Impact of glacial isostatic adjustment on the long-term stability of the Antarctic ice sheet

Violaine Coulon[1], Kevin Bulthuis[2], Pippa L. Whitehouse[3], Sainan Sun[1] and Frank Pattyn[1].

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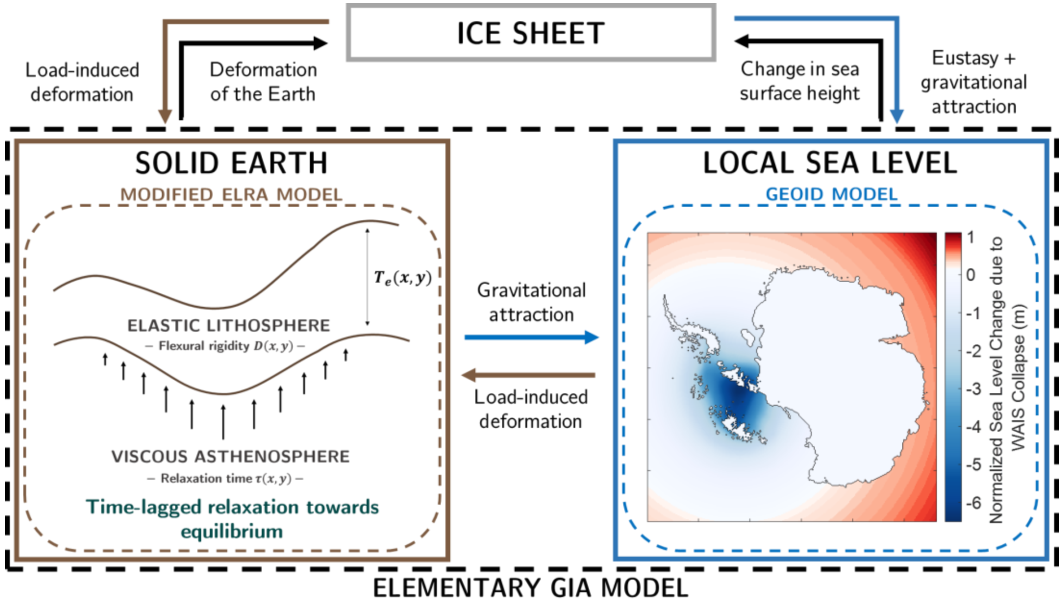
We designed an **Elementary GIA model** with
- **spatially-varying viscoelastic properties**
- **gravitationally-consistent geoid changes**.

Its computational efficiency facilitates ensemble approaches to study the **impact of glacial isostatic adjustment on the long-term stability of the Antarctic ice sheet**.

Results show that
- the weak Earth structure beneath the West Antarctic ice sheet significantly promotes its stability
- considering a uniform Antarctic Earth structure may overestimate GIA stabilisation in East Antarctica



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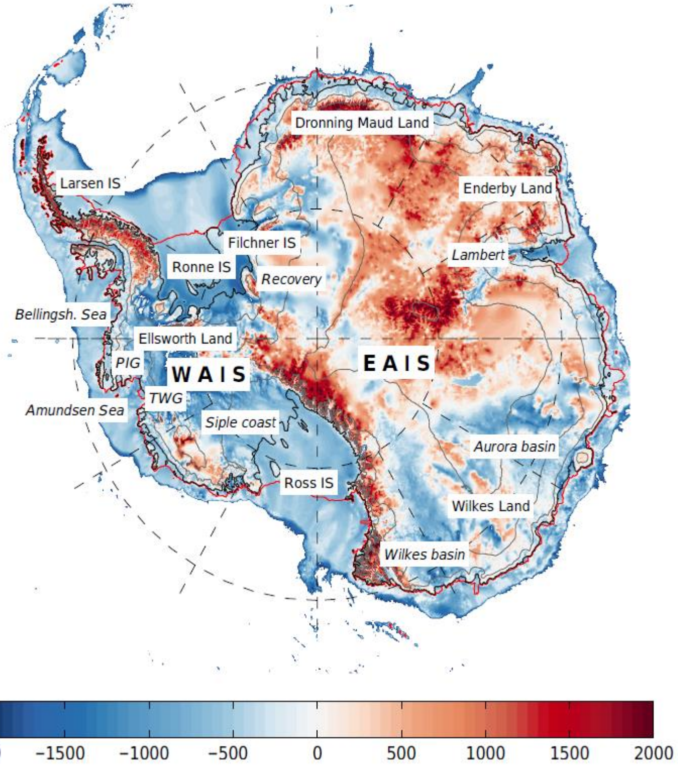
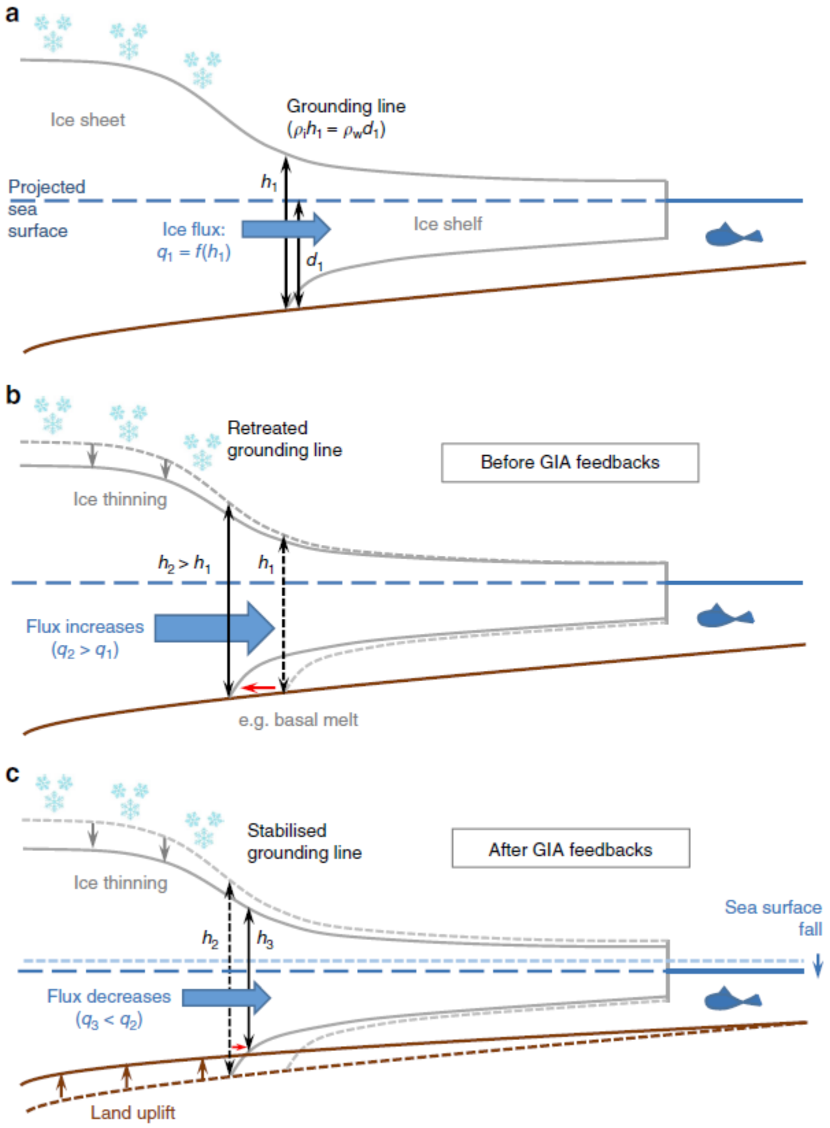
OUTLINE

The **Antarctic ice sheet** is largely **grounded below sea-level** on an **inward deepening bed**. This setting makes it sensitive to the **Marine Ice Sheet Instability** (MISI)...

However, **Glacial Isostatic Adjustment** has the potential to **stabilise** a marine ice sheet **undergoing MISI**!



