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Sensitivity of Totten Glacier to basal sliding laws and sub-shelf melt rates

Yiliang Ma, Liyun Zhao, Rupert Gladstone, Thomas Zwinger,
Michael Wolovick and John Moore

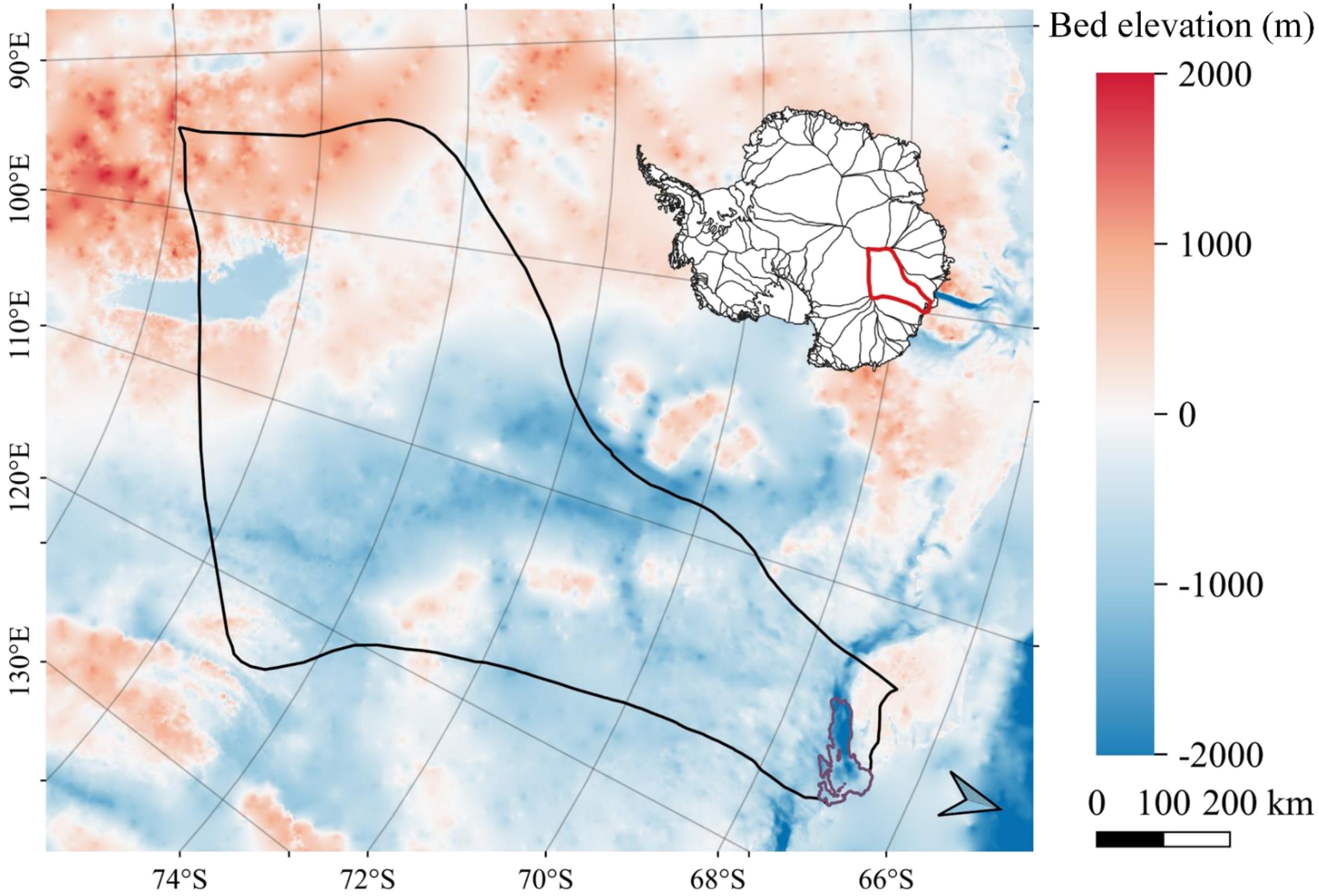
Yiliang, MSc student at BNU
Email: mayiliang@mail.bnu.edu.cn

Introduction

Totten Glacier

- 3.85 m SLRe
- 71.4 ± 2.6 Gt/yr, largest ice discharge in the EAIS
- Most of bedrock below SL deepest nearly 2000 m upstream of the GL

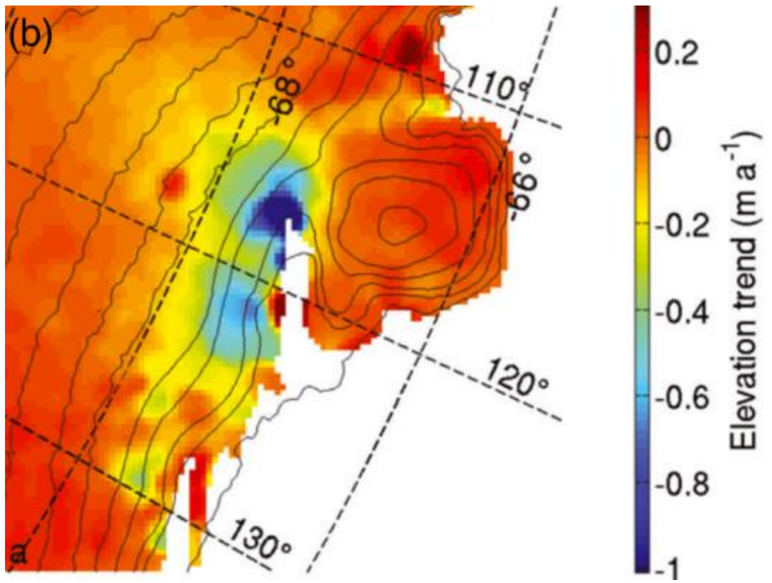
(Greenbaum et al., 2015)



Introduction

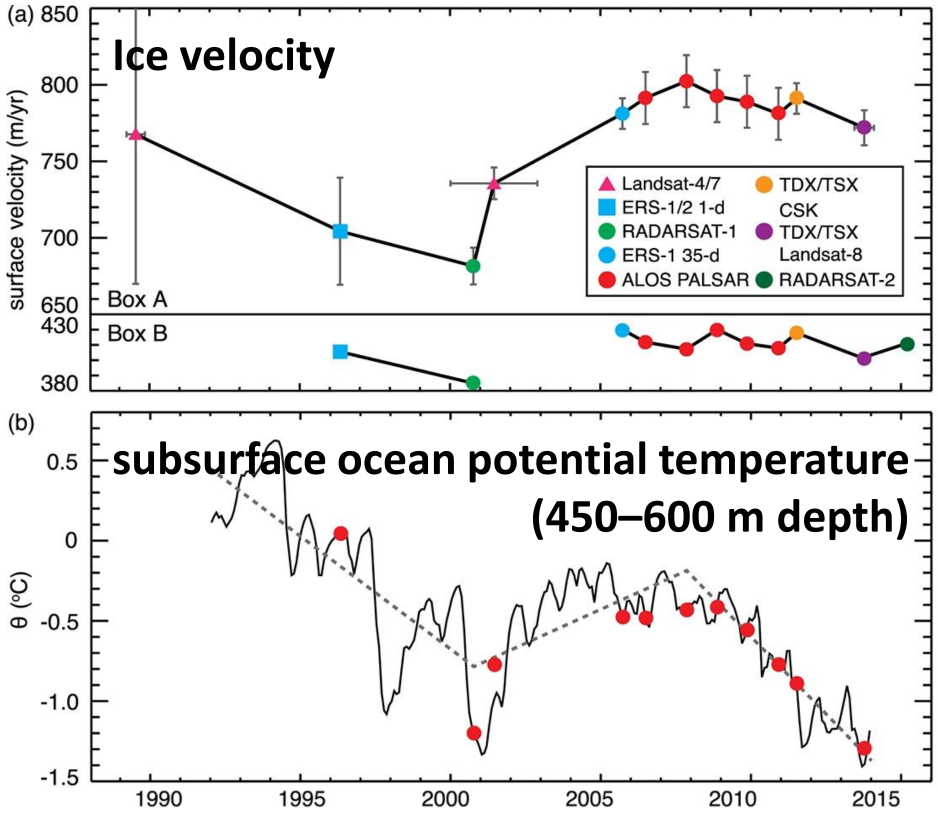
Grounded ice observations

- Changes in surface elevation: continuous thinning near the GL



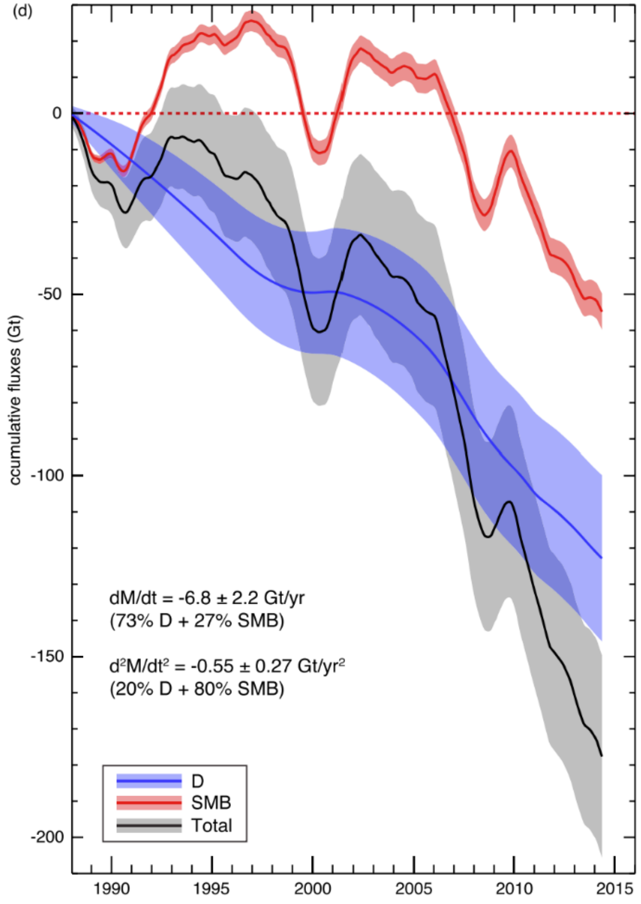
surface elevation trend
(Flament et al., 2012)

- Glacier dynamics may be strongly sensitive to ocean temperature



(Li et al., 2016)

- The average ice mass loss is dominated by ice dynamics (73%)



(Li et al., 2016)

