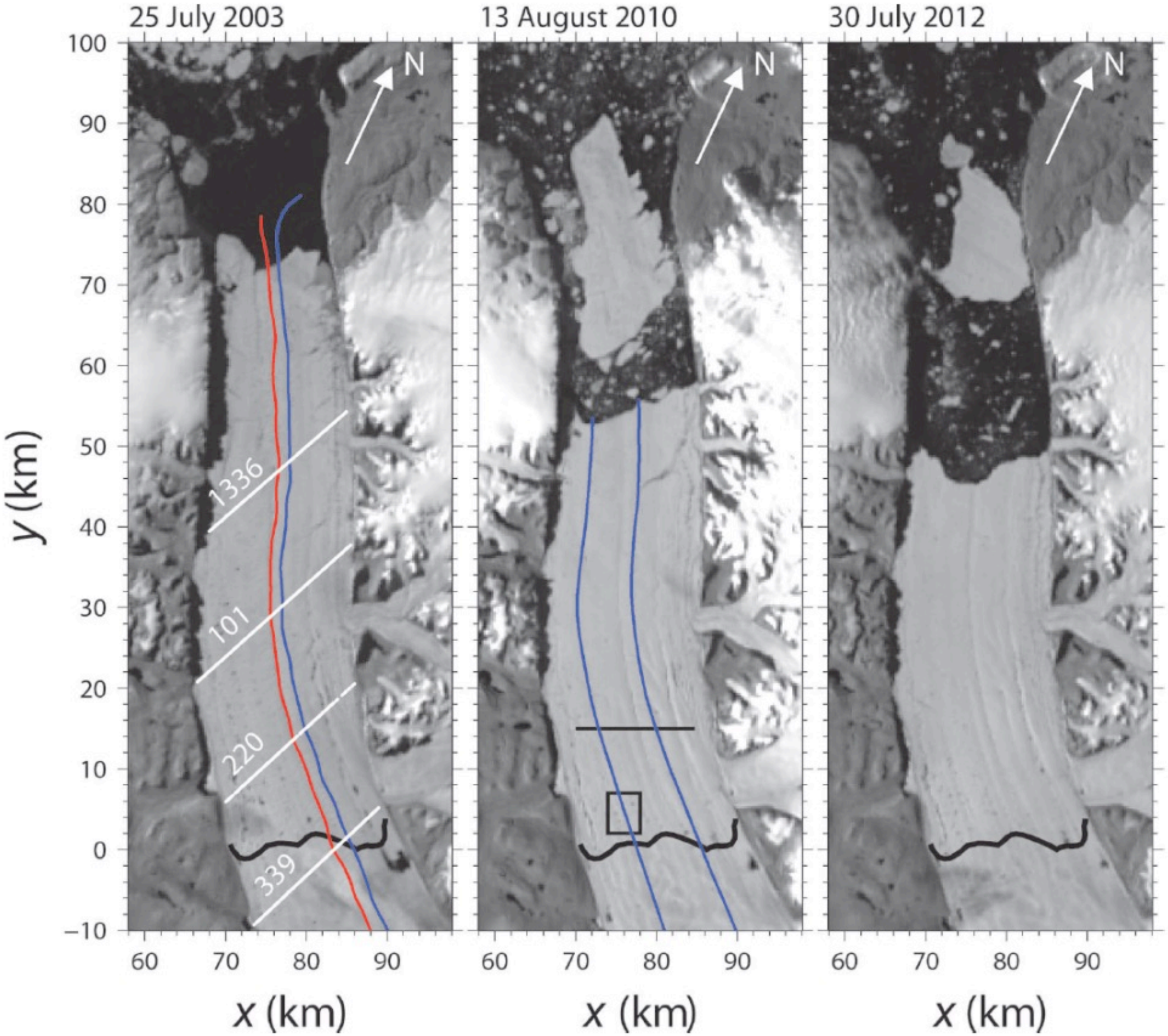
Ice shelves

Antarctic ice shelves

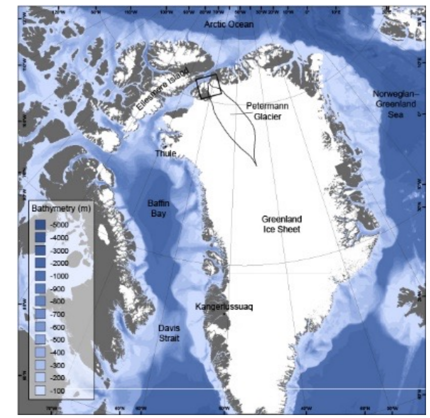


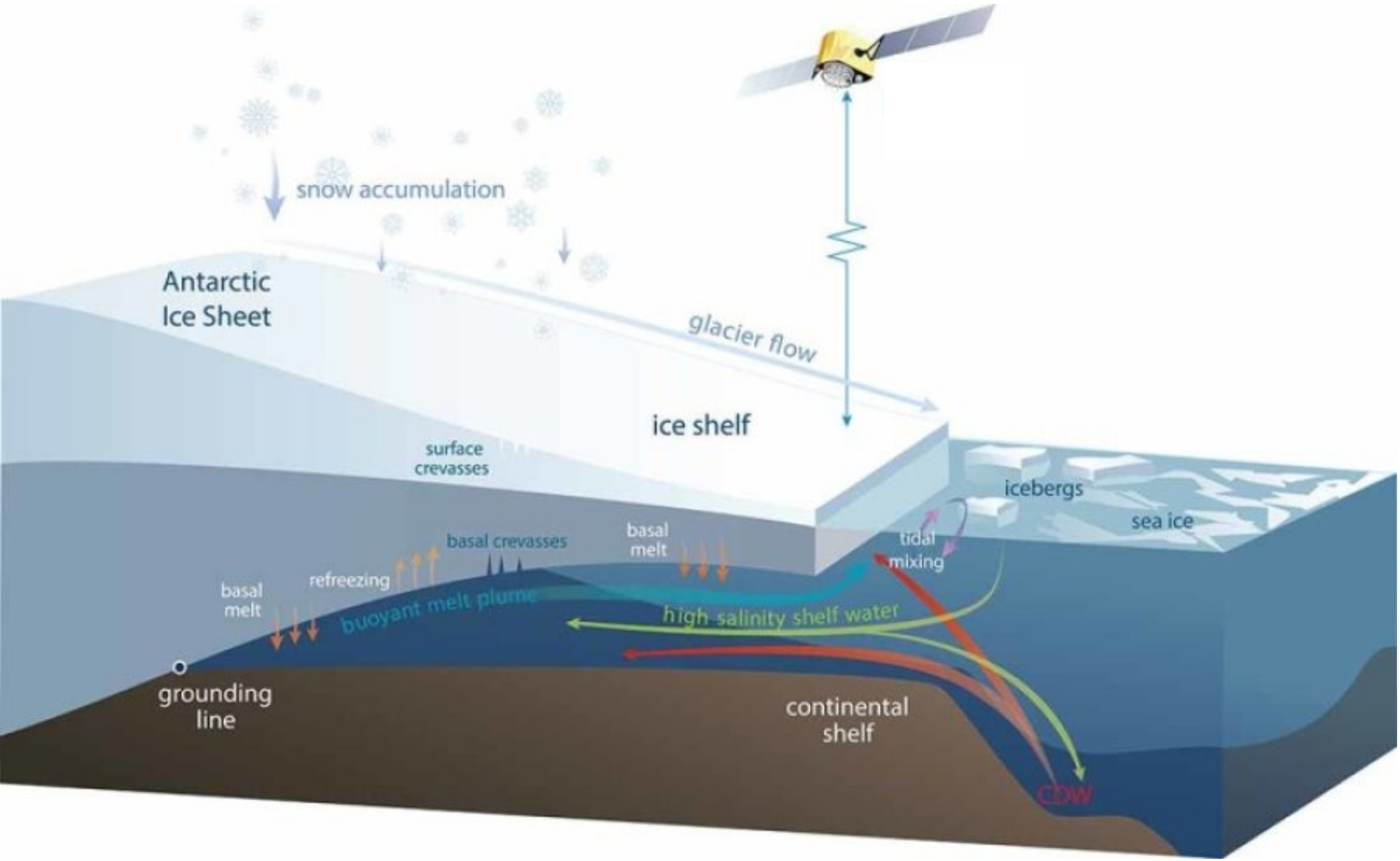
Fürst et al. (2016)