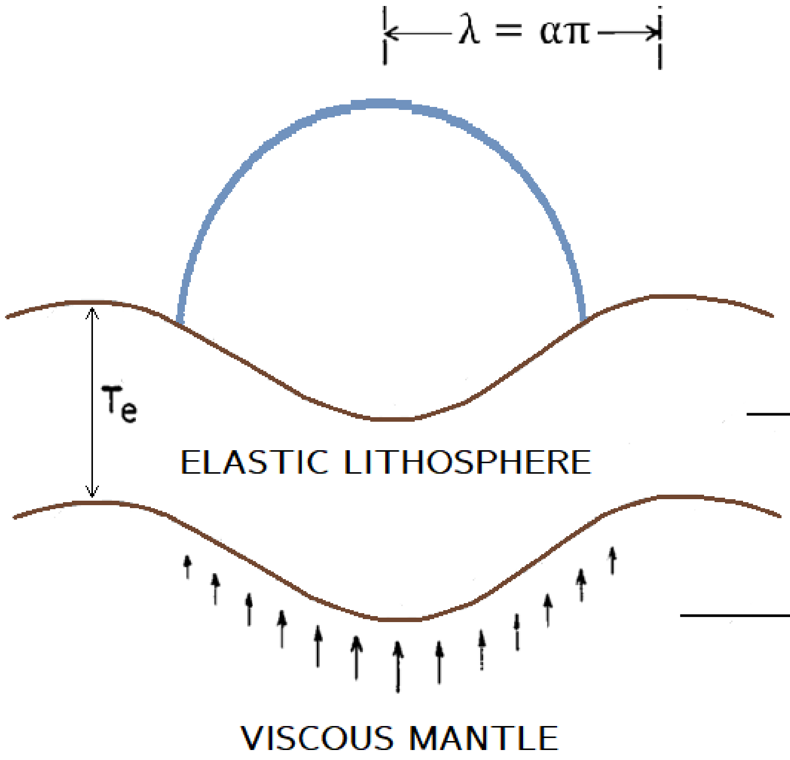
Bedrock topography (Fretwell et al., 2013) of the Antarctic ice sheet, Grounding lines are shown in black; ice shelf edges are shown as a red line.
[From Pattyn, The Cryosphere, 2017]



Stabilising effect of GIA on ice dynamics.
[From Whitehouse et al., Nature Communications, 2019]

The strength of **GIA stabilising feedbacks** depends on the pattern and rate of isostatic adjustment…

which in turn depend on the **rheological properties** of the solid Earth.



The pattern of the deformation depends on the thickness of the lithosphere: the thinner the lithosphere, the larger and the more local the deformation (λ ↘).

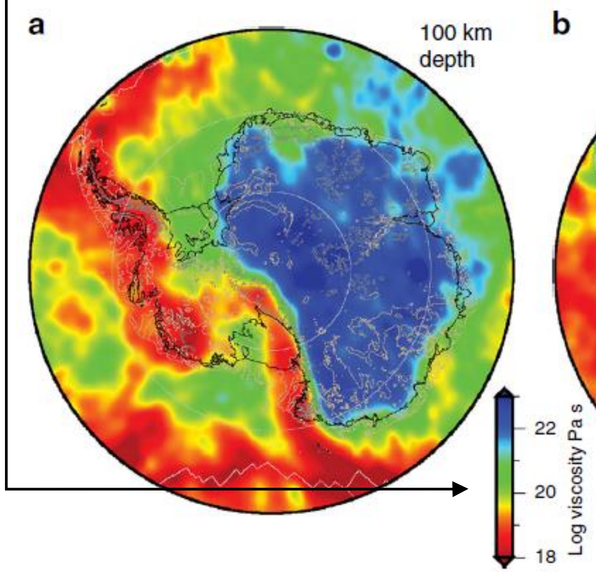
The rate of solid Earth changes depends on the viscosity of the mantle: the lower the viscosity, the faster the deformation.

The thinner the lithosphere and the lower the mantle viscosity, the stronger the GIA stabilising feedbacks!

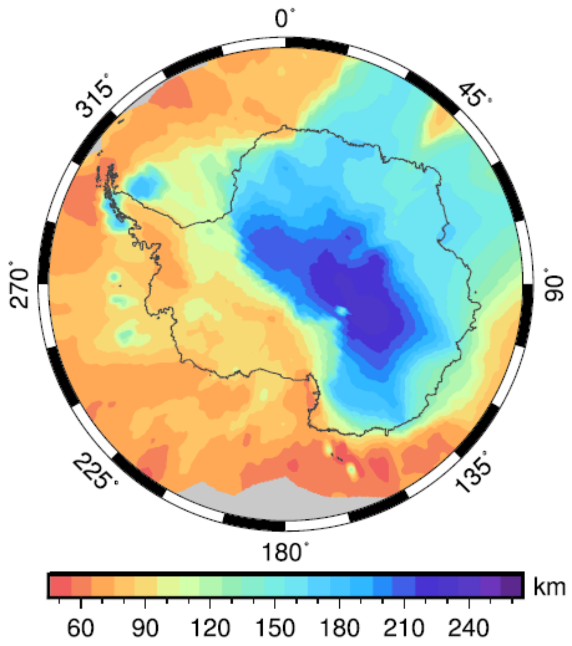
The Antarctic solid Earth displays **strong lateral variations in viscoelastic properties**…

which can have a **strong influence on grounding line stability**!

Uniform upper mantle value typically considered in the literature:
2 x 10^{20} to 10^{21} Pa s



Spatial variations in estimated upper mantle viscosity beneath Antarctica at depths of (a) 100 km and (b) 250 km.
[From Whitehouse et al., Nature Communications, 2019]



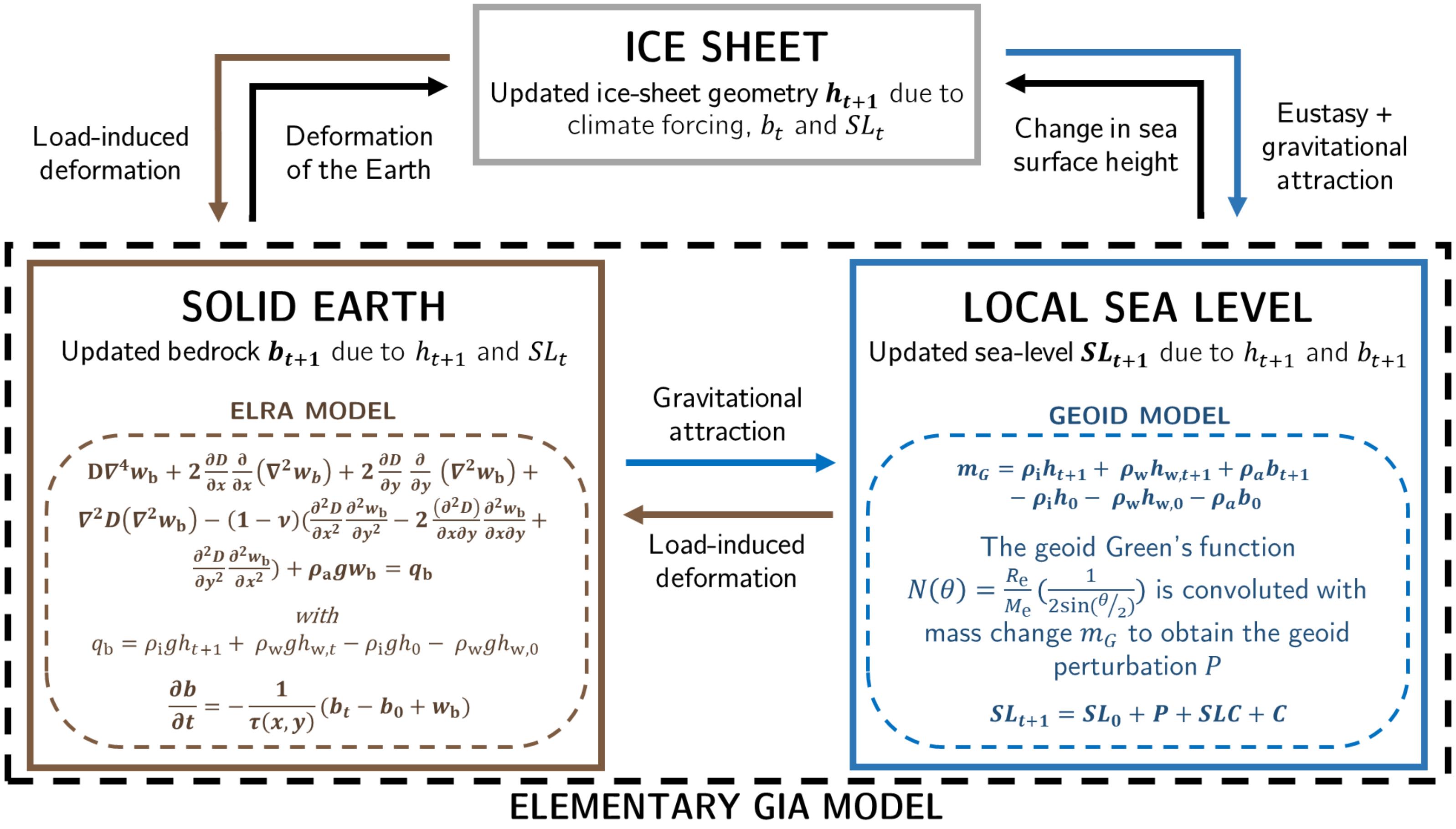
Lithosphere Thickness (AN1-LAB)
[From Pappa et al., JGR: Solid Earth, 2019]

WEST ANTARCTICA: Thin lithosphere and low mantle viscosity
→ Weak solid Earth - Faster and more localised response
EAST ANTARCTICA: Thick lithosphere and high mantle viscosity
→ Rigid solid Earth - Slower and dampened response

However, **big unknowns remain** in determining **absolute values** of these rheological properties with precision…

We designed an **Elementary GIA model** consisting of

- a **modified** Elastic Lithosphere–Relaxing Asthenosphere (**ELRA**) model able to consider **spatially-varying viscoelastic properties**
- supplemented with an **approximation of gravitationally-consistent geoid changes**.