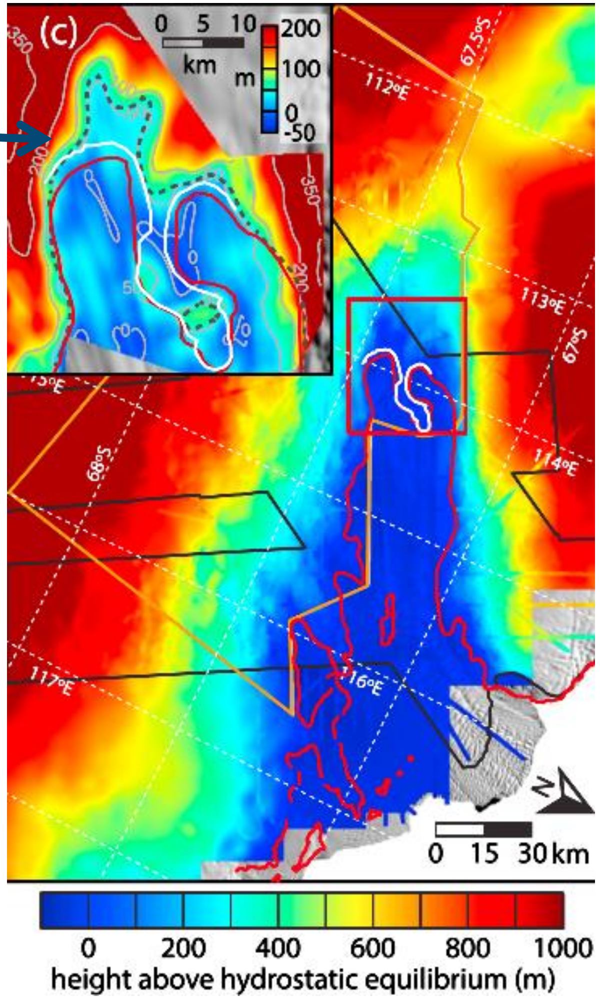
Introduction

Grounding line observations

- **Retreats 1 to 3 km** in 1996 – 2013
  Southern lobe retreat 1.1 to 2.6 km
  Northern lobe retreat 0.4 to 1.3 km
- Far greater than 60 m, the maximum grounding line migration due to tides

▬ 2013 GL
▬ 1996 GL
▪▪▪▪▪▪ 10 m thinning

(Li and Rignot et al., 2015)



Introduction

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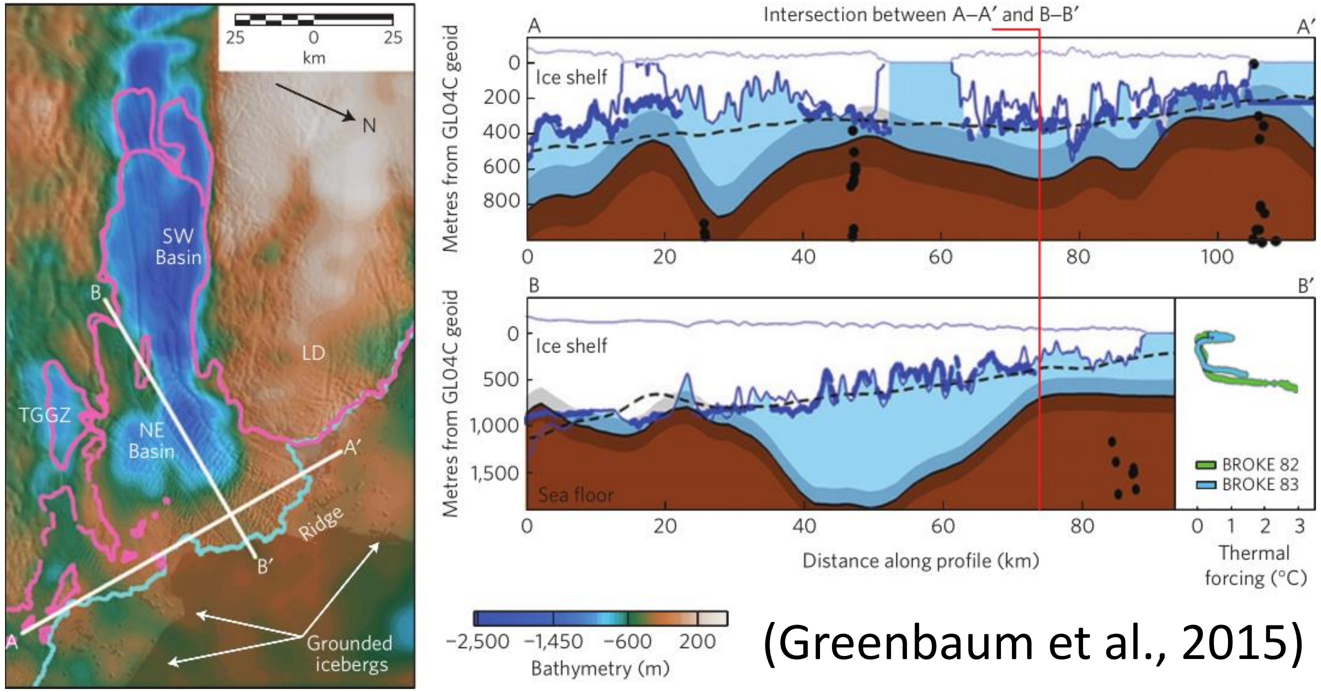
Intrusions of mCDW

- There are entrances to the ice-shelf cavity below depths of 400 to 500 m
- Ice shelf thinning mainly caused by ocean forcing



(Greenbaum et al., 2015)

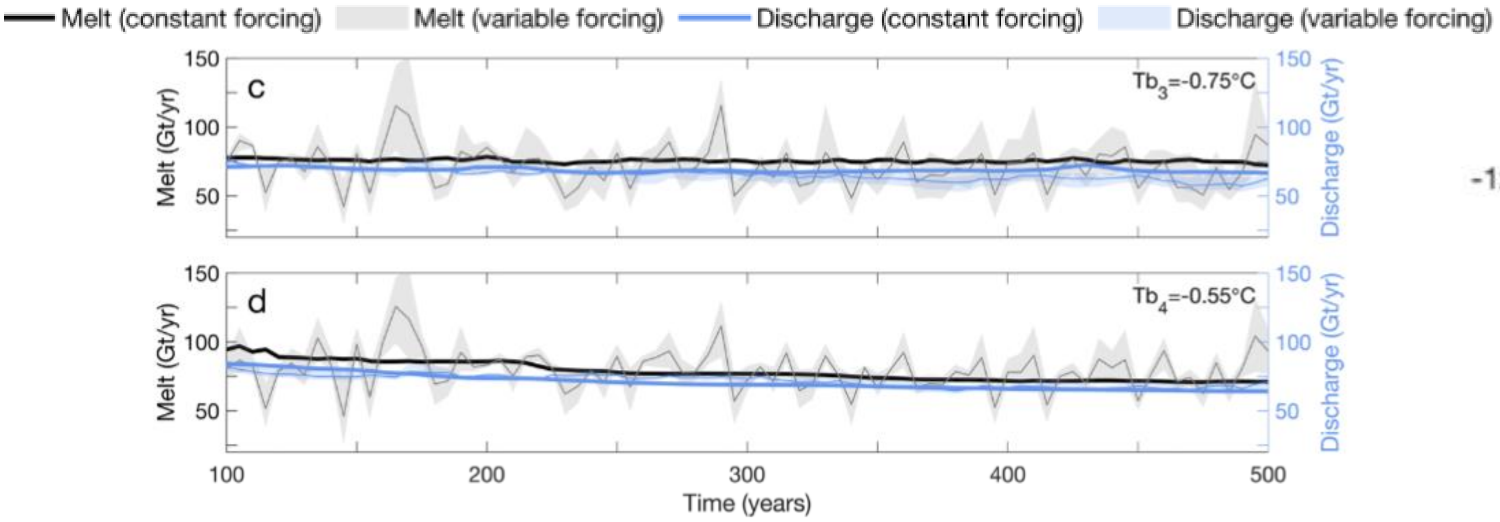
Overall, in recent years the Totten Glacier has experienced a process of ice thinning and continued retreat of the grounding line caused by ice dynamics and related to the sub-shelf melting and ocean forcing.

Introduction

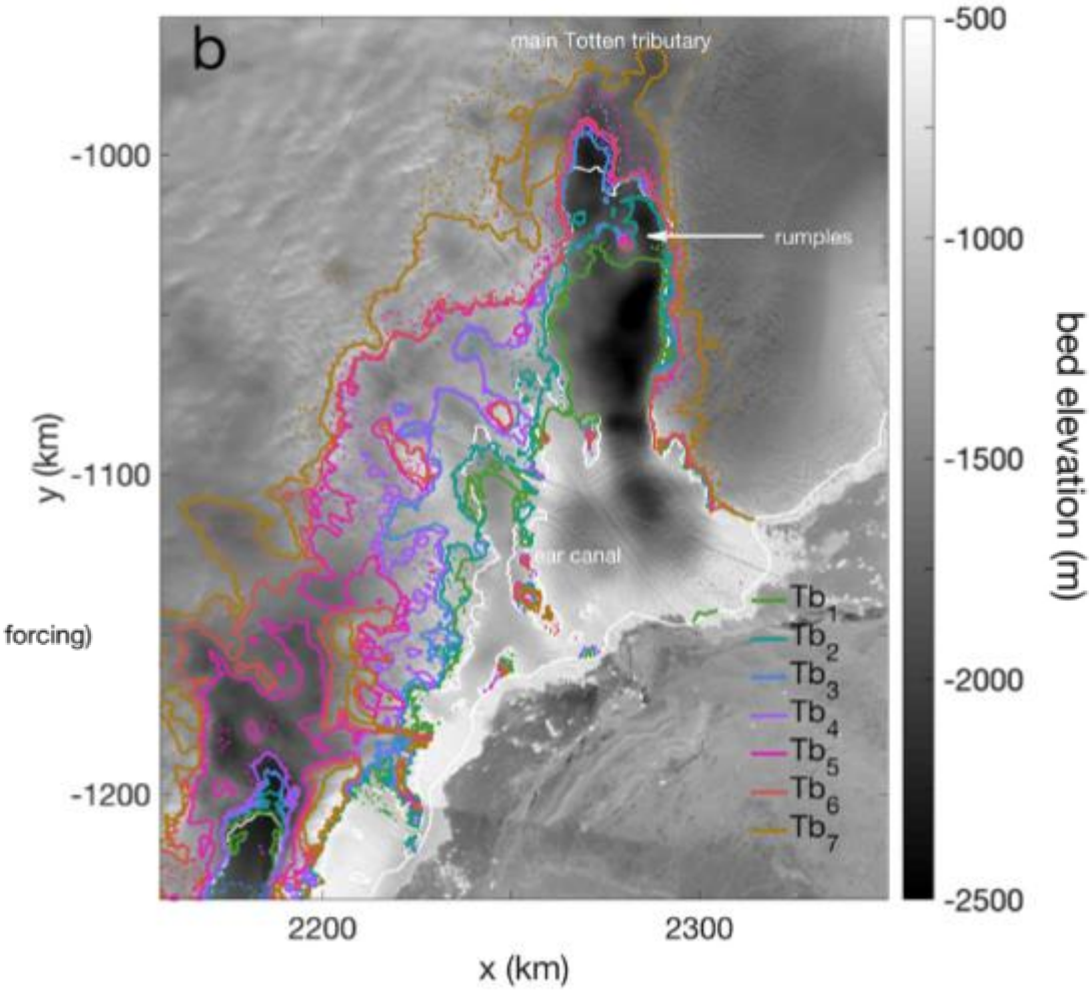
Model simulations

McCormack et al. (2021) couple ISSM to PICOP

- As the background temperatures increase, the melt rates and discharge generally increase and the GLs retreat more.