Greenlandic ice shelves

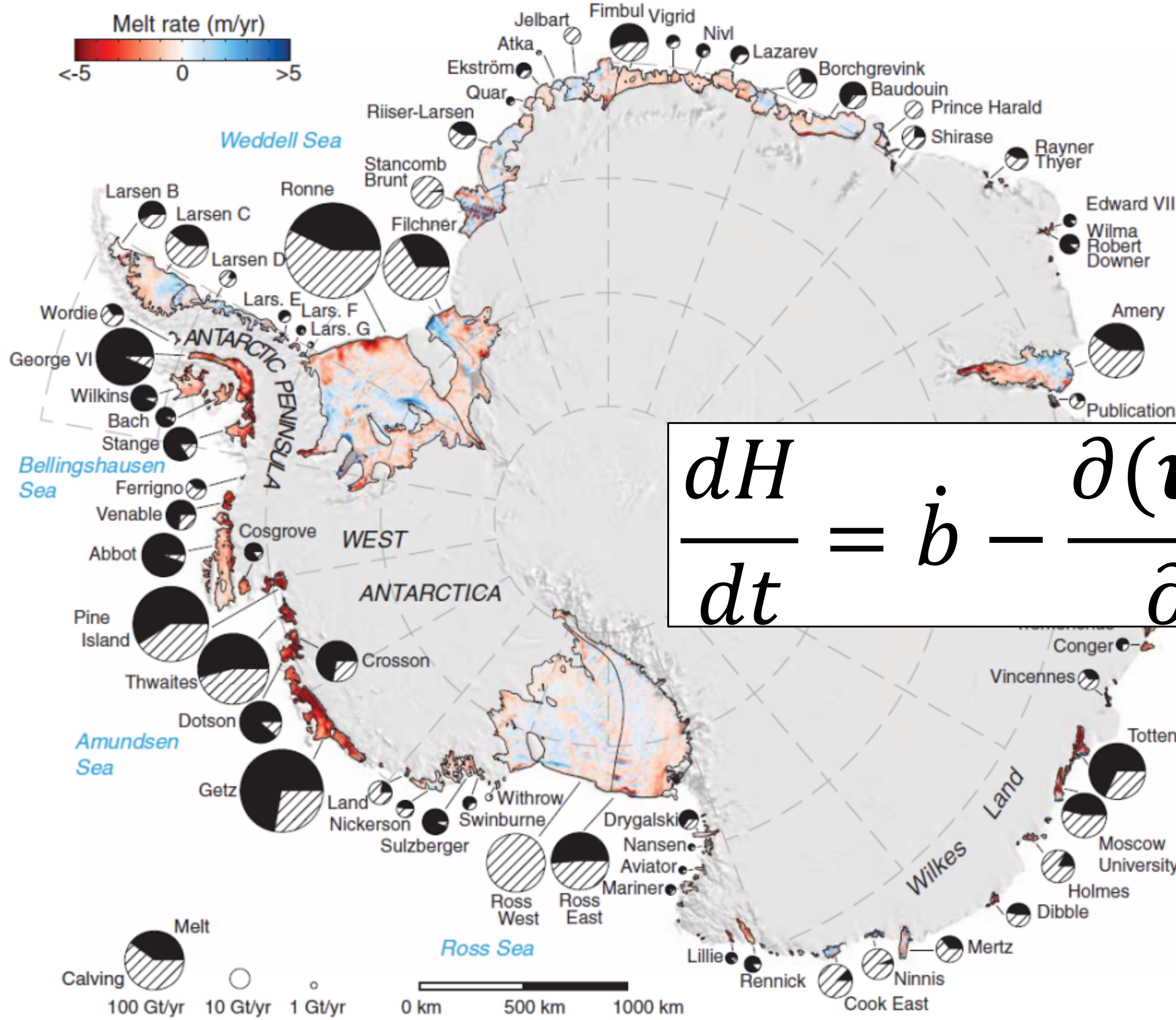


Münchow et al. (2014)




snow accumulation
Antarctic
Ice Sheet
glacier flow
ice shelf
surface
crevasses
icebergs
sea ice
basal crevasses
basal
melt
tidal
mixing
refreezing
basal
melt
buoyant melt plume
high salinity shelf water
grounding
line
continental
shelf
CDW

Ice Shelf mass balance



$$\frac{dH}{dt} = \dot{b} - \frac{\partial(\boldsymbol{u}H)}{\partial x}$$

From satellites

Rignot et al. (2013)

$$\frac{dH}{dt}$$

and

$$H$$

from satellite altimetry.