Interactions between the ice sheet, the local sea level, and the solid Earth in the regional coupled system described here, adapted from de Boer et al. (2017), In the solid-Earth system, $D(x,y)$ is the flexural rigidity of the lithosphere, ν the lithospheric Poisson's ratio, w_b the equilibrium deflection of the lithosphere, q_b the applied load, g the gravitational acceleration, and $\tau(x,y)$ the relaxation time of the asthenosphere. In addition, ρ_i, ρ_w, and ρ_a are the ice, ocean water, and asthenosphere densities, respectively. The ocean column thickness at time steps t and $t+1$ are $h_{w,t} = SL_t - b_t$ and $h_{w,t+1} = SL_{t+1} - b_{t+1}$ respectively, while h_t and h_{t+1} are the ice thicknesses at time t and $t+1$ and h_0 and $h_{w,0}$ are the initial ice and ocean column thicknesses. Similarly, b_0 is the initial bedrock elevation and b_t and b_{t+1} the ones at time t and $t+1$, In the local sea-level system, R_e and M_e are the Earth radius and mass, respectively, and θ is the spherical distance from the load. SLC is the barystatic sea-level contribution due to ice sheet mass changes, and C is a mass conservation term [Coulon et al., submitted].

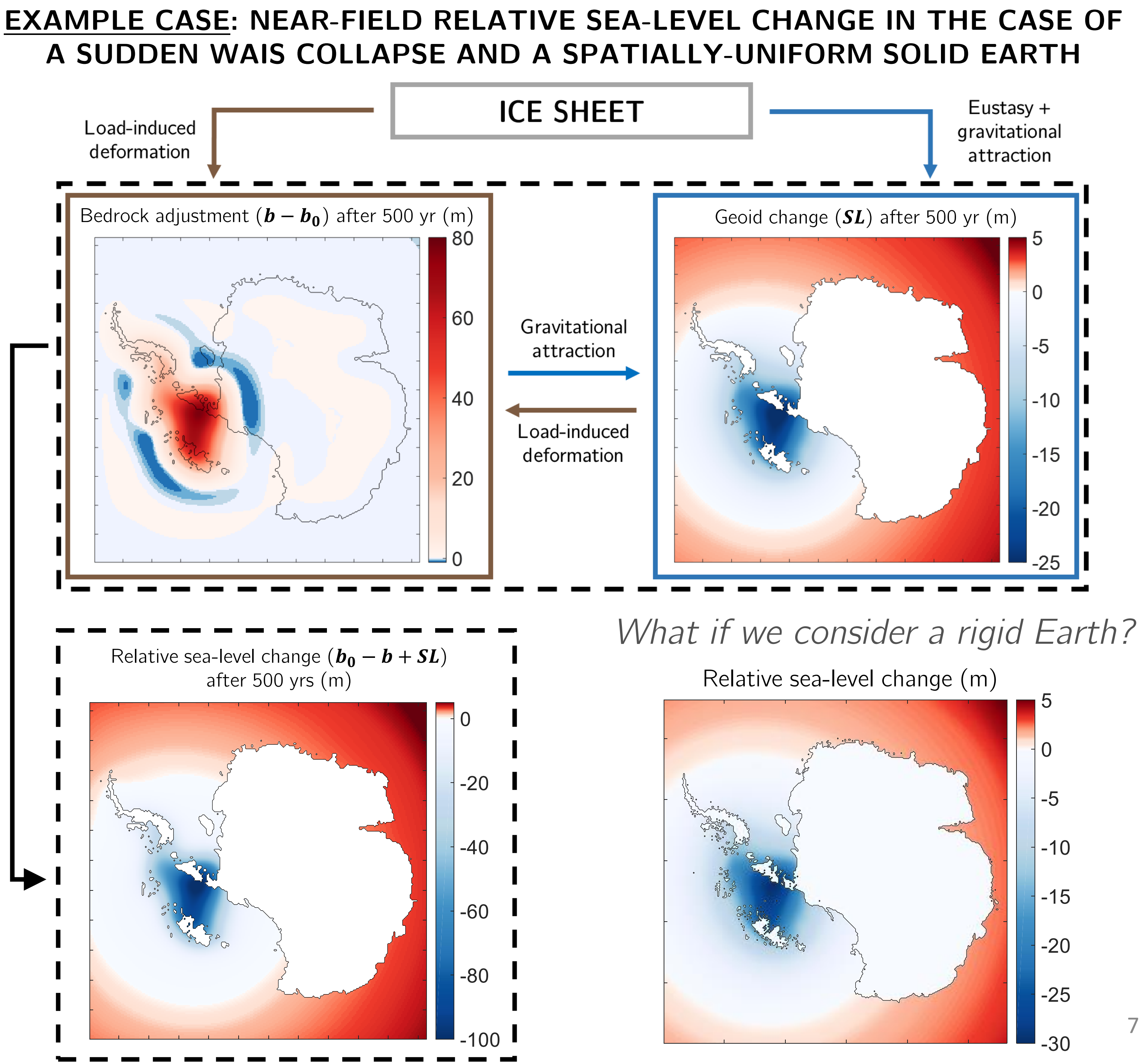
Easy to implement in a standalone ice-sheet model!

(here: implemented within the f.ETISh ice-sheet model)

II. OUR TOOL: THE ELEMENTARY GIA MODEL

While ice-sheet models are typically run with a uniform adjacent sea surface, this simple GIA model allows to **approximate spatially variable near-field relative sea-level changes** in a **computationally-efficient** way.

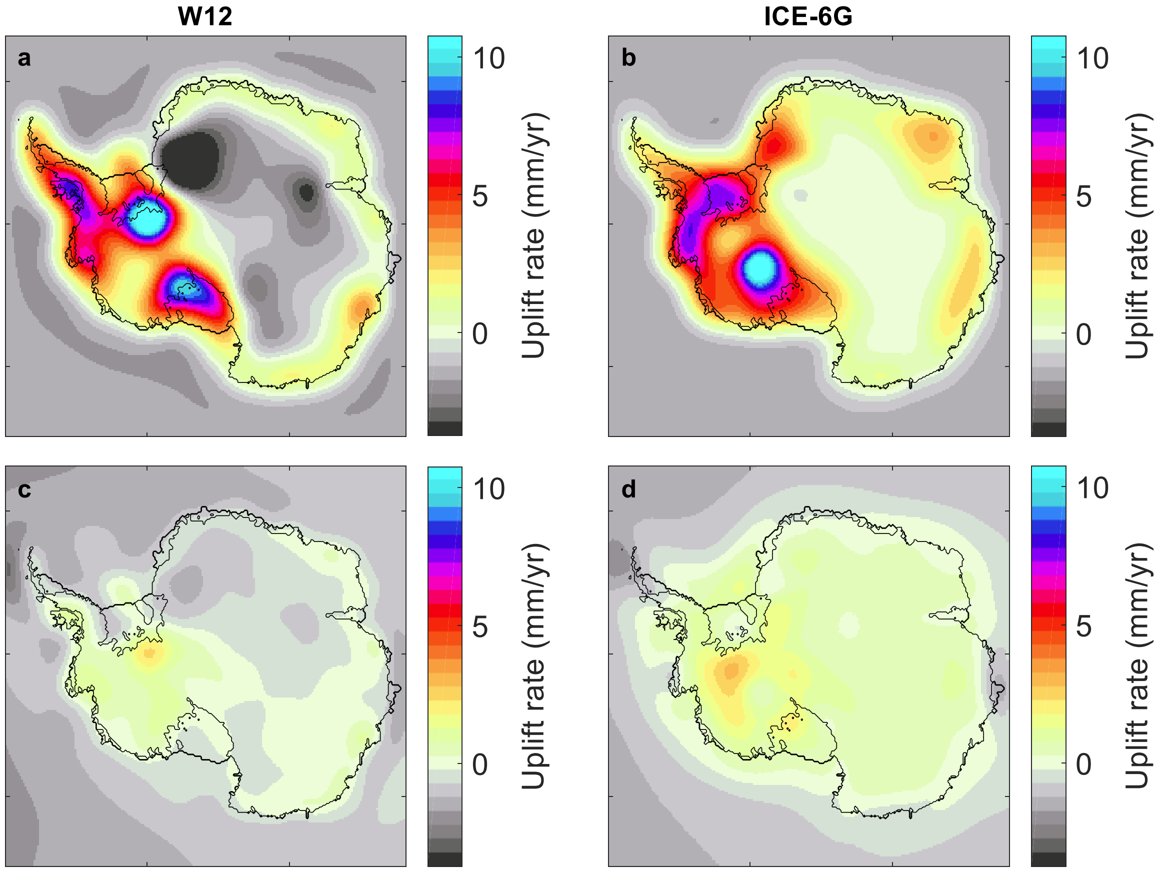
- It is adapted to **account for lateral variations in viscoelastic properties** (and therefore reproduce the specific Antarctic setting)
- It allows for the realisation of **large ensembles of simulations** and **parameter exploration**.