melt rates increase with background temperatures
(McCormack et al., 2021)



GL position over 500 yrs
(McCormack et al., 2021)

Introduction

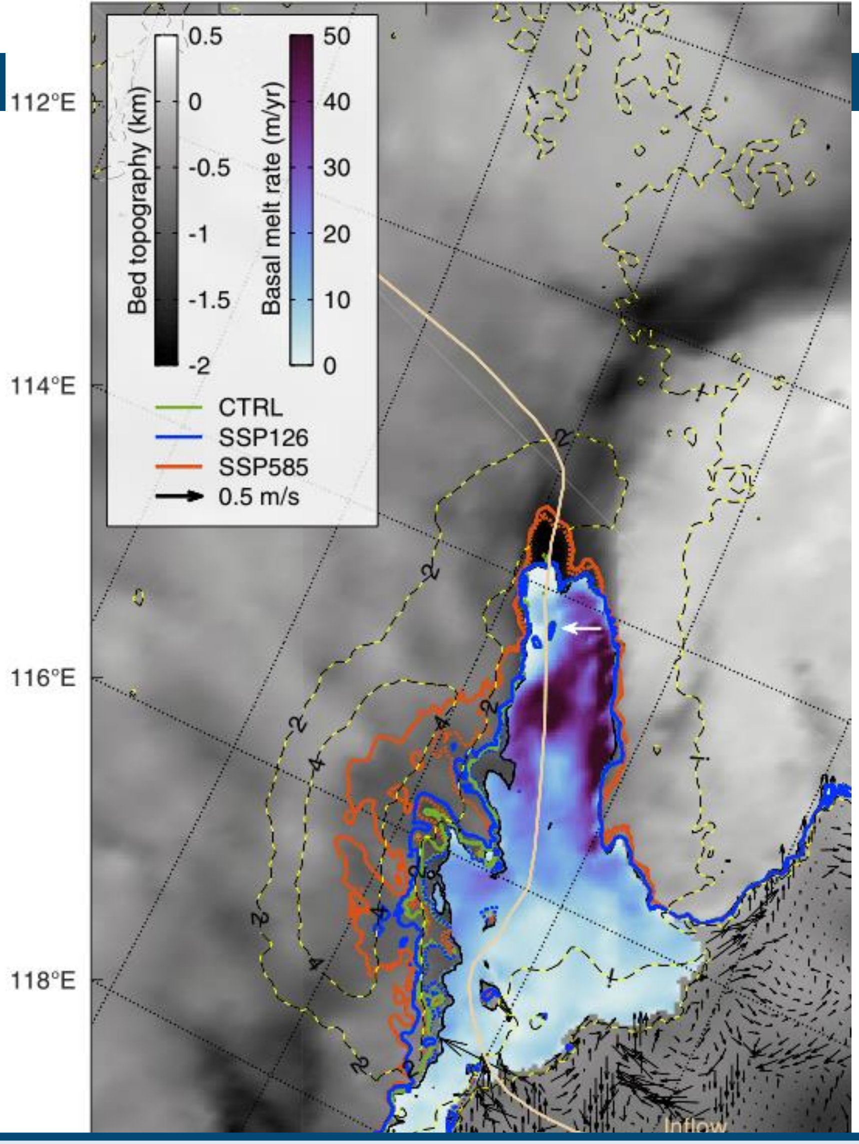
Model simulations

McCormack et al. (2021) couple ISSM to PICOP

- As the background temperatures increase, the melt rates and discharge generally increase and the GLs retreat more.

Pelle et al.(2021) couple ISSM to MITgcm via MATLAB

- SSP585 & SSA & Budd friction law results in SLRe loss of 4.2 mm by 2100.



GL position in 2100
(Pelle et al., 2021)

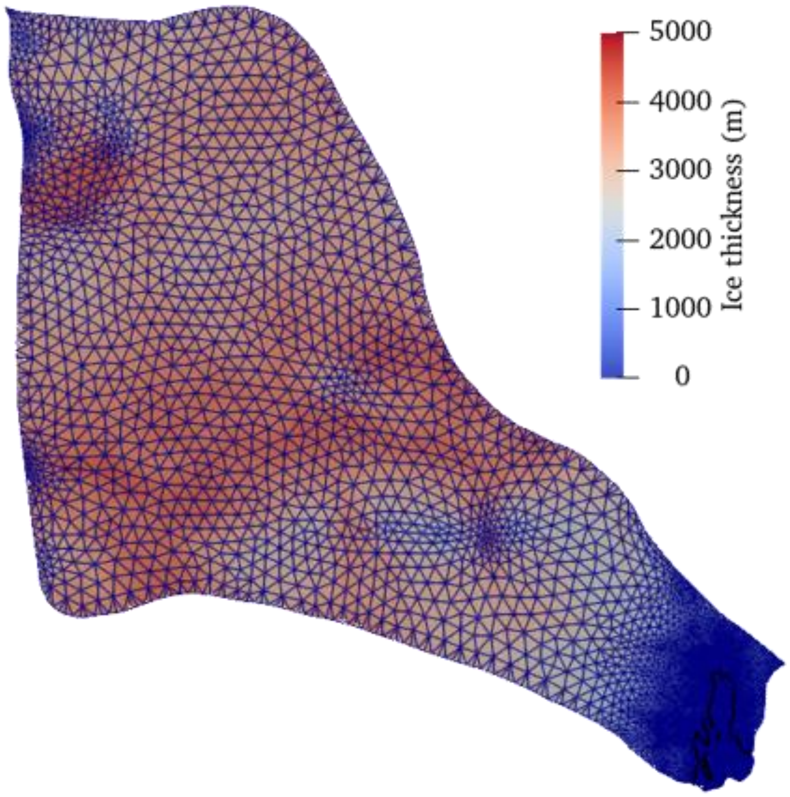
Overall, ocean forcing variability and changes in ice shelf basal melt rates are decisive for Totten Glacier dynamics, with the position of the grounding line being very sensitive to ocean temperature.

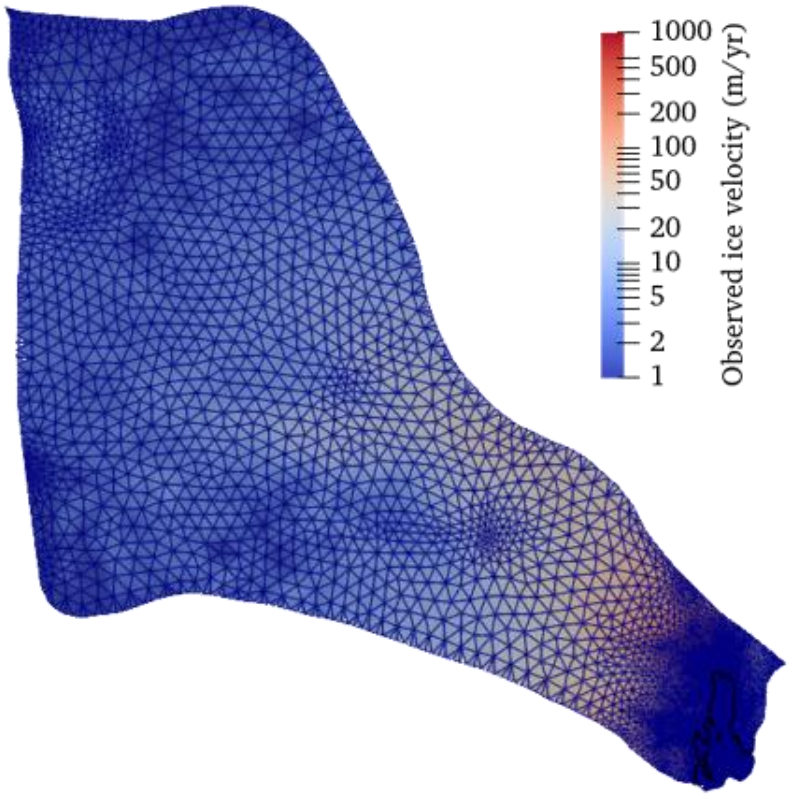
Introduction

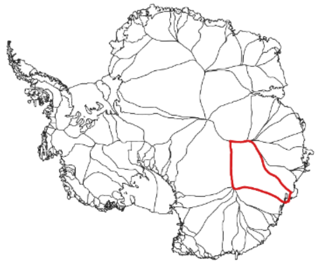
1. How sensitive are dynamic processes to the sub-ice shelf melt rates?
2. Are dynamic processes sensitive to different sliding laws which apply to the bottom of grounded ice?

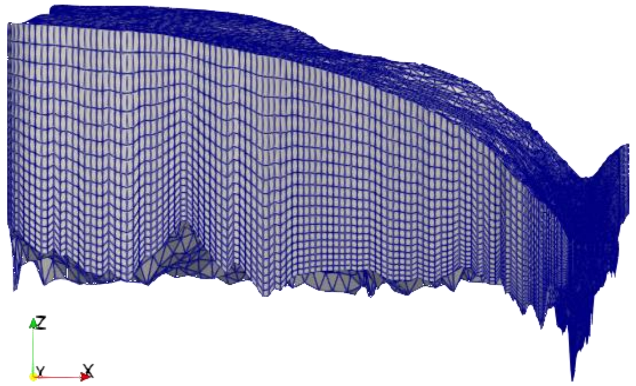
Methodology

mesh generation & optimization → surface relaxation → **basal drag inversion** → **viscosity inversion** → drag coeff. conversion → sensitivity test