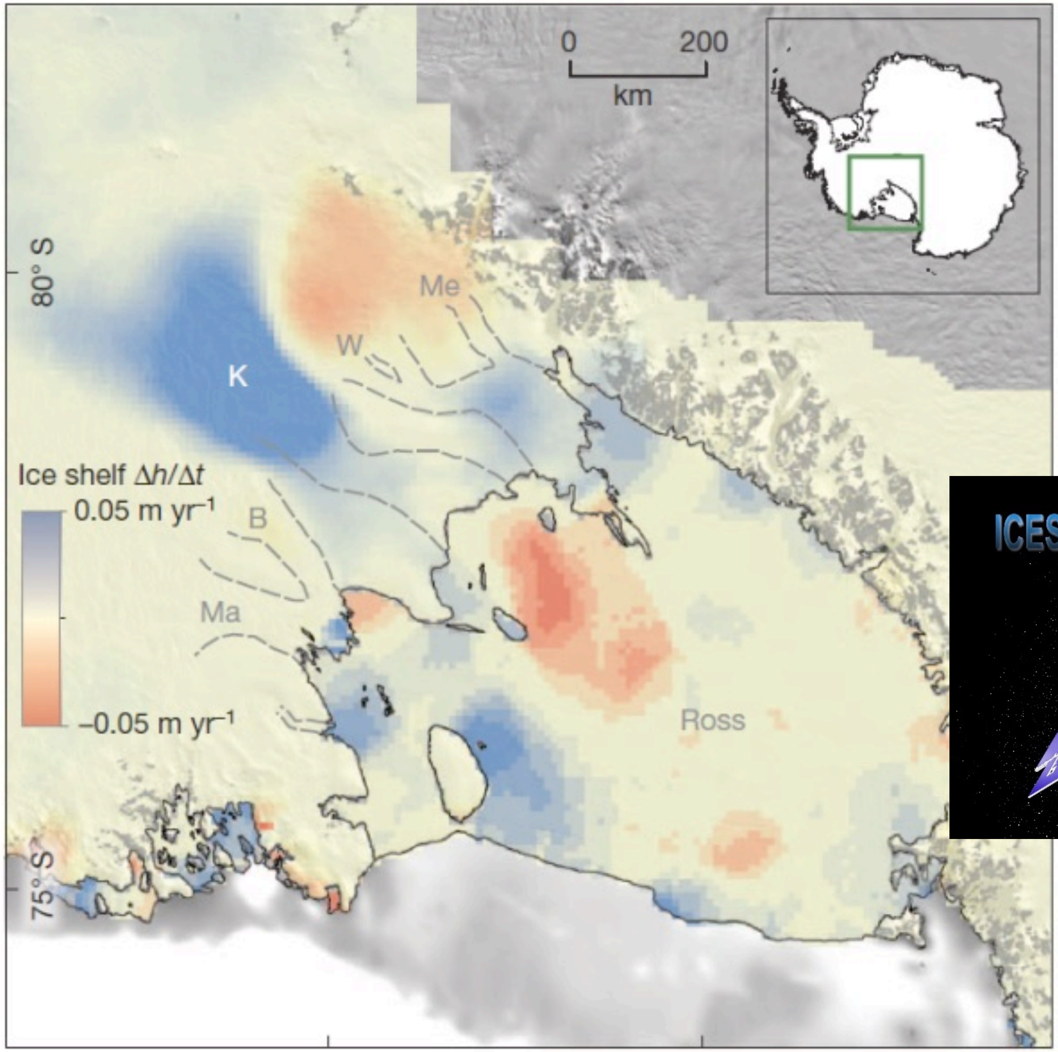
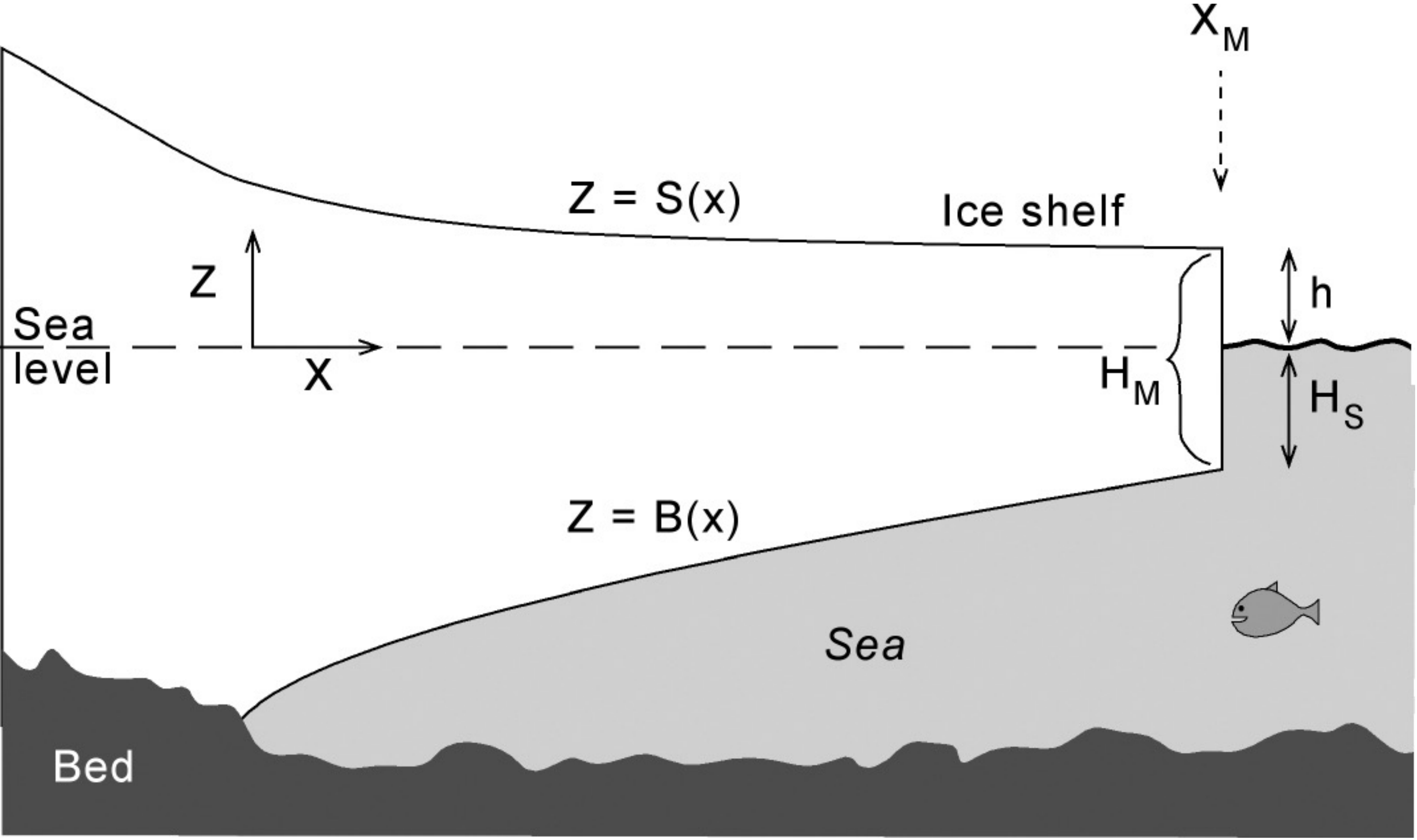


Figure 1 | Surface $\Delta h/\Delta t$ of Ross Ice Shelf, 2003–2008.

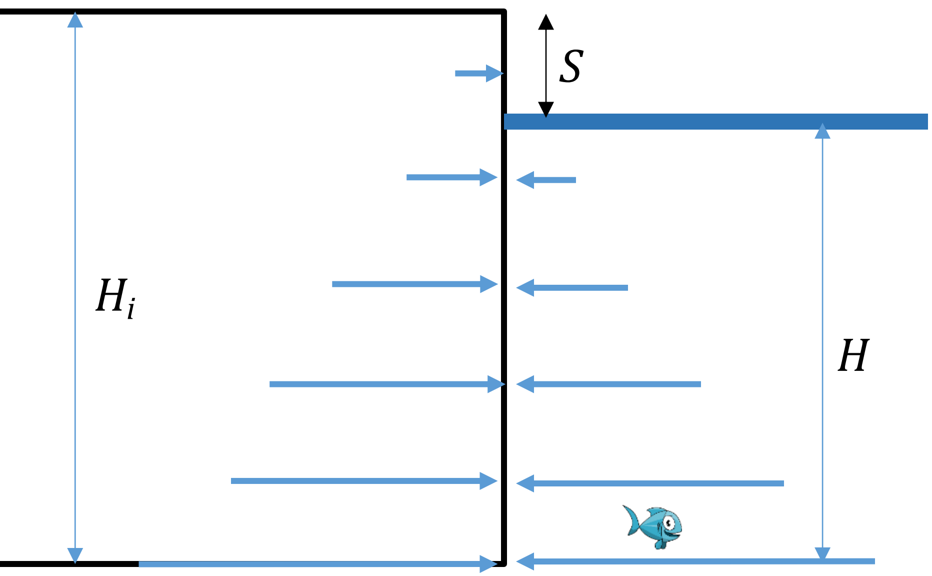
Pritchard et al. (2012)

Ice shelf dynamics



Ice shelf dynamics

Driving stresses



Hydrostatic equilibrium

$$\rho_i g H_i = \rho_w g H$$

$$H = \frac{\rho_i}{\rho_w} H_i$$

There are two sources of driving stress:

1. Surface slope (same as for grounded ice)

$$\rho_i g H_i \frac{dS}{dx}$$

2. Stress imbalance at the front

$$= \int_0^{H_i} \rho_i g z \, dz - \int_0^{H} \rho_w g z \, dz$$

$$= \frac{1}{2} \rho_i g H_i^2 - \frac{1}{2} \rho_w g H^2$$

$$= \frac{1}{2} \rho_i \, g H_i^2 \left(1 - \frac{\rho_i}{\rho_w}\right)$$

Ice shelf dynamics

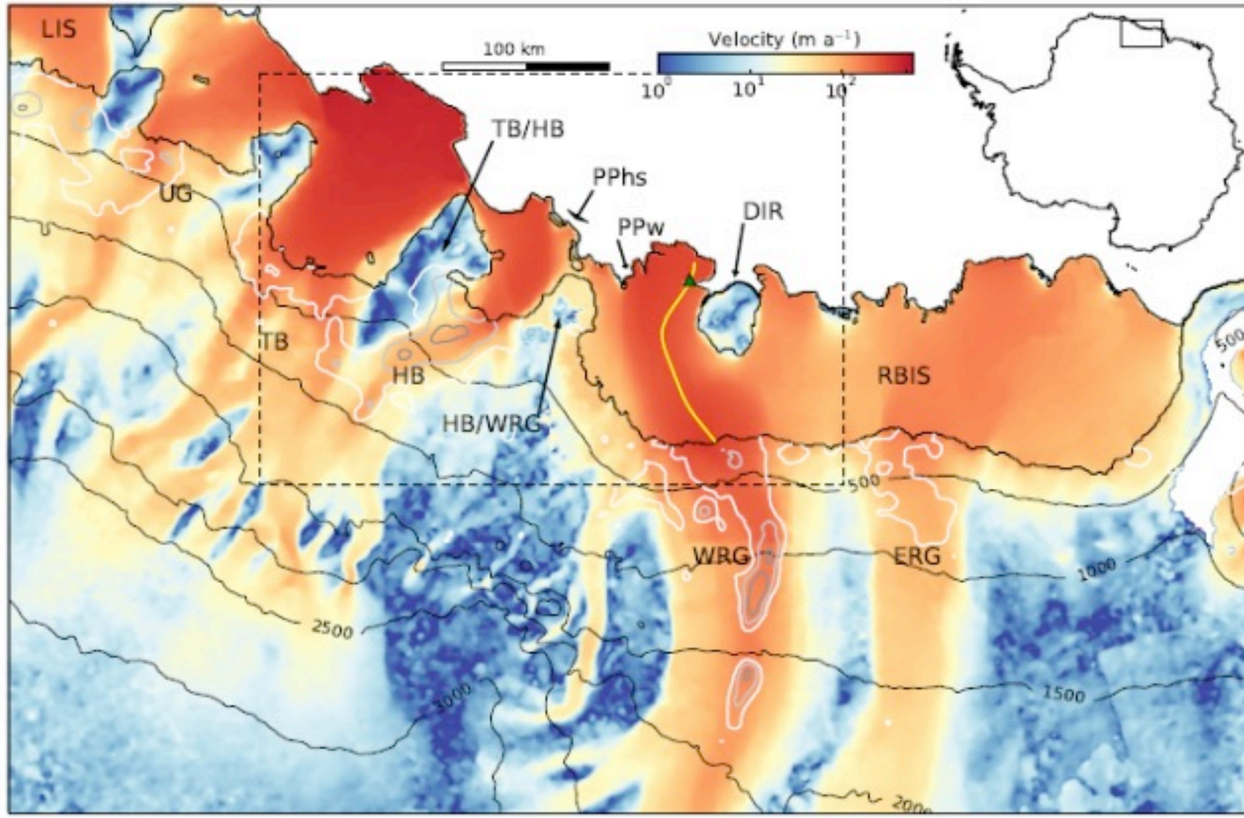
Resistive stresses

There are three sources of resistive stress:

1. Extensional stresses in the ice

2. Lateral shear stresses

3. Basal shear stress where the ice temporarily grounds.



Favier et al. (2016)

Ice shelf dynamics

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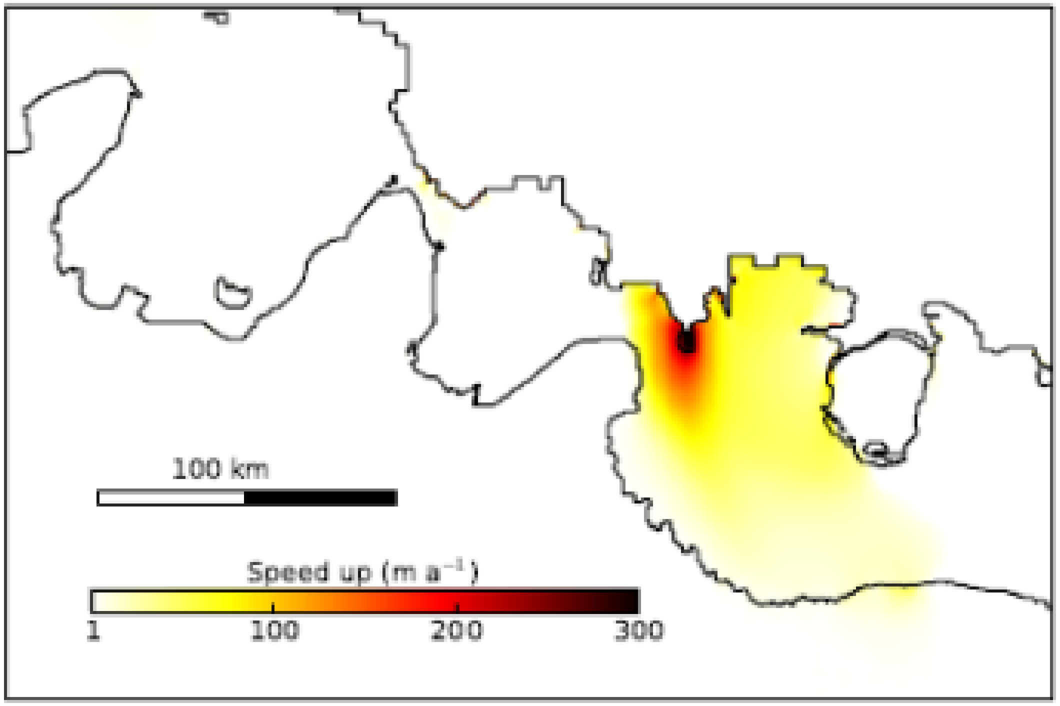
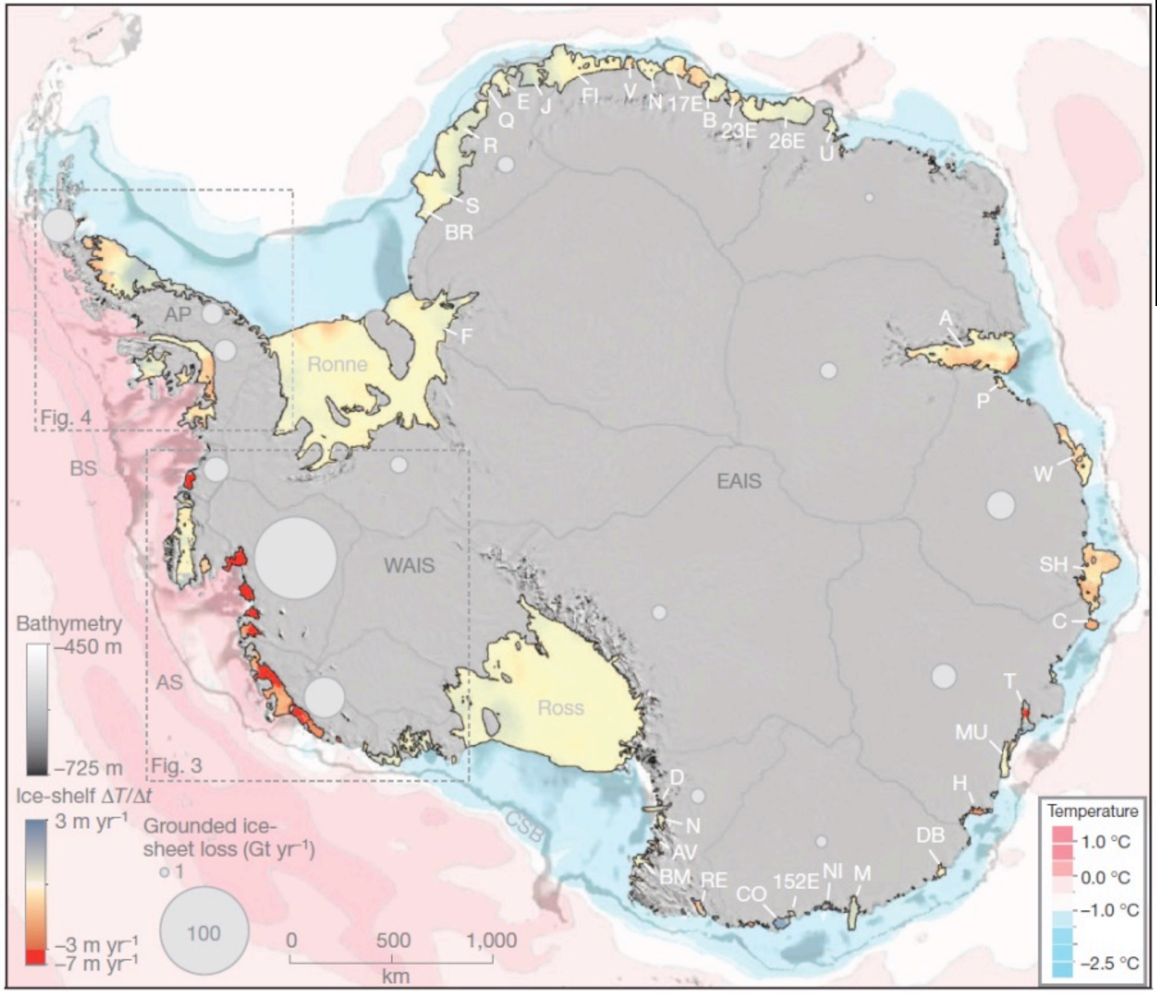