But it comes with **some drawbacks**:

- It is a **regional model**: direct and indirect gravitational and earth-deformational effects due to **ice masses other than the Antarctic ice sheet are neglected**.
- **A part of the GIA signal is ignored:**
  - The **depth-variability of the Earth structure within the mantle** (implying a full spectrum of relaxation times)
  - The **elastic** component of the Earth's **response**
  - The **Earth rotational feedback**

COMPARISON WITH SELF-GRAVITATING VISCOELASTIC EARTH MODELS (SGVEMs):



Uplift rate maps for the W12 (a) and ICE-6G (b) ice-loading histories obtained by coupling with an ELRA model using uniform ELRA parameters ($\tau = 8000\,yr$ and D = 10^{25} Nm in (a) and $\tau = 4000\,yr$ and D = 10^{25} Nm in (b), based on Argus et al. (2014) and Le Meur and Huybrechts (1996)). Only the Antarctic component (Antarctic ice-sheet reconstruction) of these ice-loading histories was used while the far-field component, when existent, was ignored. No gravitationally-consistent local sea-level variations are considered. In (c--d), these maps are compared with those obtained by coupling these ice loading histories with an SGVEM: (c) displays the difference between (a) and the modeled uplift rates reproduced in Whitehouse et al. (2012) and (d) displays the difference between (b) and the modeled uplift rates reproduced in Argus et al. (2014) [Coulon et al., submitted].

Nonetheless, this elementary GIA model captures the essence of global SGVEMs - and therefore the essential features and processes influencing Antarctic grounding-line stability - in a computationally-efficient way.

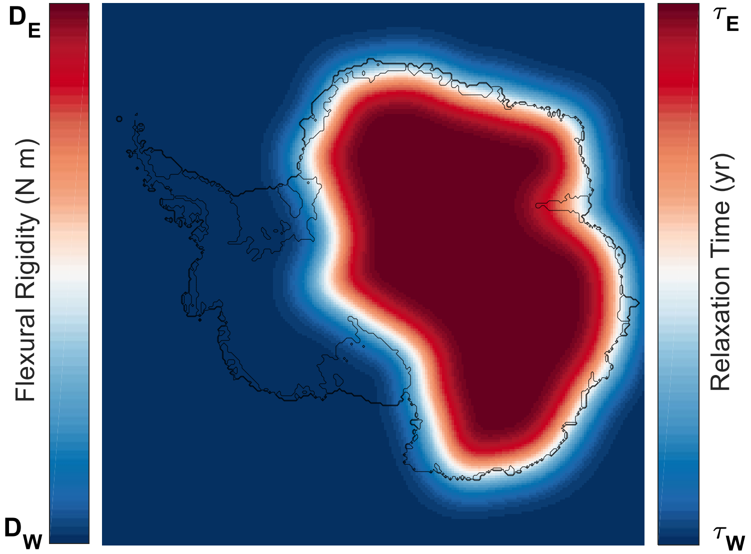
① PROBABILISTIC ASSESSMENT OF THE INFLUENCE OF UNCERTAINTIES IN VISCOELASTIC PROPERTIES ON THE RESPONSE OF THE ANTARCTIC ICE SHEET TO FUTURE WARMING

- We run an ensemble of **2000 Monte Carlo experiments** spanning **plausible solid Earth configurations** for both **West** and **East Antarctica.**
- For each of the 2000 Monte Carlo configurations:
  - **5000-yr simulation of the Antarctic ice sheet** from present-day configuration at 25km resolution
  - **f.ETISh** ice-sheet **model** (Pattyn, 2017)
  - **Extended RCP scenarios** (Golledge et al., 2015)

Flexural rigidity D

ELRA parameter representative of **elastic lithosphere thickness**

Uniform D value typically considered in the literature:
10^{25} N m



Dual pattern for the ELRA solid-Earth parameters - Flexural rigidity D (N m) and Relaxation time τ (yr) - approximating lateral variations between Eastern and Western Antarctica. The values of D_W and τ_W are applied to the dark blue areas while the values of D_E and τ_E are applied to the red areas. Smoothing (Gaussian filter) is applied at the boundary between the two regions. The values of D_W, D_E, τ_W and τ_E are randomly sampled from the table below.

Relaxation time τ

ELRA parameter representative of **upper mantle viscosity**

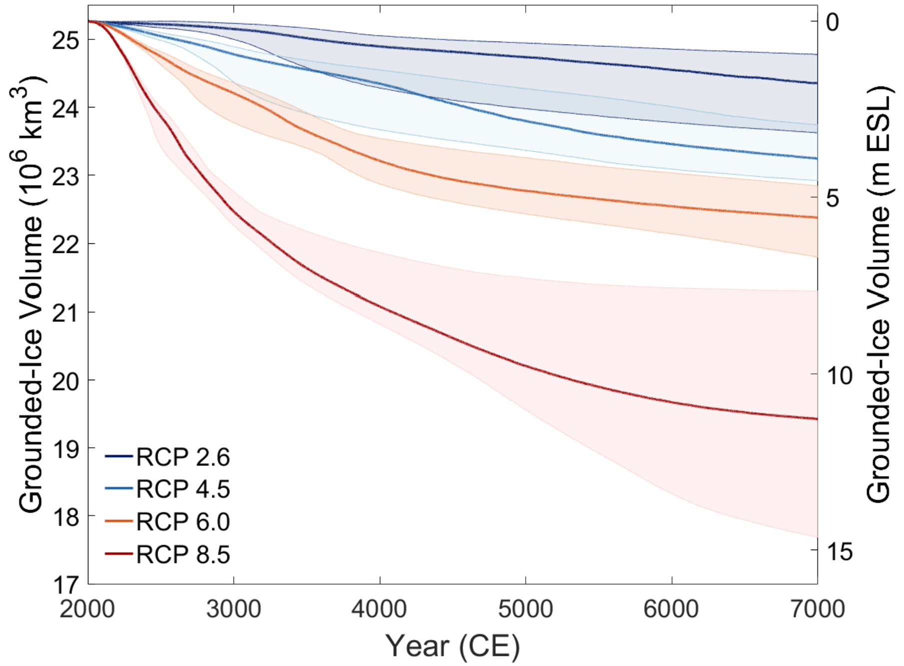
Uniform τ value typically considered in the literature:
3000 years

ELRA parameter	Uncertainty range	Associated viscoelastic property
τ_W	$[1 \times 10^0 - 5 \times 10^3]$ yr	$\sim 10^{18} - 10^{21}$ Pa s
τ_E	$[1 \times 10^3 - 5 \times 10^4]$ yr	$\sim 10^{20} - 5 \times 10^{22}$ Pa s
D_W	$[1 \times 10^{22} - 1 \times 10^{24}]$ N m	~10 – 50 km
D_E	$[5 \times 10^{23} - 5 \times 10^{25}]$ N m	~40 – 150 km