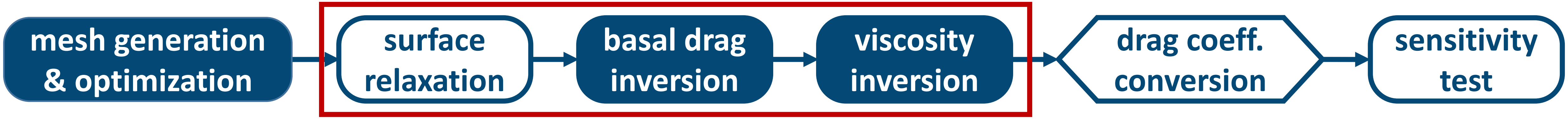








Methodology



Timestep size

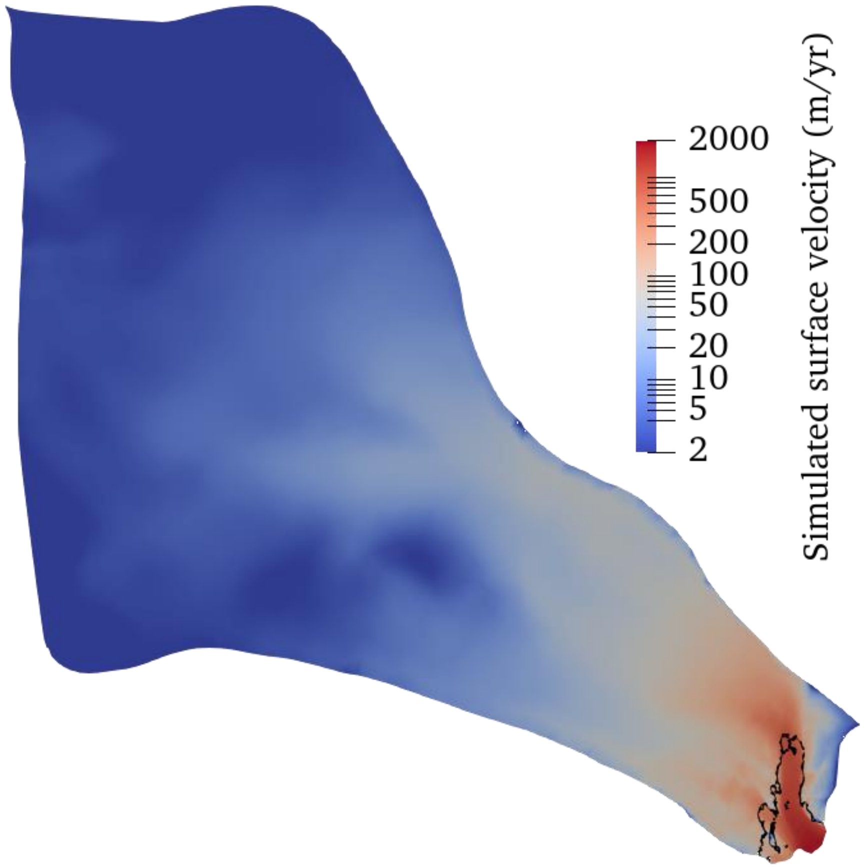
$$\Delta t(n) = \begin{cases} 0.01 & 1 < n < 34 \\ 0.01 \times 1.5^{n} & 35 < n < 41 \\ 0.1 & n >= 41 \end{cases}$$

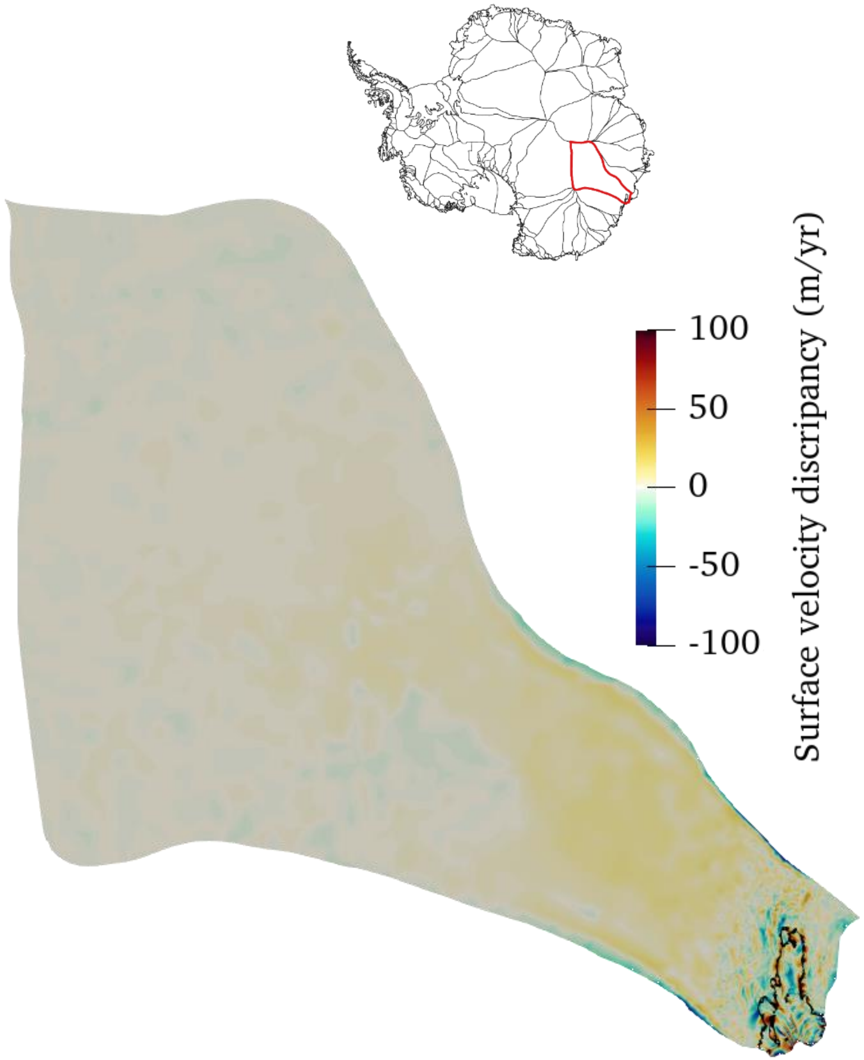
~ 0.65 yrs

Velocity mismatch

L.T. 25 m/yr for all nodes

~ 2.5 m/yr for the TG area





Methodology

mesh generation & optimization → surface relaxation → basal drag inversion → viscosity inversion → drag coeff. conversion → sensitivity test

Linear Weertman -> Nonlinear Weertman

$$\boxed{\boldsymbol{\tau}_{\mathrm{b}} = C_1 \boldsymbol{u}_{\mathrm{b}}}, \boldsymbol{\tau}_{\mathrm{b}} = C_2 \boldsymbol{u}_{\mathrm{b}}^{1/3},$$

$$C_2 = C_1 \boldsymbol{u}_{\mathrm{b}}^{2/3}.$$

Linear Weertman -> Coulomb friction law

$$\boxed{\boldsymbol{\tau}_{\mathrm{b}} = C_1 \boldsymbol{u}_{\mathrm{b}}}, \boldsymbol{\tau}_{\mathrm{b}} = C_3 N[\chi \cdot \boldsymbol{u}_{\mathrm{b}}^{-n} / (1 + a \cdot \chi_1^q)]^{1/n} \cdot \boldsymbol{u}_{\mathrm{b}},$$

$$\chi_1 = u_b / C_3^n N^n A_{s1}$$

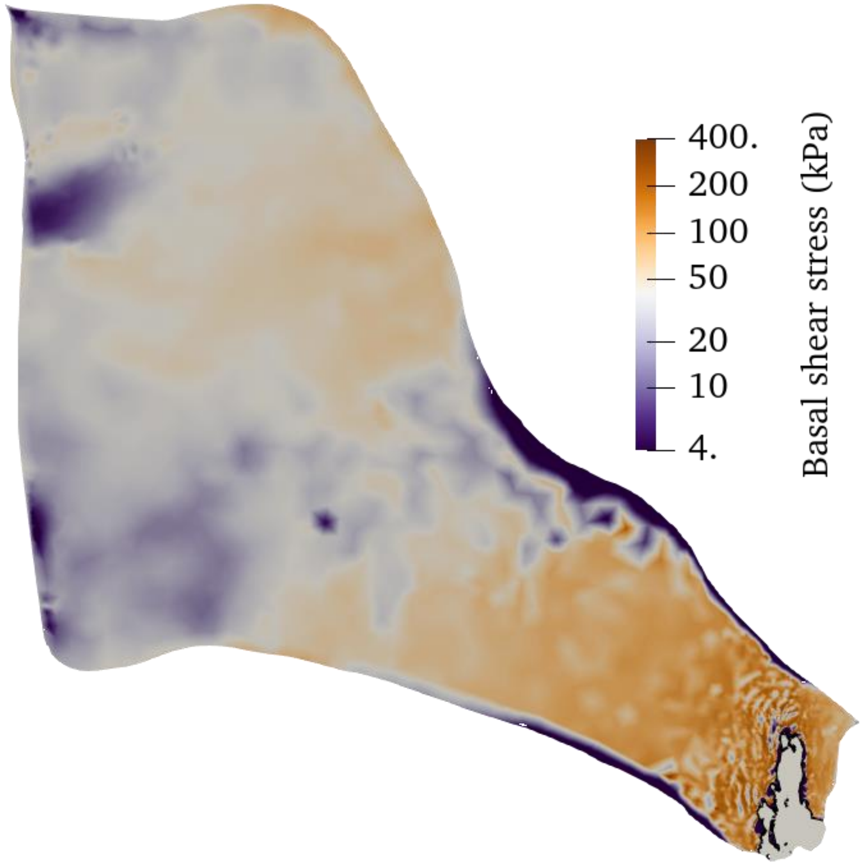
$\Rightarrow A_{s1}, C_3$ **using Weertman2Coulomb.F90 coded by Thomas**

Linear Weertman -> Modified Coulomb friction law

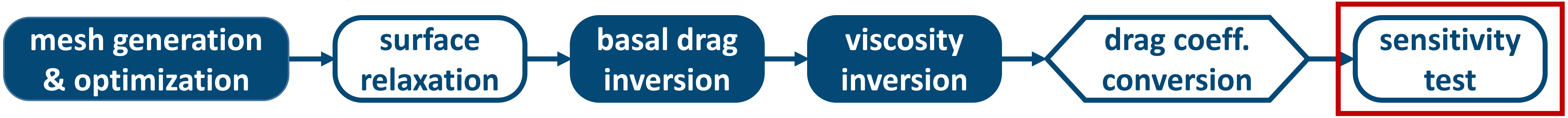
$$\boxed{\boldsymbol{\tau}_{\mathrm{b}} = C_1 \boldsymbol{u}_{\mathrm{b}}}, C_1 = 10^{\beta}$$

$\beta_{\mathrm{new}} = \beta_{\mathrm{old}} + (T_{\mathrm{m}} - T_{\mathrm{bed}})$ **(Kang et al., 2022)**

$$\Rightarrow A_{s2}, C_4$$



Methodology



mesh generation & optimization → surface relaxation → basal drag inversion → viscosity inversion → drag coeff. conversion → sensitivity test