Favier et al. (2016)

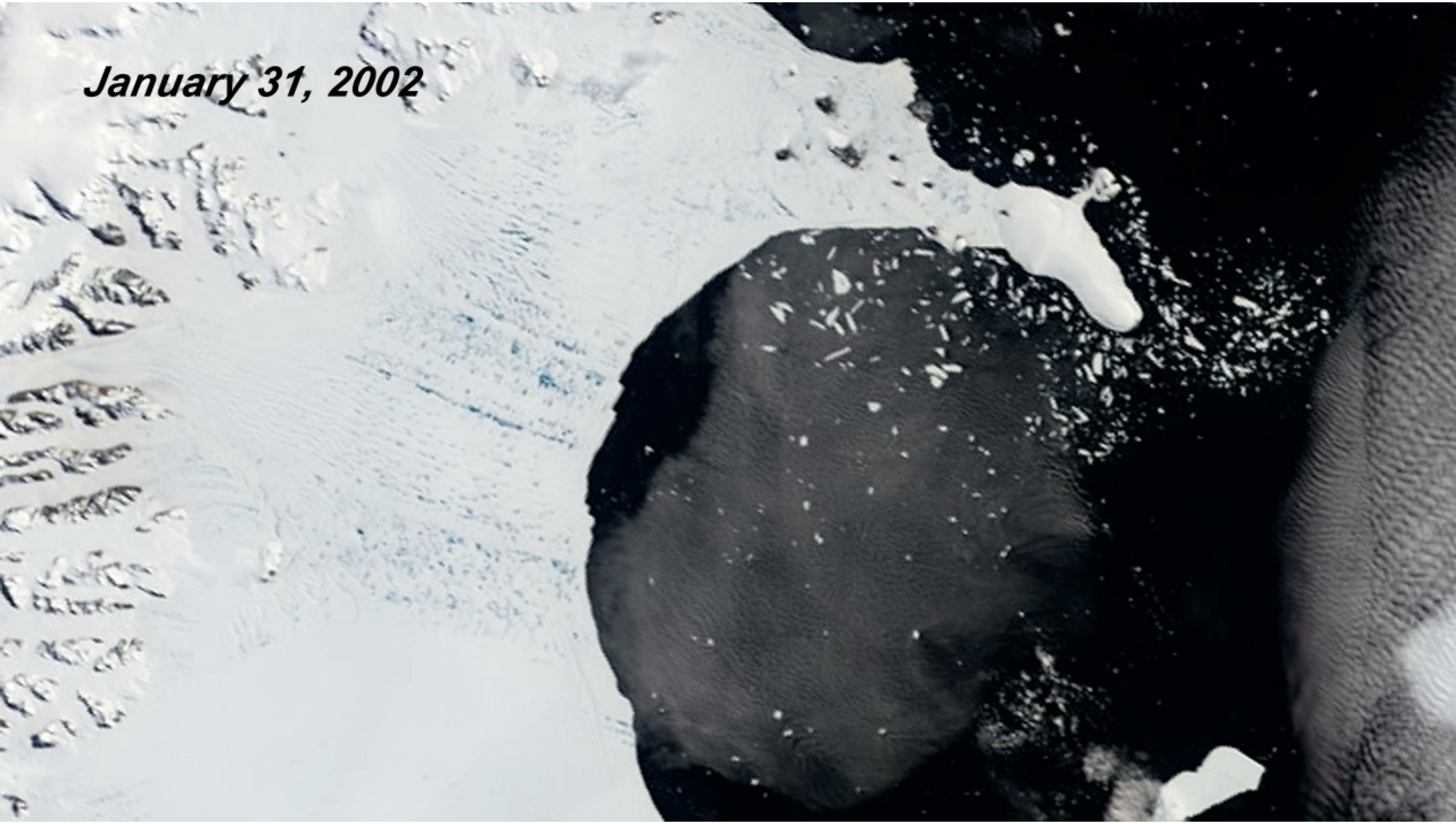
Ice shelf mass loss: thinning



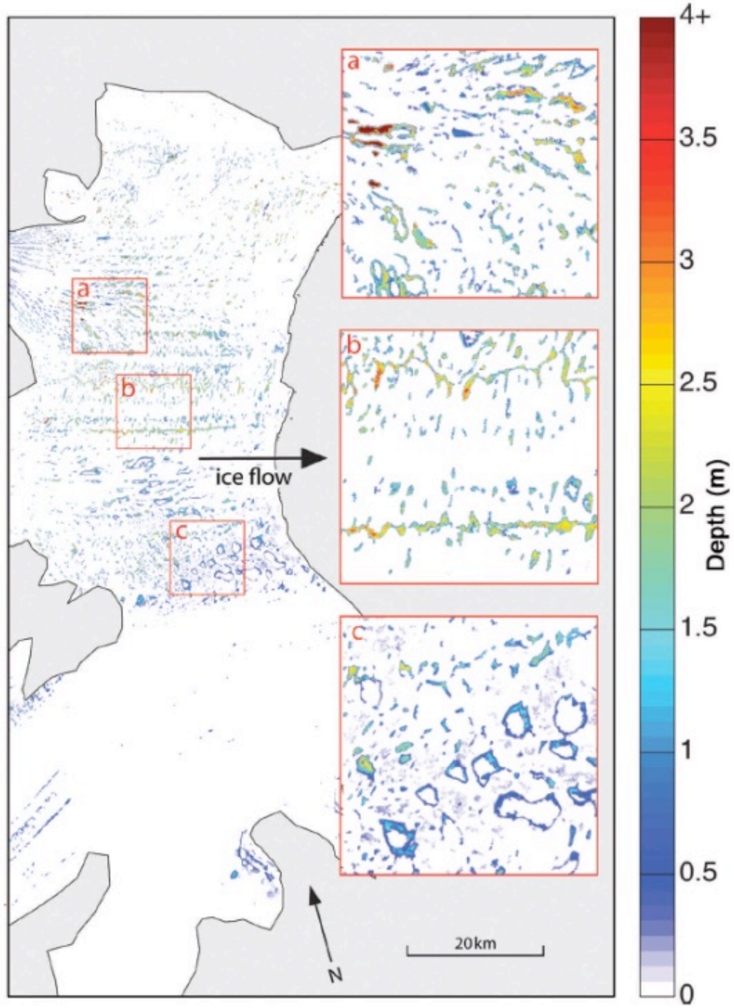
Pritchard et al. (2012)

Ice shelf mass loss: collapse