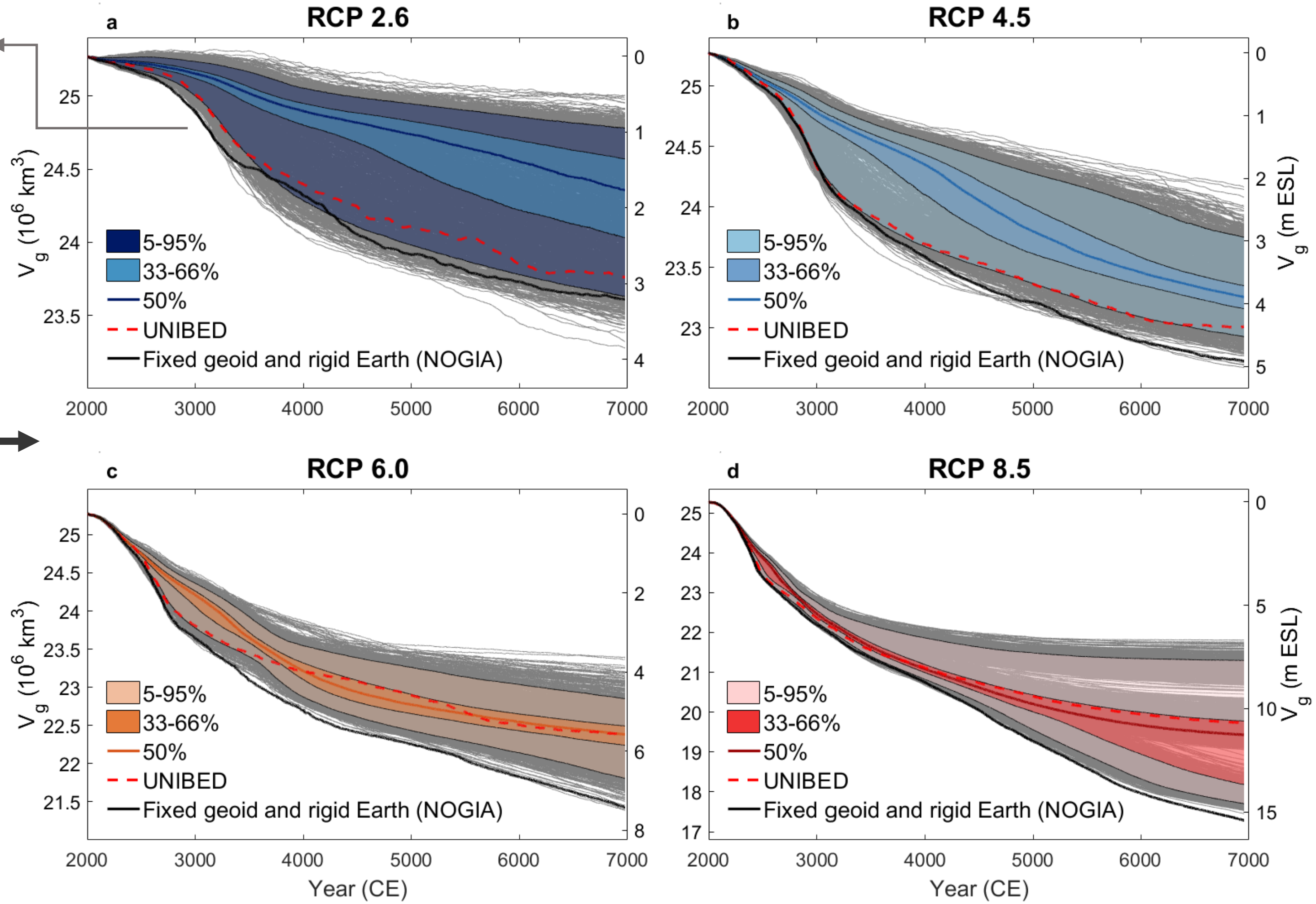
Solid-Earth parameters in the ELRA model with their uncertainty range used in the uncertainty analysis (determined in order to be representative of observations-based inferences of 3D Earth structure in Antarctica). Uncertainty ranges of associated viscoelastic properties are provided for the sake of illustration but should not be considered as exactly equivalent. We consider wide ranges of values in order to account for the large variations observed locally and the associated uncertainty.

When compared to spatially-uniform ELRA simulations, our probabilistic projections show a **stabilising effect**, **except under strong forcing at longer timescale**.

Each single projection from the ensembles (grey lines) considers a random plausible solid Earth configuration, with different Earth properties in West and East Antarctica!



Probabilistic projections of the grounded-ice volume under different RCP scenarios. Lines represent the median projections while shaded areas are the 5-95% probability intervals that represent the uncertainty in grounded-ice volume projections due to uncertainty in ELRA parameters. The right ordinate gives an approximation of the equivalent sea-level contribution,



Antarctic grounded-ice volume (Vg) projections considering uncertainty in Antarctic viscoelastic properties under different RCP scenarios. Colored solid lines are the median projections while shaded areas are the 33-66% and 5-95% probability intervals that represent the uncertainty in grounded-ice volume projections due to uncertainty in ELRA parameters. Black lines correspond to control simulations in which neither bedrock nor geoid changes are included (NOGIA). Dashed red lines correspond to simulations with uniform ELRA parameters (UNIBED) taken from Le Meur and Huybrechts (1996). Grey lines represent time series of Antarctic grounded-ice volume for the ensemble of 2000 Monte Carlo simulations [Coulon et al., submitted],

UNIBED

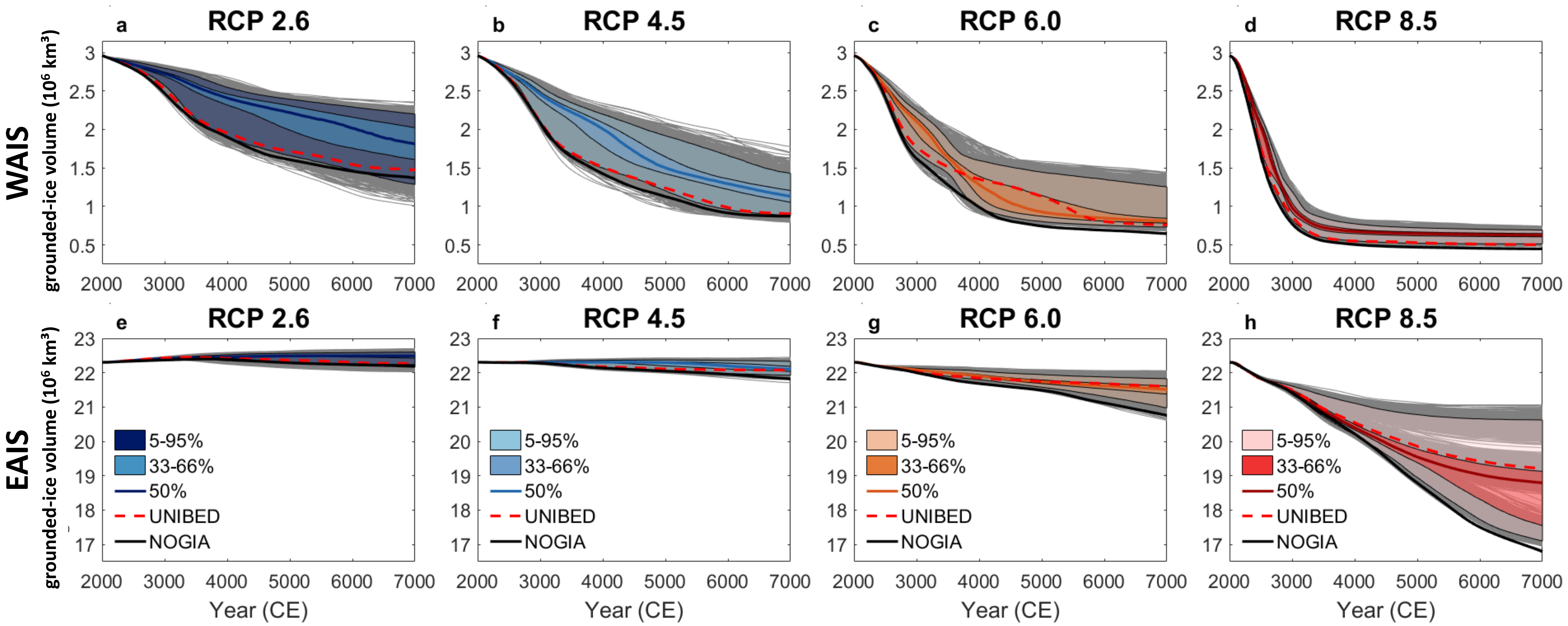
Projections from the ensemble are **compared to** simulations considering **spatially-uniform** values of **ELRA** parameters commonly used in the literature:

$\mathbf{D = 10^{25}\ N\ m\ \&\ \tau = 3000\ yr}$ (Le Meur & Huybrechts, 1996)

Spatial variations in viscoelastic properties VS spatially-uniform ELRA model:

- WAIS: GIA feedbacks promote stability.
- EAIS: strong Earth structure provides limited GIA stabilisation.