Sub-shelf melt rates parameterisation

$$M_{\mathrm{d}} = 22.5142 \times \frac{1}{\frac{d}{20}+d_0} + 1.1917,$$

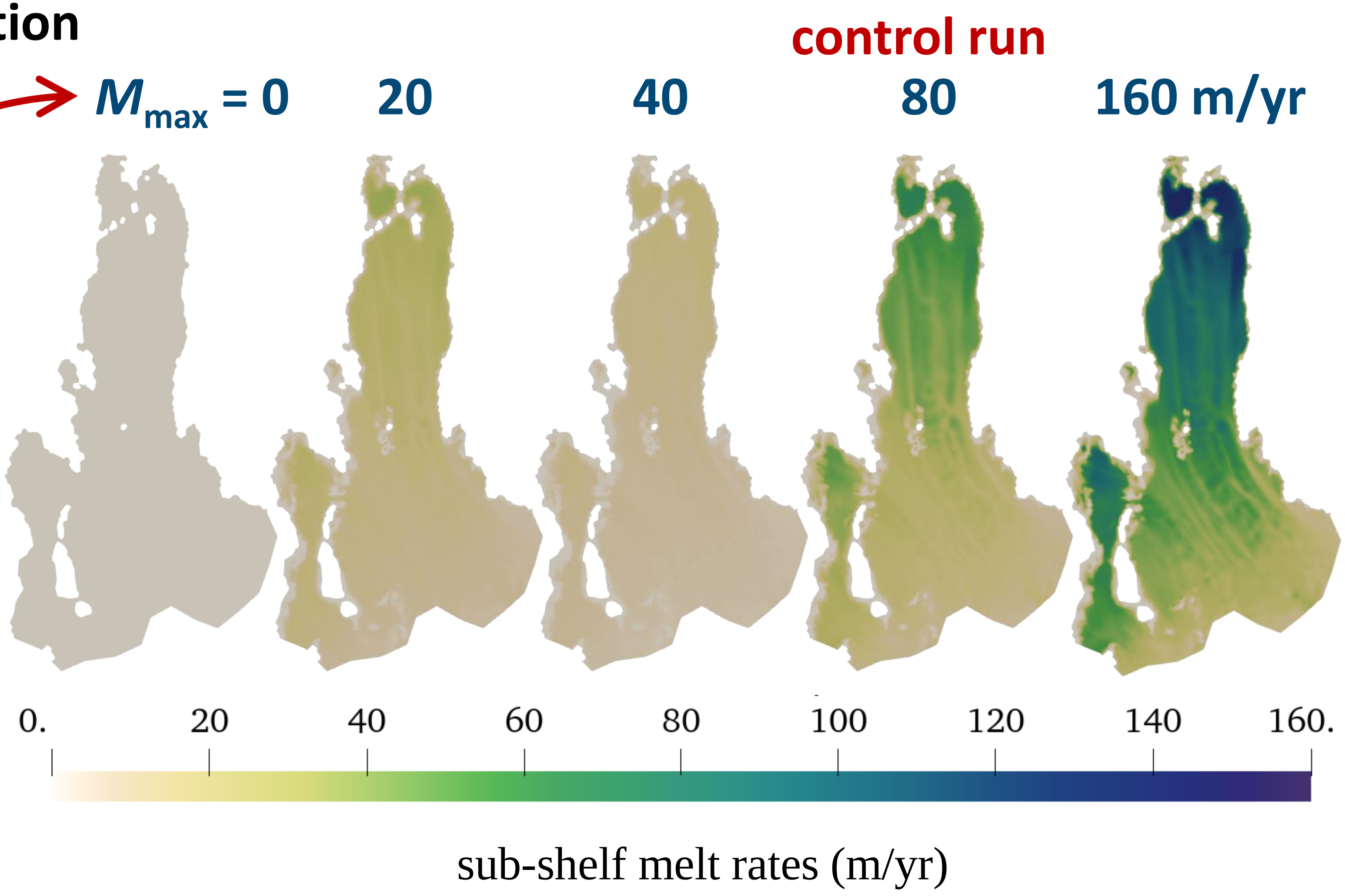
$$M_{\mathrm{e}} = \begin{cases} \boxed{M_{\max}} \times \left(\frac{d}{2000}\right), & d < 2000 \ \mathrm{m}, \\ \boxed{M_{\max},} & d \geq 2000 \ \mathrm{m}, \end{cases}$$

$$S_{\mathrm{w}} = \tanh\left(e\frac{H_{\mathrm{w}}}{H_{w0}}\right),$$

$$S_i = \max\left[\tanh\left(e\frac{z_{\mathrm{i0}}-z_{\mathrm{i}}}{z_{\mathrm{s}}}\right), 0\right],$$

$$M = S_{\mathrm{w}} \cdot S_{\mathrm{i}}\left(M_{\mathrm{d}} + M_{\mathrm{e}}\right).$$

(Gladstone et al., 2017)



Methodology

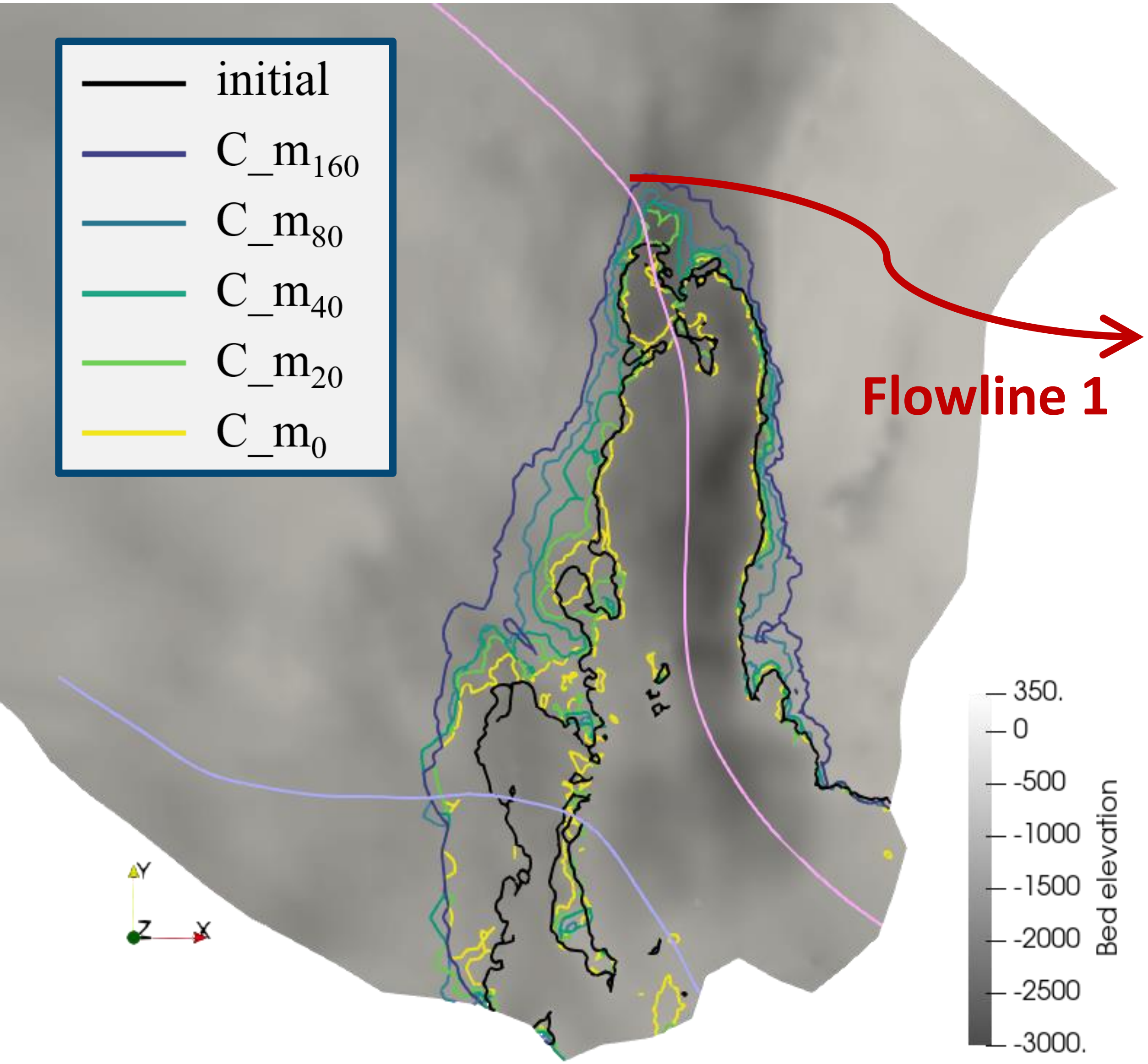
mesh generation & optimization → surface relaxation → basal drag inversion → viscosity inversion → drag coeff. conversion → **sensitivity test**

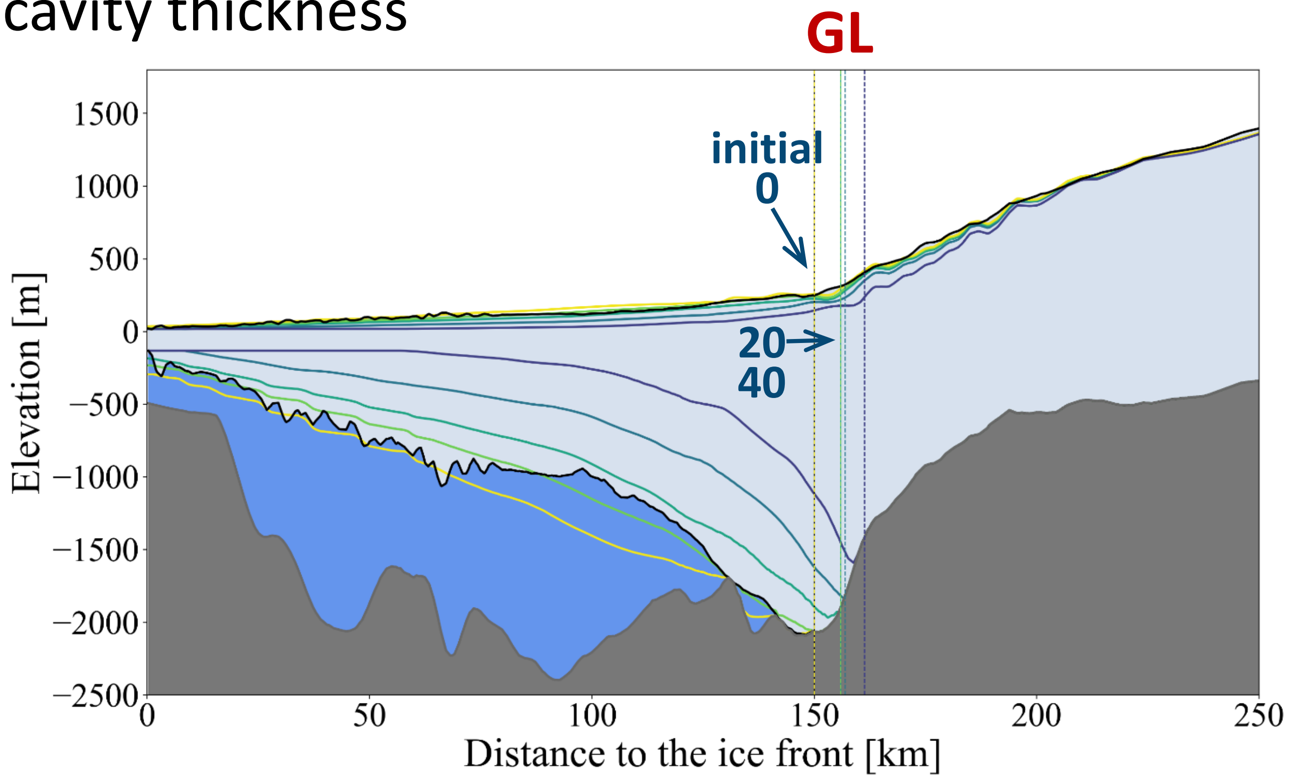
2 groups: sliding laws & melt rates, 30 yrs simulation (2015-2045)