Larsen B Ice Shelf

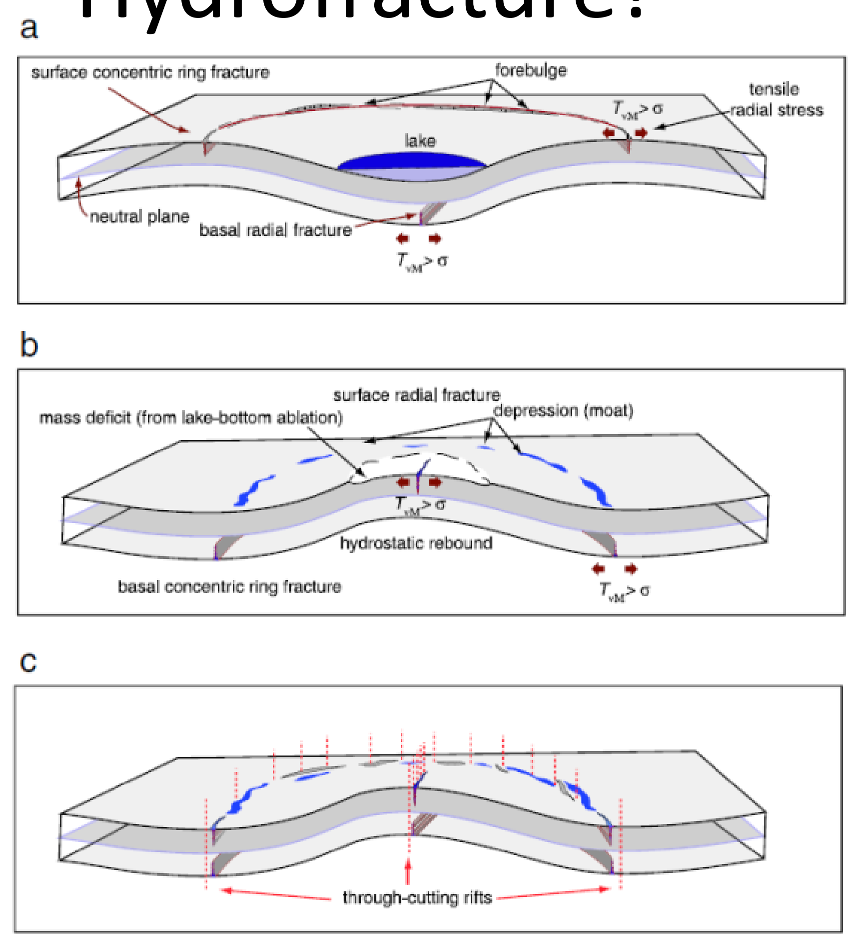


Causes of ice shelf collapse



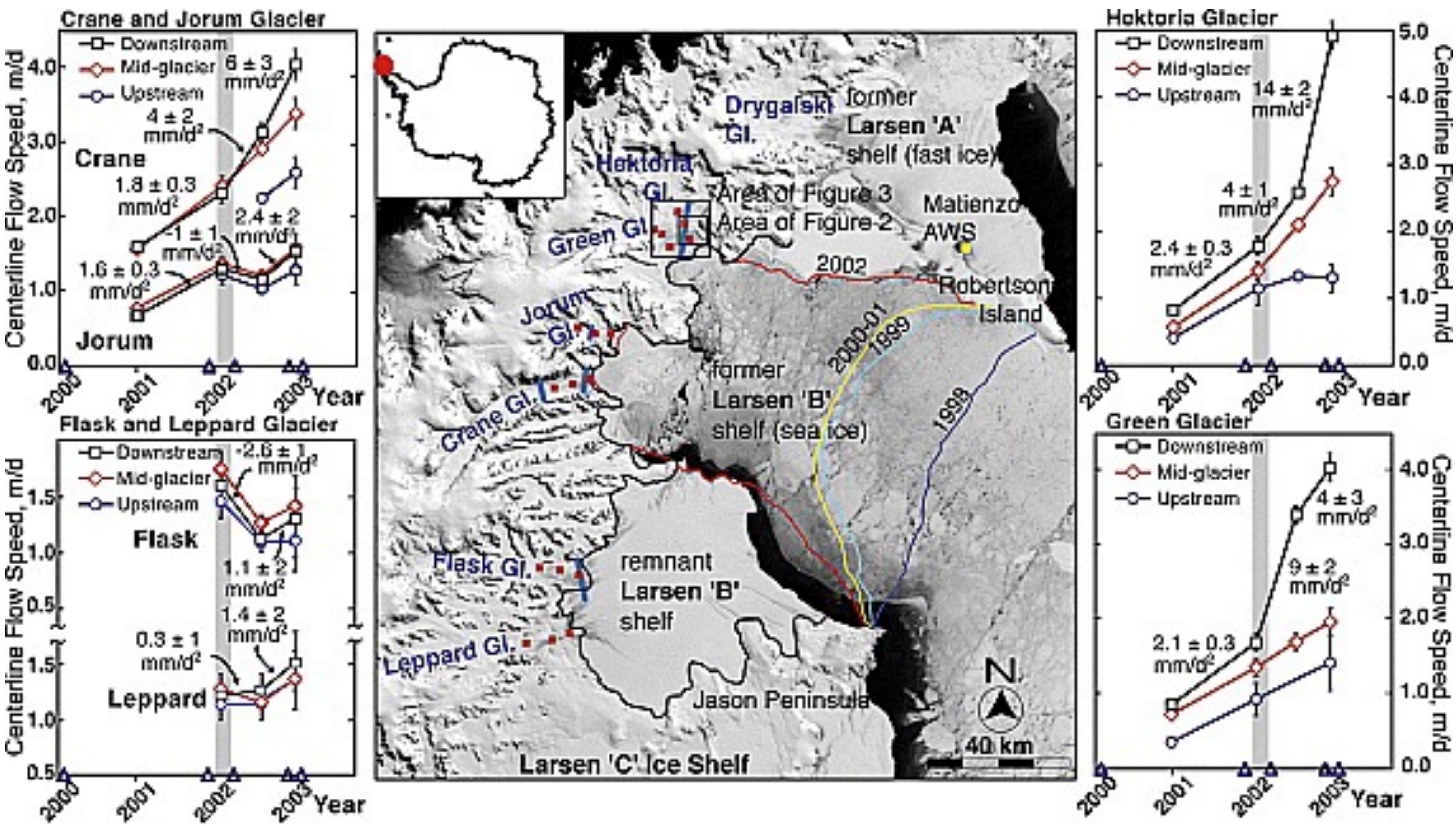
Banwell et al. (2014)

Hydrofracture!