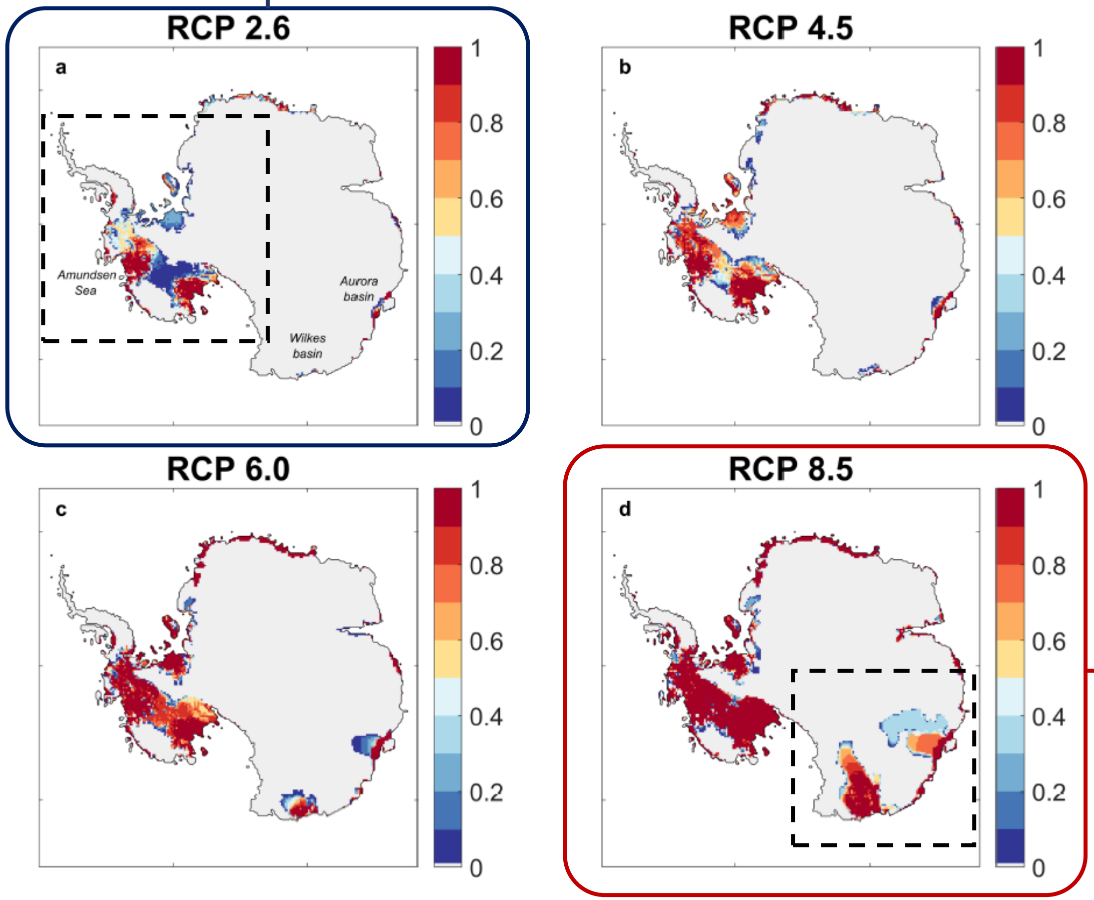
What if we look at the West (top row) and East (bottom row) Antarctic ice sheets separately?



West (a—d) and East (e—h) Antarctic grounded-ice volume (Vg) projections considering uncertainty in Antarctic viscoelastic properties under different RCP scenarios. [Coulon et al., submitted]

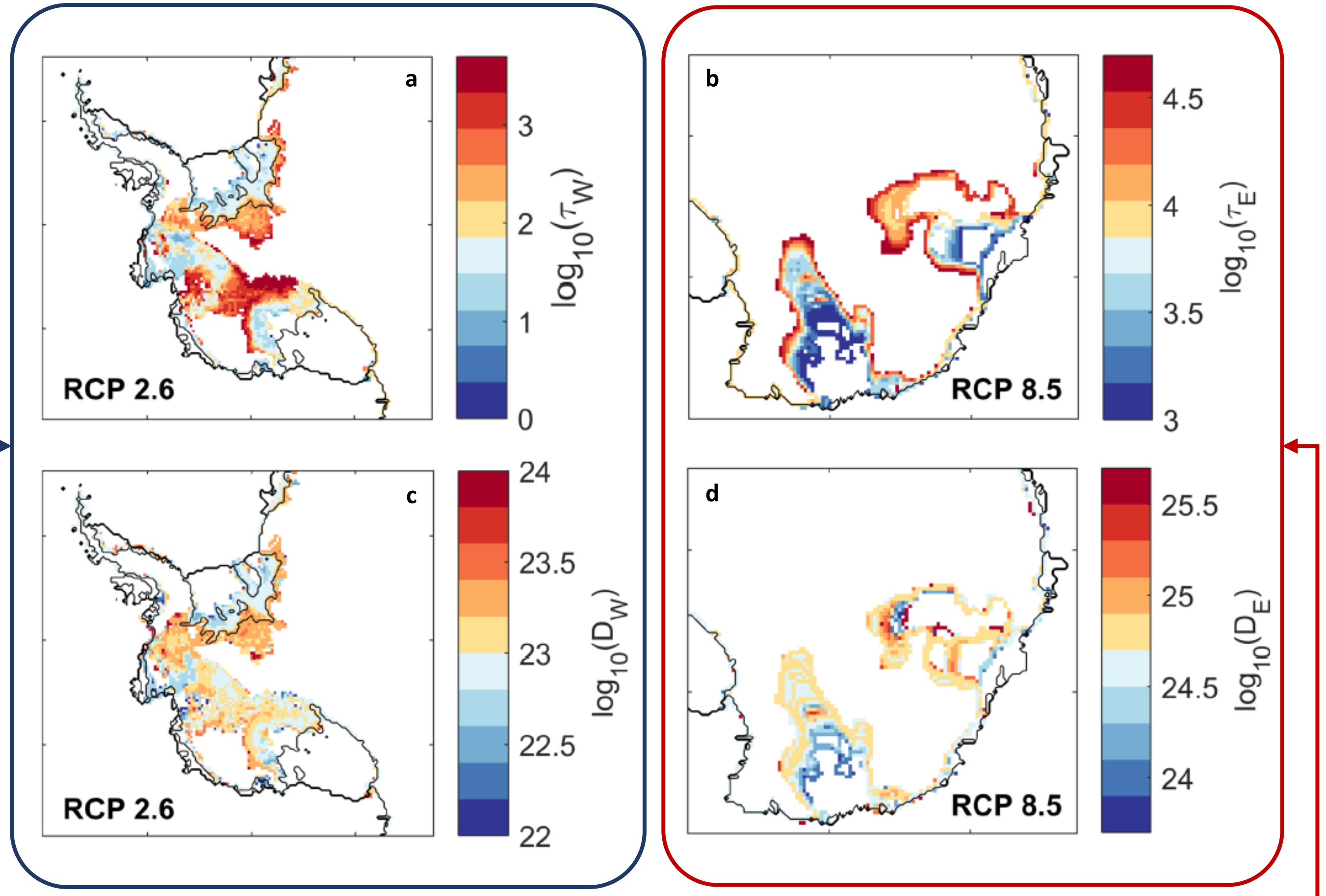
- Weak solid Earth structures (low D and τ) are able to delay or even prevent WAIS collapse under weak forcing.
- Retreat in Wilkes and Aurora basins under stronger forcing (RCP 6.0 and 8.5) at longer timescales.
- Retreat in Aurora basin is strongly GIA-dependent.

What are the sensitive areas?