Run code	Sliding law	Maximal melt (m/yr)	Basal drag coeff. before conversion
C_m$_{80}$ (Control)	**Coulomb**	**80**	**β**
C_β_m$_{80}$	**Modified Coulomb**	80	**$\min\{0,\beta+(T_m-T_{bed})\}$**
LW_m$_{80}$	**Linear Weertman**	80	β
NW_m$_{80}$	**Nonlinear Weertman**	80	β
C_m$_{160}$	Coulomb	**160**	β
C_m$_{40}$	Coulomb	**40**	β
C_m$_{20}$	Coulomb	**20**	β
C_m$_{0}$	Coulomb	**0**	β

Results

Melt rates group: grounding line position & ice cavity thickness

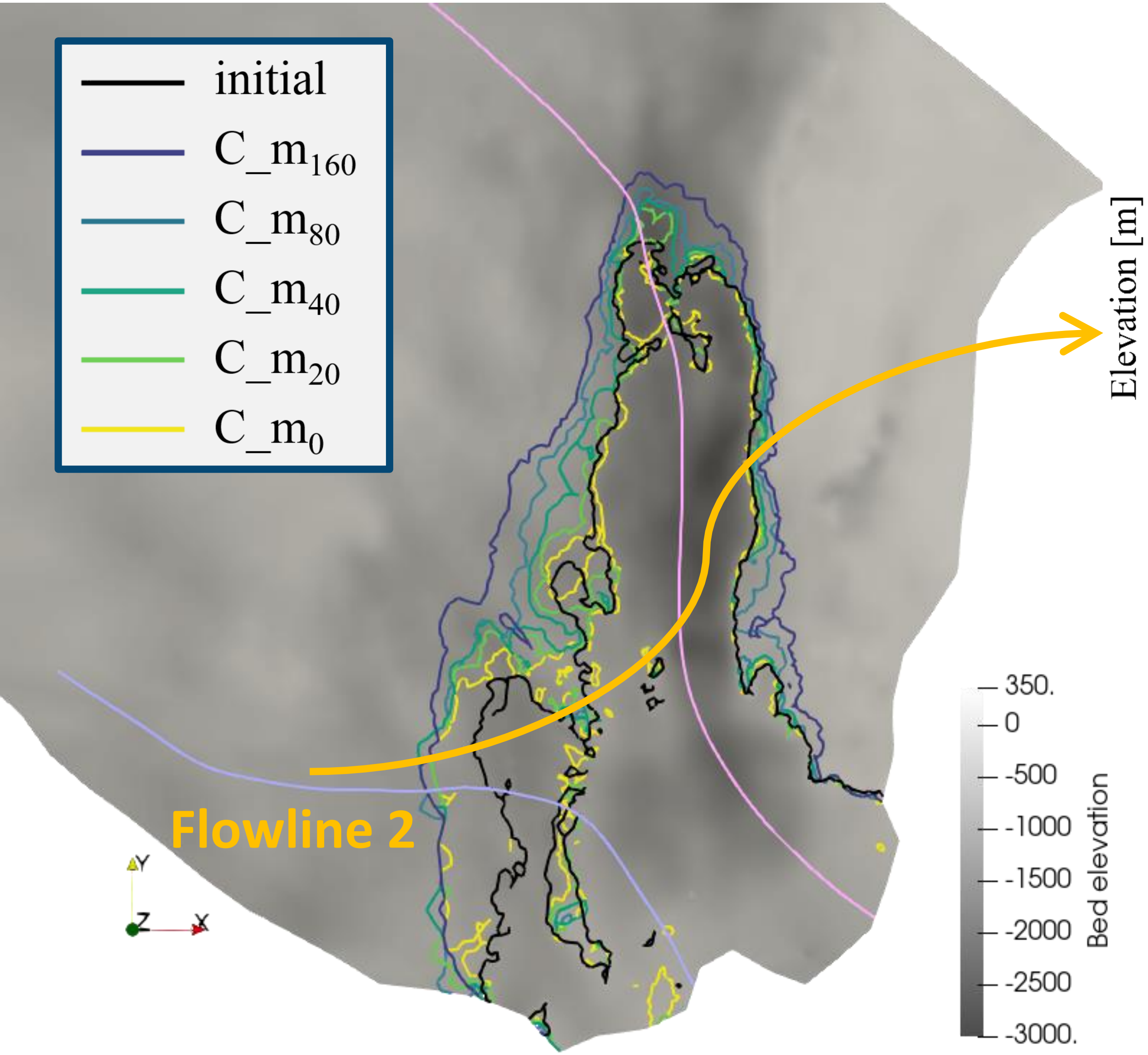


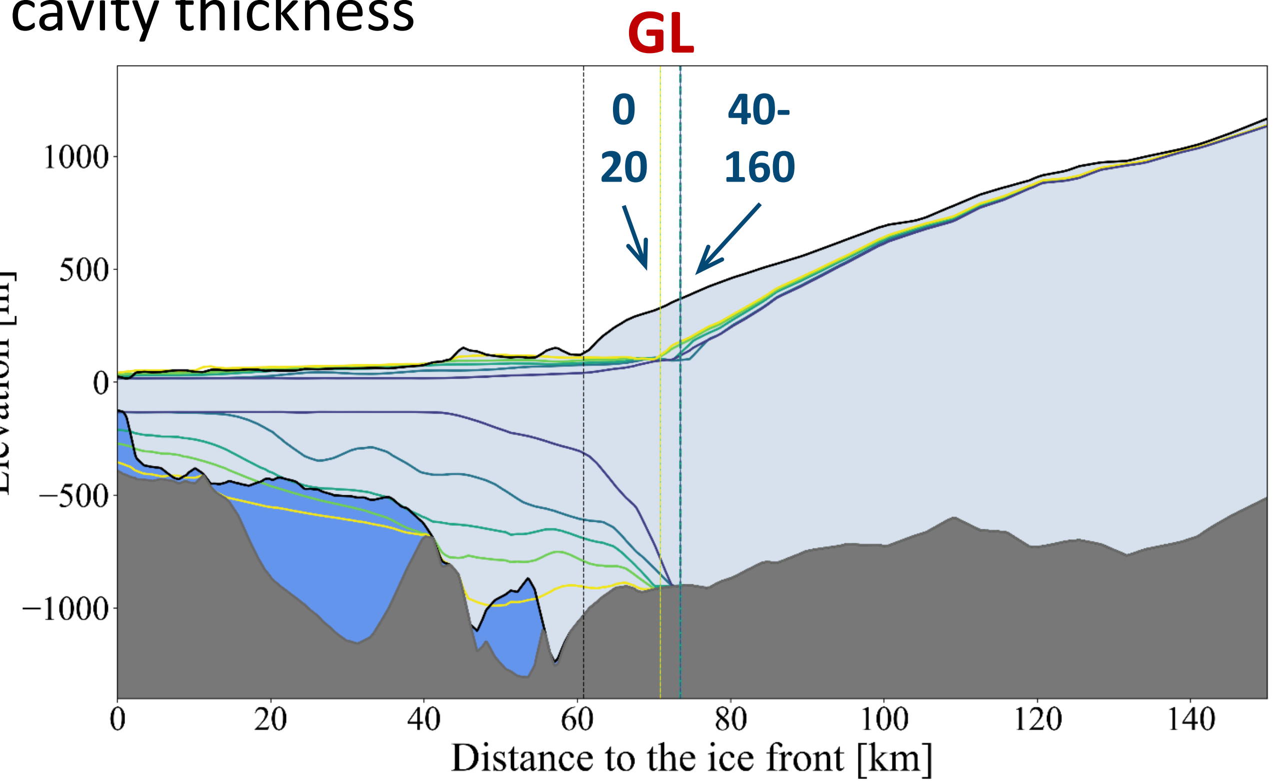


- GLs retreat 0-11.23 km
  Control run GL retreats 6.95 km

Results