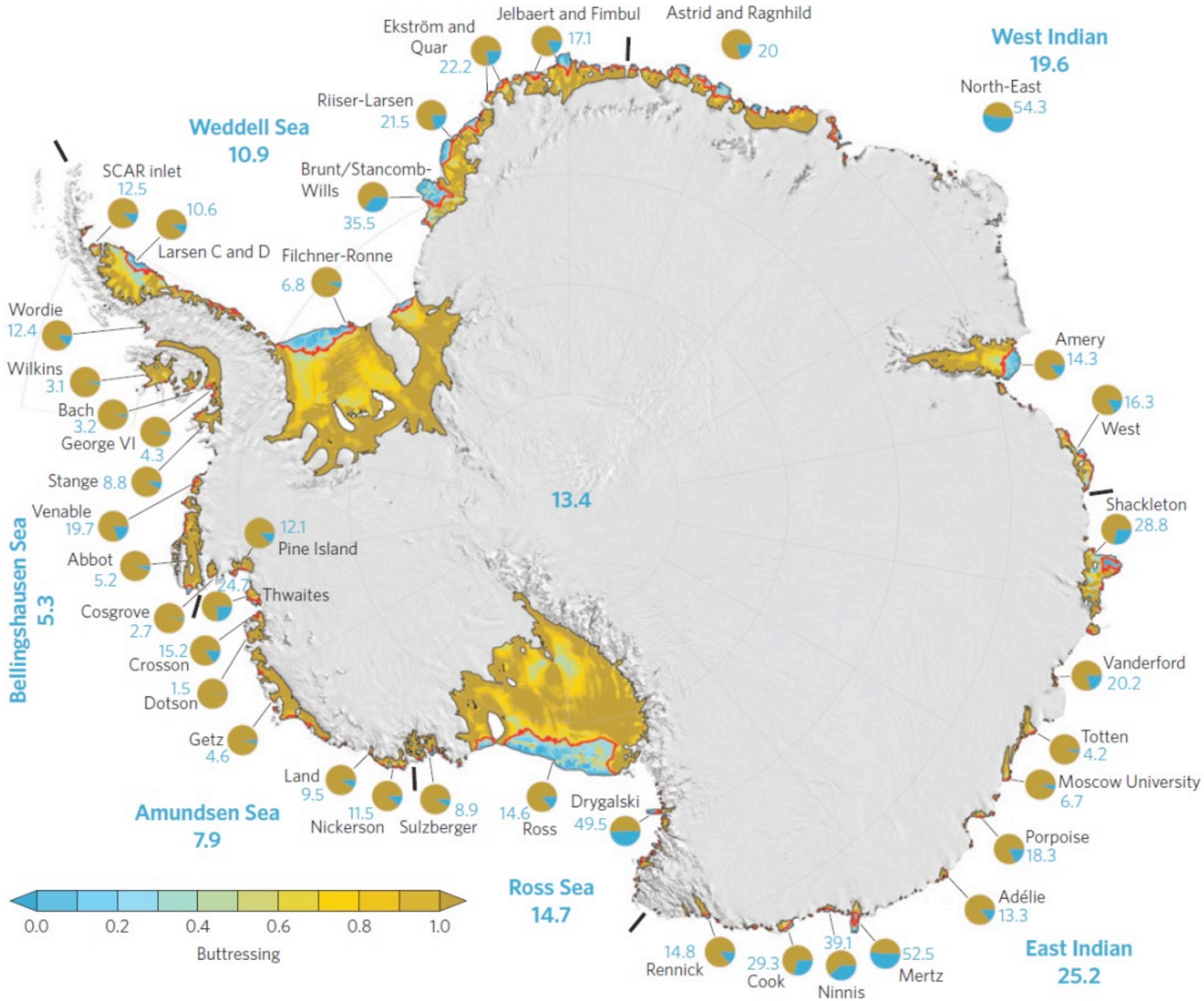
Banwell et al. (2013)

Implications of ice shelf loss

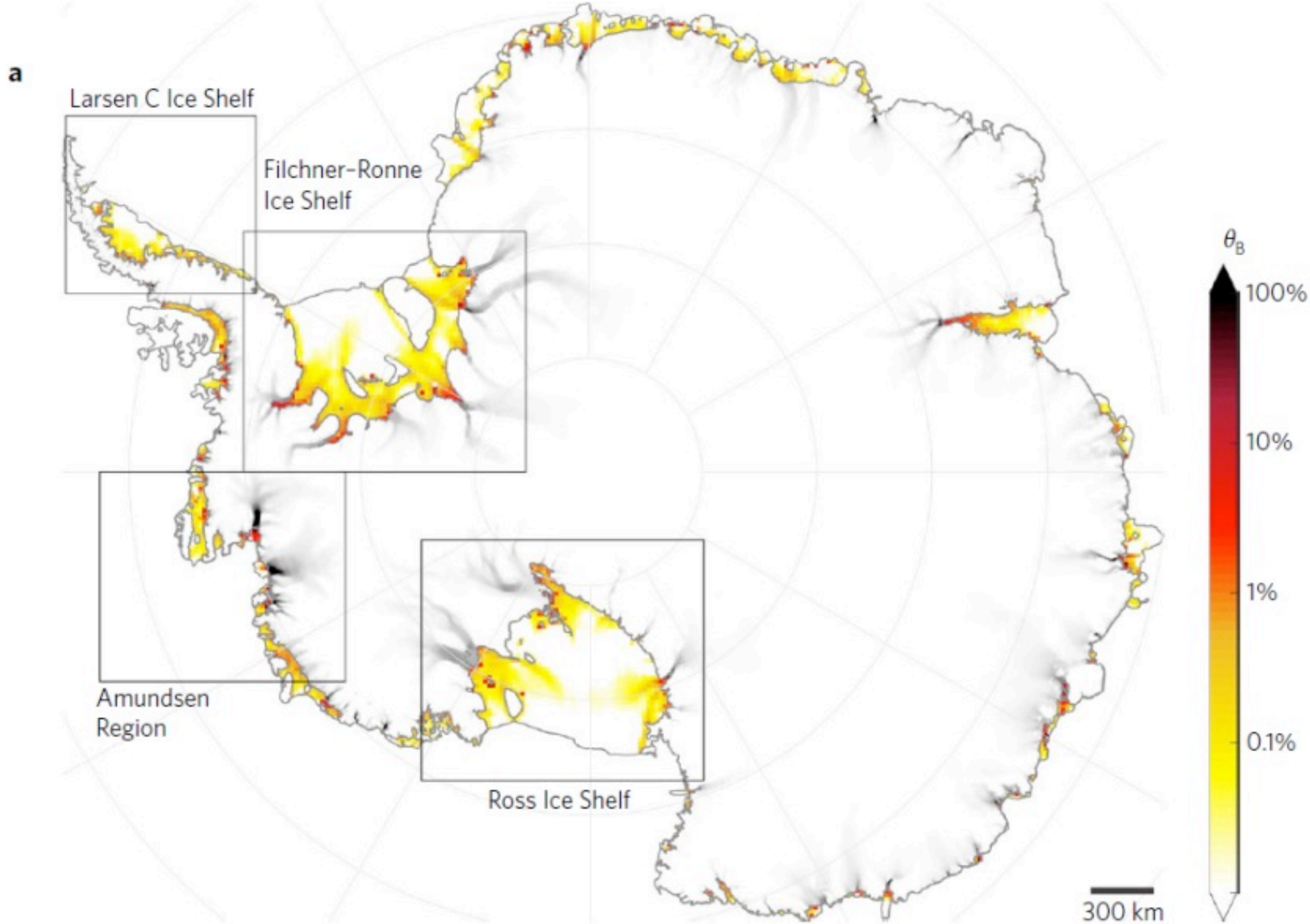


Scambos et al. (2004)