Marginal probability of being ungrounded under the four RCP scenarios at 7000 CE.
For each RCP scenario, the marginal probability of being ungrounded at a given point is computed using Monte Carlo estimation with the ensemble of 2000 Monte Carlo simulations. Results are for RCP 2.6 (a), 4.5 (b), 6.0 (c), and 8.5 (d). [Coulon et al., submitted]

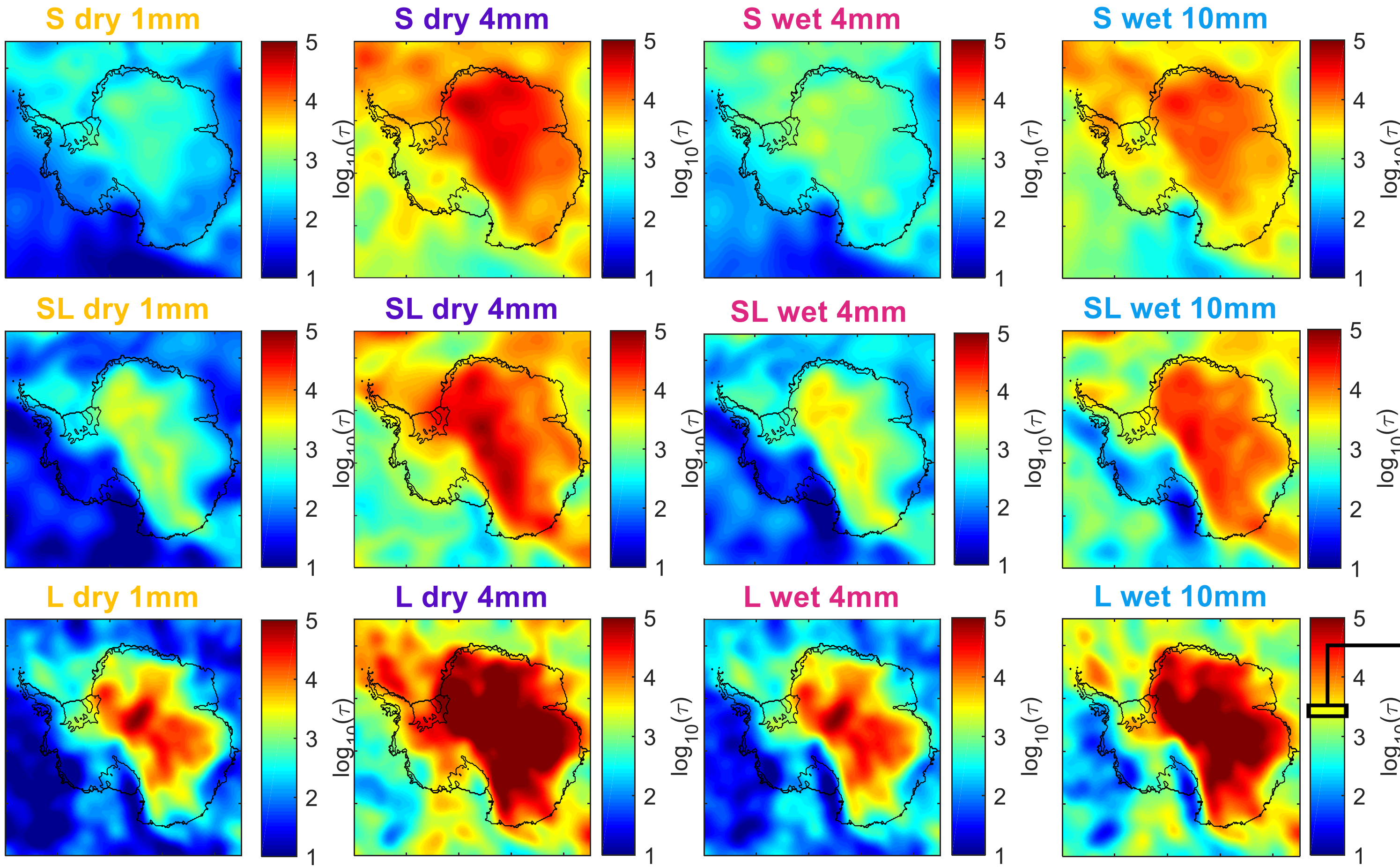
How do parameters influence the projections?



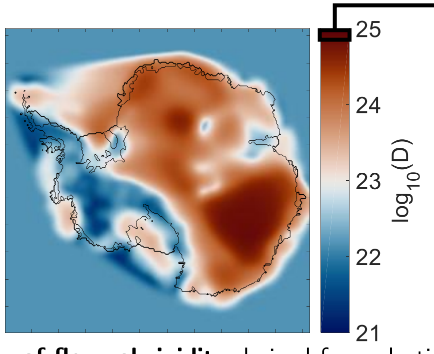
Sensitivity of future grounding-line retreat to solid-Earth structure,
The position of the grounding line at the end of the 5000-yr simulation for the 2000 Monte Carlo simulations is color-coded following the value of one of the ELRA parameters. Figures (a-d) show the sensitivity of final grounding-line position under RCP 2.6 to τ_W (a) and D_W (c) and under RCP 8.5 to τ_E (b) and D_E (d). [Coulon et al., submitted]

② EVALUATE THE INFLUENCE OF INTRA-REGIONAL VARIABILITY IN VISCOELASTIC PROPERTIES ON ANTARCTIC LONG-TERM STABILITY

- **Flexural rigidity**: we use data of elastic lithosphere thickness from Chen et al. (2017).
- **Relaxation time**: we transform the average upper-mantle viscosity derived from various 3D GIA models (Whitehouse et al., in prep) into relaxation time maps, making the following **assumptions**:
  - The **relaxation time** is **proportional to** the **average upper-mantle viscosity.**
  - $\eta = 5 \text{ x } 10^{20}$ Pa s is equivalent to $\tau = 3000$ yr (Le Meur and Huychrechts, 1996).



Maps of relaxation time derived from the average upper-mantle viscosity obtained from 12 different 3D GIA models (provided by Pippa L. Whitehouse) generated using the W12 global ice model and different seismic models (S = S40RTS; Ritsema et al., 2011, SL = Schaeffer and Lebedev, 2013 L = Lloyd et al., 2020), mantle water content (dry or wet) and grain size (1, 4 or 10 mm).



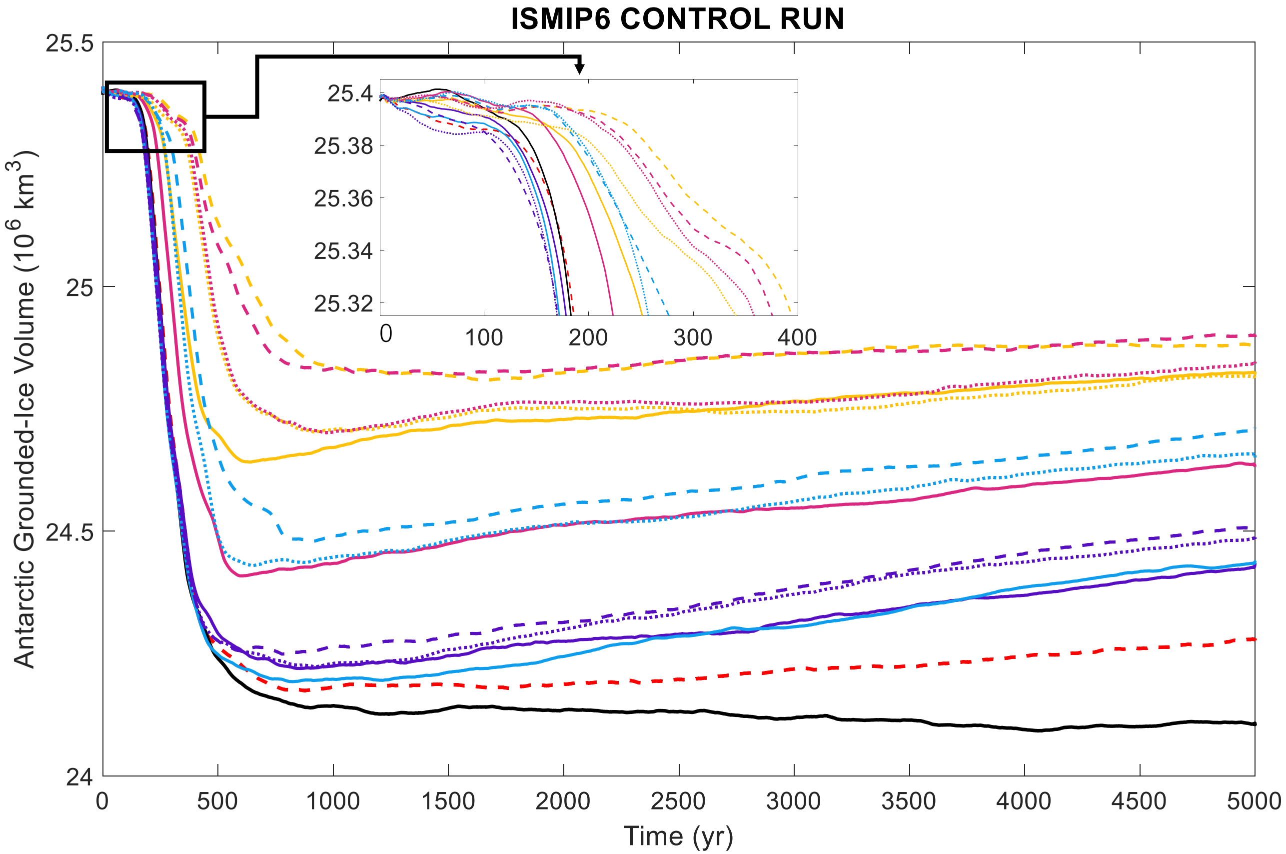
Map of flexural rigidity derived from elastic lithosphere thickness data from Chen et al. (2017)