Melt rates group: grounding line position & ice cavity thickness

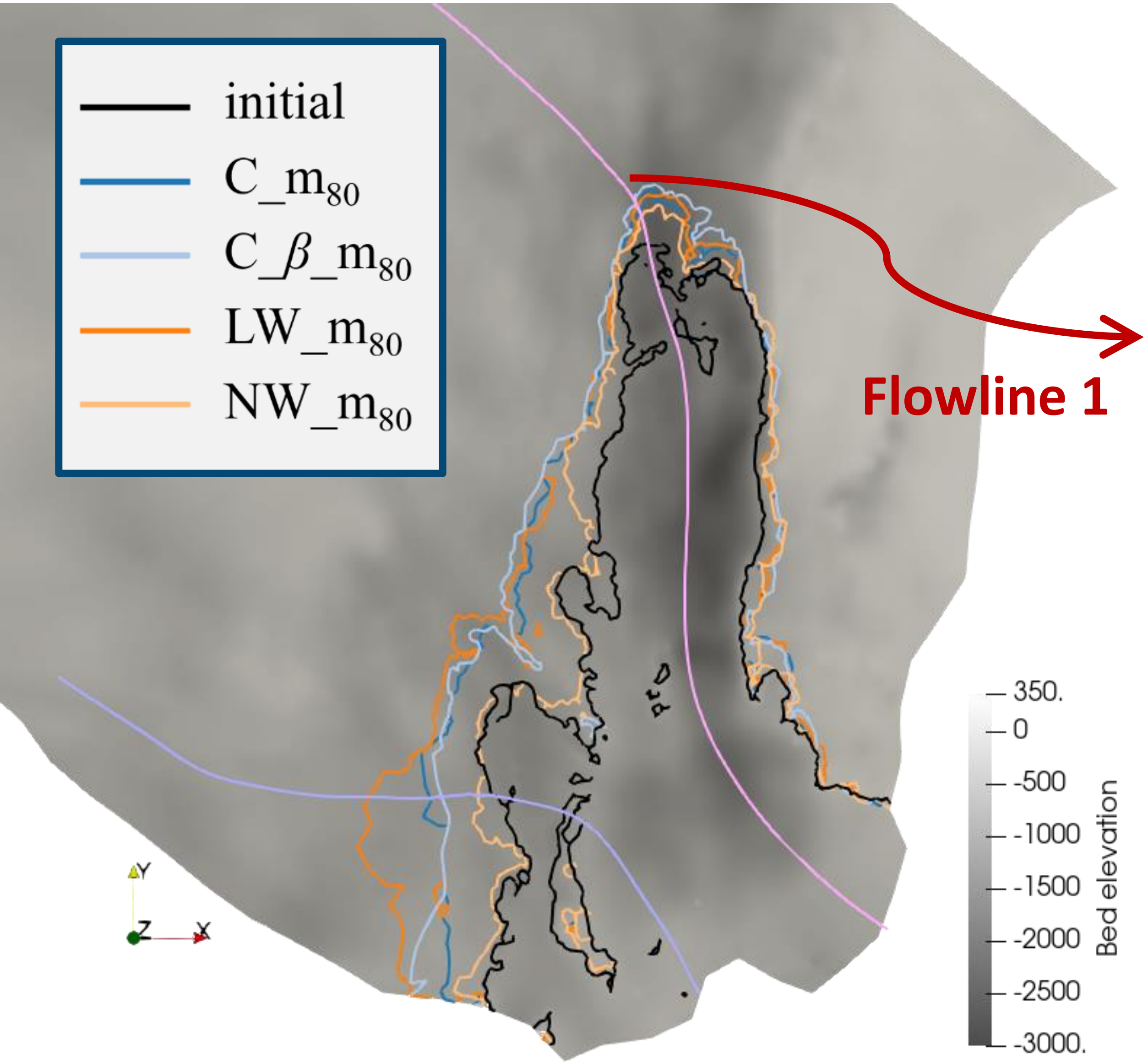


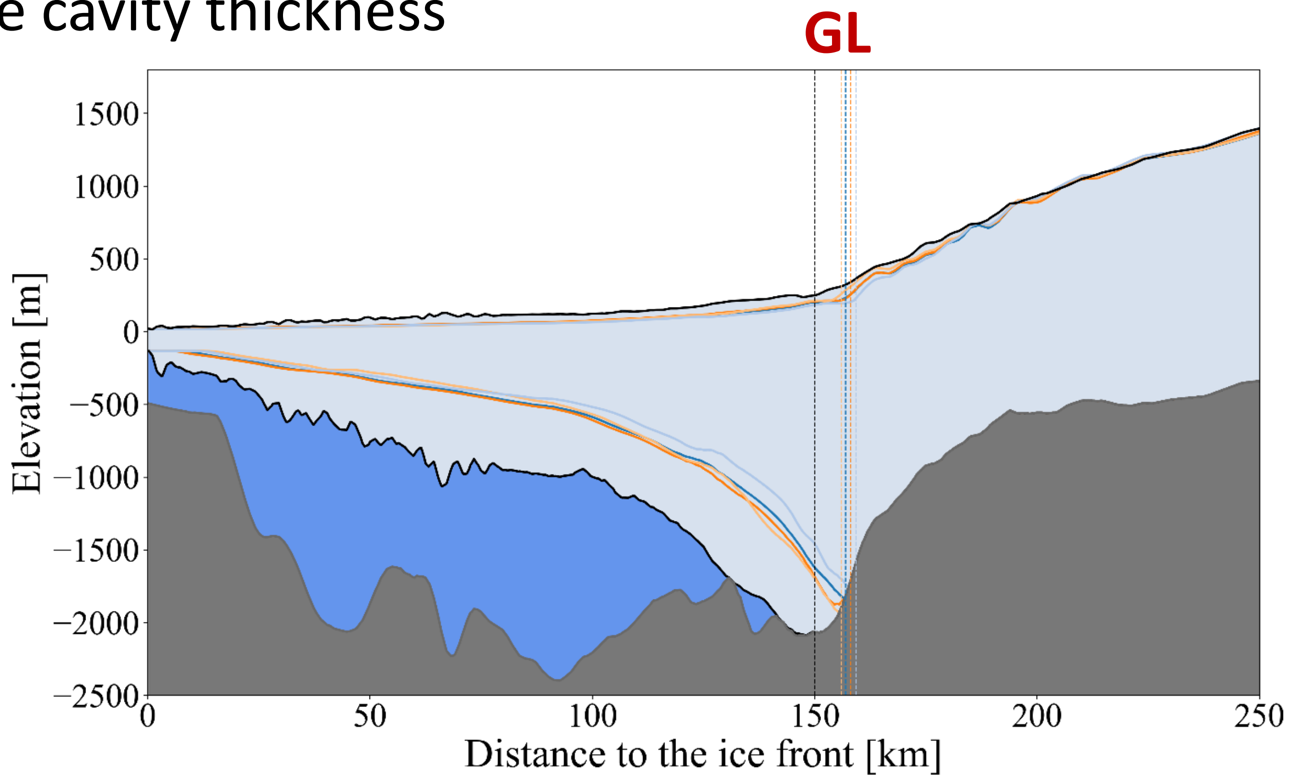


- GLs retreat 10.02-12.63 km
  Higher melt rates GLs retreat the most
- Higher melt rates result in larger ice cavities, while lower melt rates (0, 20 m/yr) produce smaller ice cavities

Results

Sliding laws group: grounding line position & ice cavity thickness

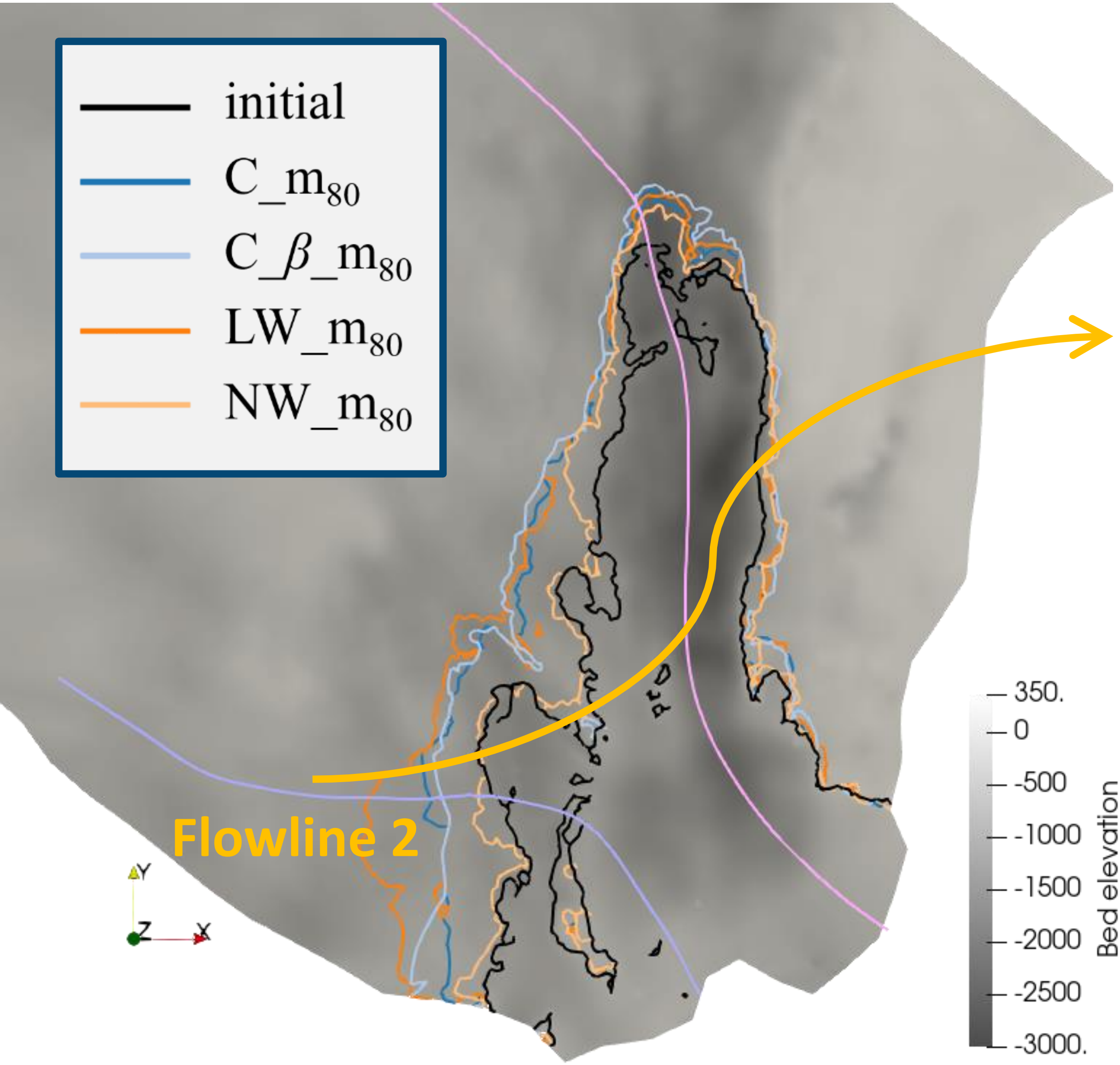


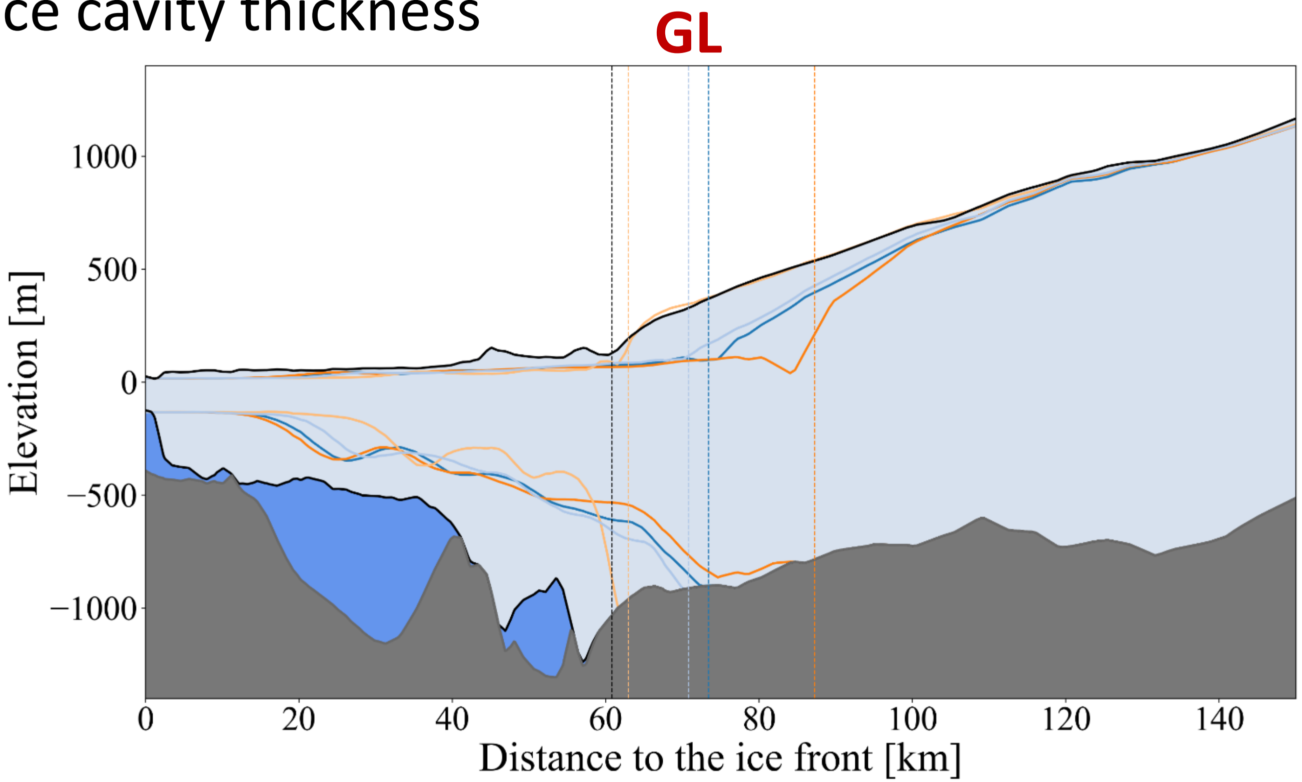


- GLs retreat 5.94-9.24 km
  Control run GL retreats 6.95 km
  Modified coulomb GL retreats the most
  Nonlinear Weertman GL retreats the least