Implications of ice shelf loss



Fürst et al. (2016)



Reese et al. (2017)

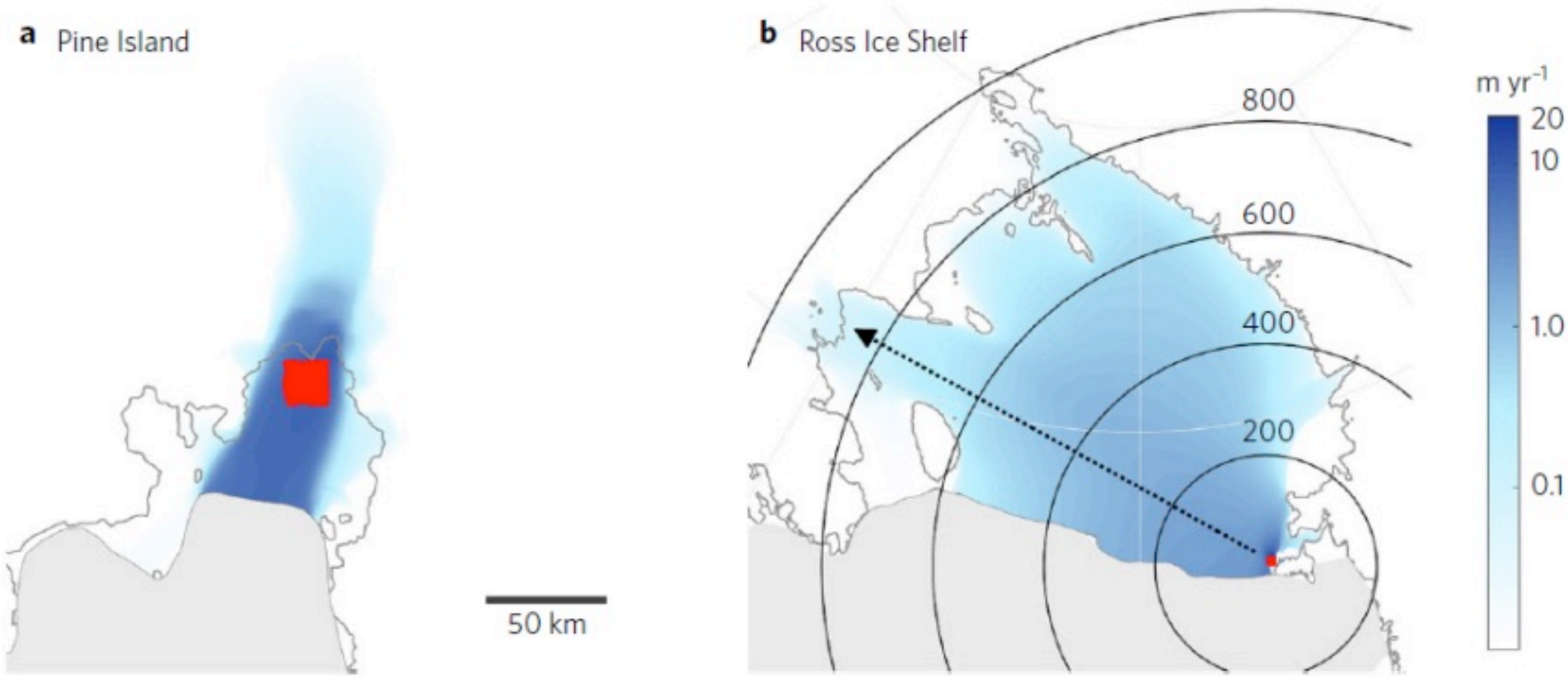


Fig. 2 | Examples of changes in speed resulting from 1 m thinning.

Reese et al. (2017)

Summary

- Ice shelves are common in Antarctica, rarer in Greenland.
- Satellite-based observations suggests Antarctic ice shelves lose half their mass via basal melting, half from calving.
- Driving forces are due to (1) surface slope and (2) stress imbalance at the front (both would be zero if $\rho_i = \rho_w$).
- Resistive forces are from shear against embayment sides and extensional stresses within ice shelves.
- When ice shelves lose mass or collapse completely, ice upstream accelerates.
- Ice shelves are thinning due to increased ocean melting.
- Collapse appears to be related to surface meltwater through processes such as hydrofracturing.

Next half of semester:

- Heat flow

- Hydrology

- Isochrones and age structure

- Start thinking about your projects

References

Banwell, A.F., MacAyeal, D.R. and Sergienko, O.V., 2013. Breakup of the Larsen B Ice Shelf triggered by chain reaction drainage of supraglacial lakes. *Geophysical Research Letters*, *40*(22), pp.5872-5876.

Banwell, A.F., Caballero, M., Arnold, N.S., Glasser, N.F., Mac Cathles, L. and MacAYEAL, D.R., 2014. Supraglacial lakes on the Larsen B ice shelf, Antarctica, and at Paakitsoq, West Greenland: a comparative study. *Annals of Glaciology*, *55*(66), pp.1-8.

Favier, L., Pattyn, F., Berger, S. and Drews, R., 2016. Dynamic influence of pinning points on marine ice-sheet stability: a numerical study in Dronning Maud Land, East Antarctica. *The Cryosphere*, *10*(6), p.2623.

Fürst, J.J., Durand, G., Gillet-Chaulet, F., Tavard, L., Rankl, M., Braun, M. and Gagliardini, O., 2016. The safety band of Antarctic ice shelves. Nature Climate Change, 6(5), pp.479-482.

Haseloff, Marianne, and Olga V. Sergienko. "The effect of buttressing on grounding line dynamics." Journal of Glaciology 64, no. 245 (2018): 417-431.

Iken, Almut. "The effect of the subglacial water pressure on the sliding velocity of a glacier in an idealized numerical model." Journal of Glaciology 27, no. 97 (1981): 407-421.

Rignot, E., Jacobs, S., Mouginot, J. and Scheuchl, B., 2013. Ice-shelf melting around Antarctica. Science, 341(6143), pp.266-270.

Reese, Ronja, G. Hilmar Gudmundsson, Anders Levermann, and Ricarda Winkelmann. "The far reach of ice-shelf thinning in Antarctica." Nature Climate Change 8, no. 1 (2018): 53.

Scambos, T., Fricker, H.A., Liu, C.C., Bohlander, J., Fastook, J., Sargent, A., Massom, R. and Wu, A.M., 2009. Ice shelf disintegration by plate bending and hydro-fracture: Satellite observations and model results of the 2008 Wilkins ice shelf break-ups. *Earth and Planetary Science Letters*, *280*(1-4), pp.51-60.

Weertman, Johannes. "On the sliding of glaciers." Journal of glaciology 3, no. 21 (1957): 33-38.