Results

Sliding laws group: grounding line position & ice cavity thickness



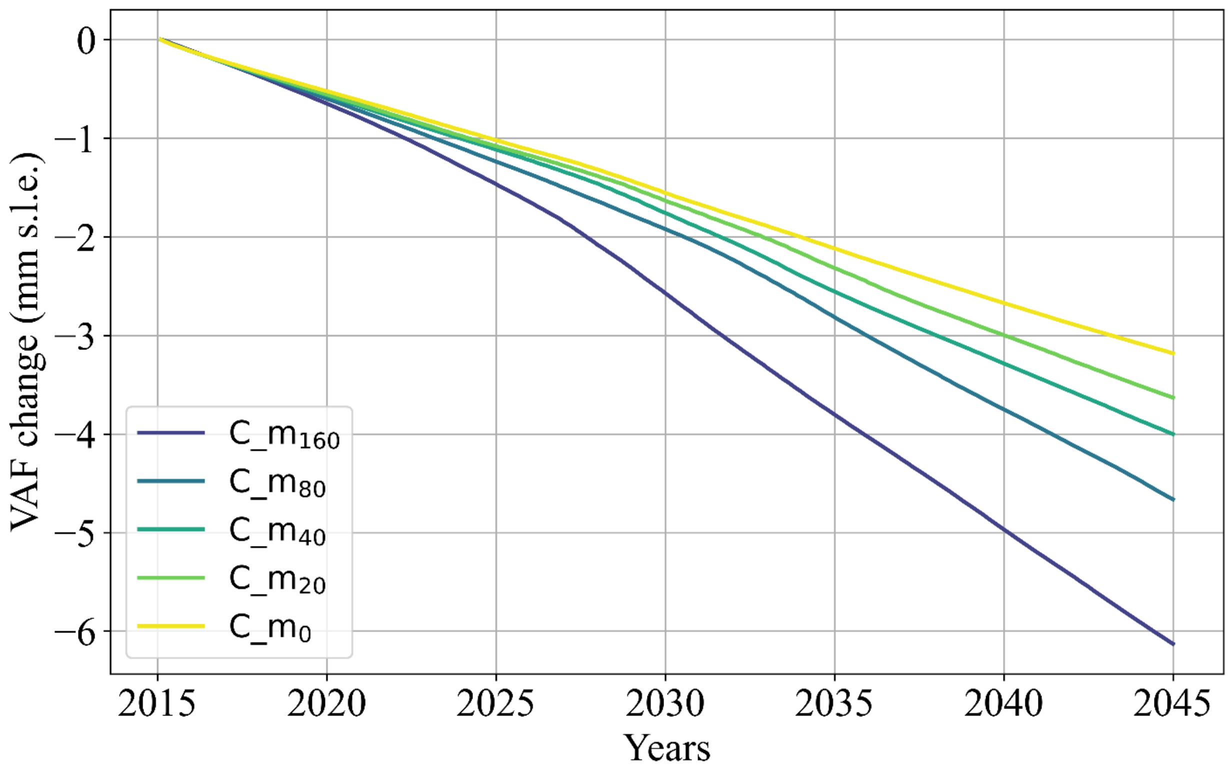


- GLs retreat 2.13-26.45 km
  control run GL retreats 12.63 km
  Linear Weertman GL retreats the most
  Nonlinear Weertman GL retreats the least
- No significant effect on ice cavities

Results

Ice volume above floatation (VAF)

Melt rates group

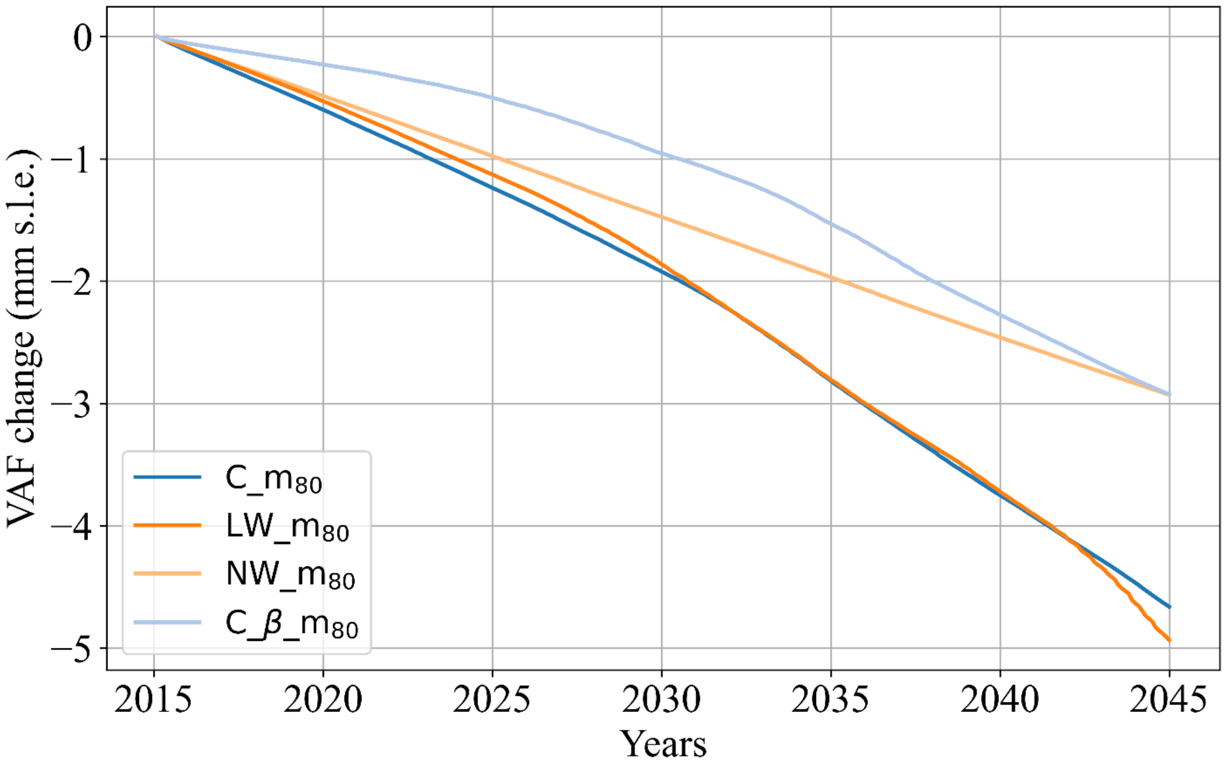


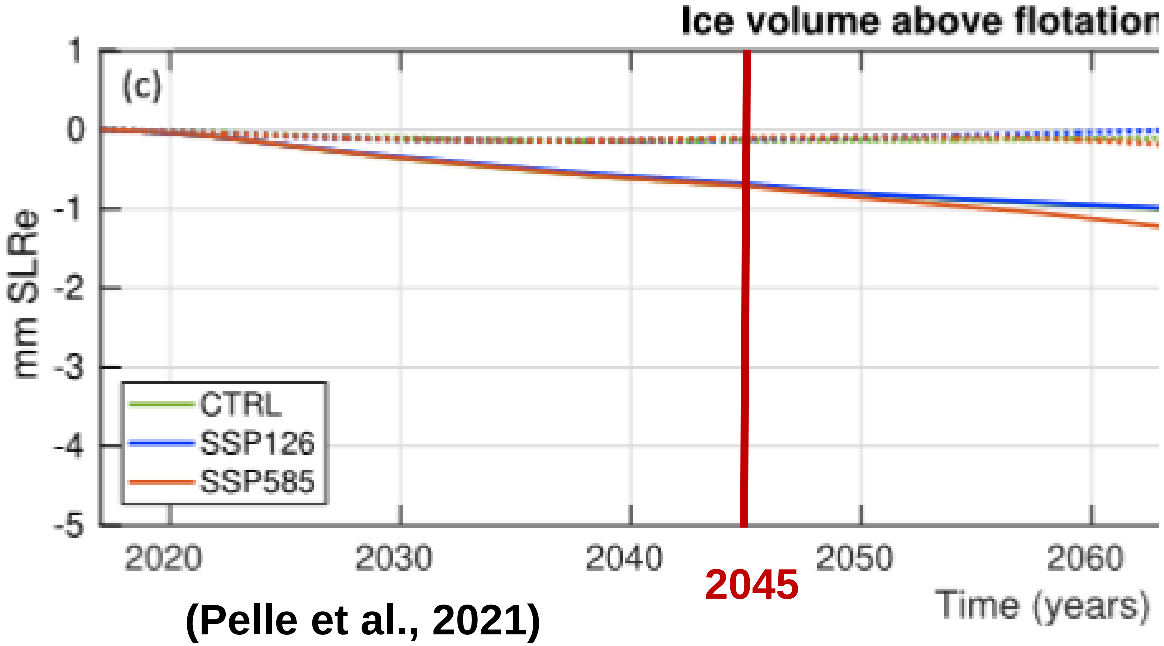
- Higher melt rates lead to more VAF changes.
- The control run (30 yrs & maximal melt rate of 80 m/yr & Coulomb sliding law) yields s.l.r contribution of 4.68 mm.

Results

Ice volume above floatation (VAF)

Sliding laws group





(Pelle et al., 2021)

- 4.68 mm SLRe ice loss for control run
- Higher than Pelle et al (2021) results, because the simulated domain and sub-shelf melt rates distribution are different.

Conclusions

- The position of the grounding line, the thickness of the ice cavity, and VAF are sensitive to the ice shelf basal melt rate, higher melt rates leading to more grounding line retreats, larger ice cavities and more VAF changes.
- The sensitivity of grounding lines retreats to different sliding laws varies spatially. Different sliding laws gives similar thickness of ice cavities.
- 30 yrs & maximal melt rate of 0-160 m/yr & Coulomb sliding law yield s.l.r contribution of 3.2-6.2 mm;
- 30 yrs & maximal melt rate of 80 m/yr & different sliding laws yield s.l.r contribution of 3-5 mm .

Outlook

- Use alternative ice shelf basal melt rate parameterization schemes, such as considering the effects of ocean temperature & salinity, and their variabilities.
- Couple Elmer/Ice to ROMS using FISOC.
- Perform prognostic simulations under different scenarios.

Advice for Elmer/Ice

- Use non-linear sliding laws in the inversion.

Thank you for your interest!

Yiliang, MSc student at BNU
Email: mayiliang@mail.bnu.edu.cn