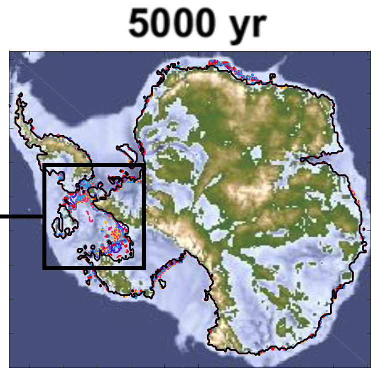
Common uniform value of $D = 10^{25}$ N m

Common uniform value of $\tau = 3000$ yr

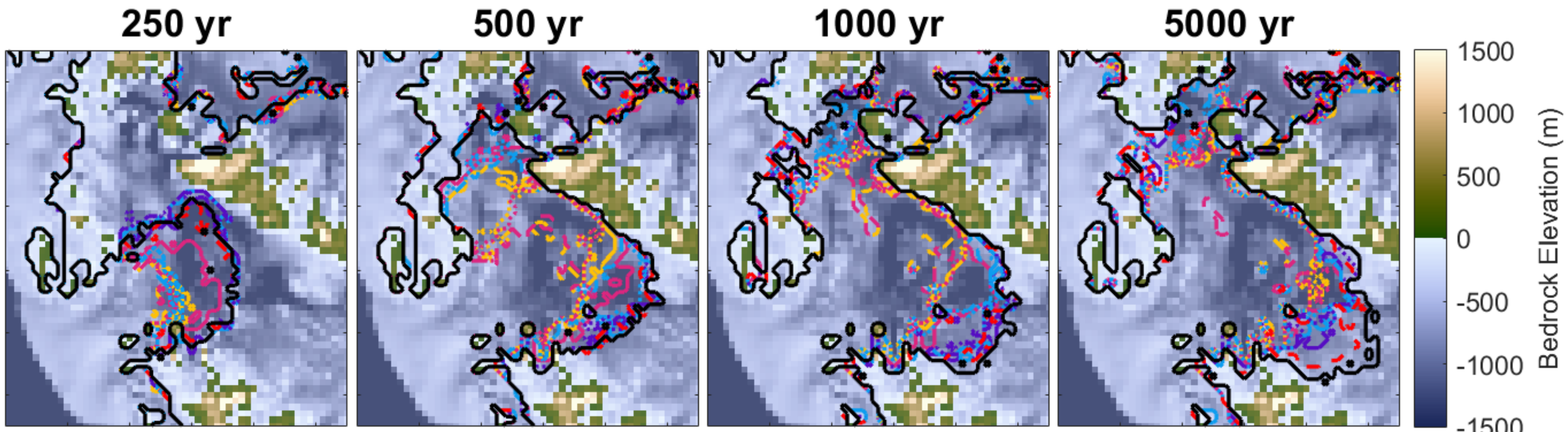
<u>EXPERIMENT I</u>: We apply **constant climate conditions** (no oceanic or atmospheric anomalies added), similar to those observed over the past several decades (ISMIP6, Seroussi et al., 2020).

- **Present-day basal melt rates** trigger **unstable retreat** in the **Amundsen Sea Sector**…
- But the local **weak Earth structure** leads to
  - **delay in the onset of the retreat** of up to a few hundreds of years
  - **less retreated** grounding-line position
  - **reduced ice mass loss** (of up to 1-meter SLE compared to the UNIBED experiment).





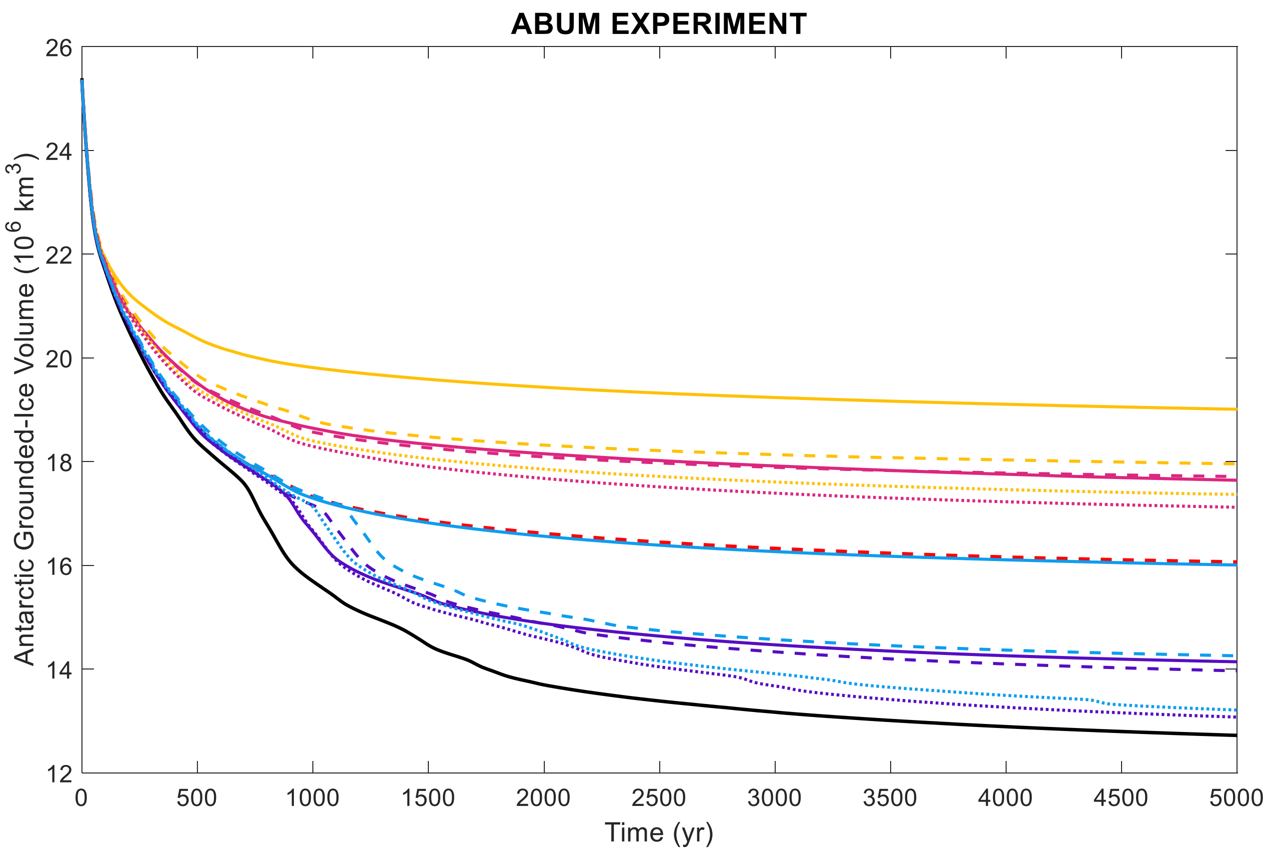
Evolution of Antarctic grounded-ice volume for the different simulations from the ensemble.



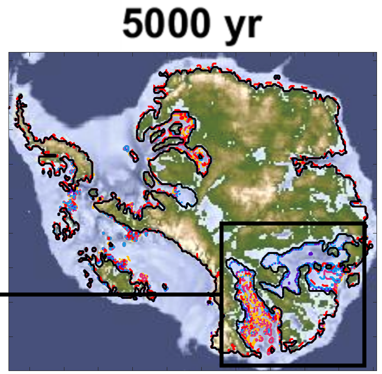
Position of the grounding line in the Amundsen Sea Embayment after 250, 500, 1000 and 5000 yr of simulations for the different simulations from the ensemble, color-coded according to the legend above. The background represents observed present-day bedrock elevations.

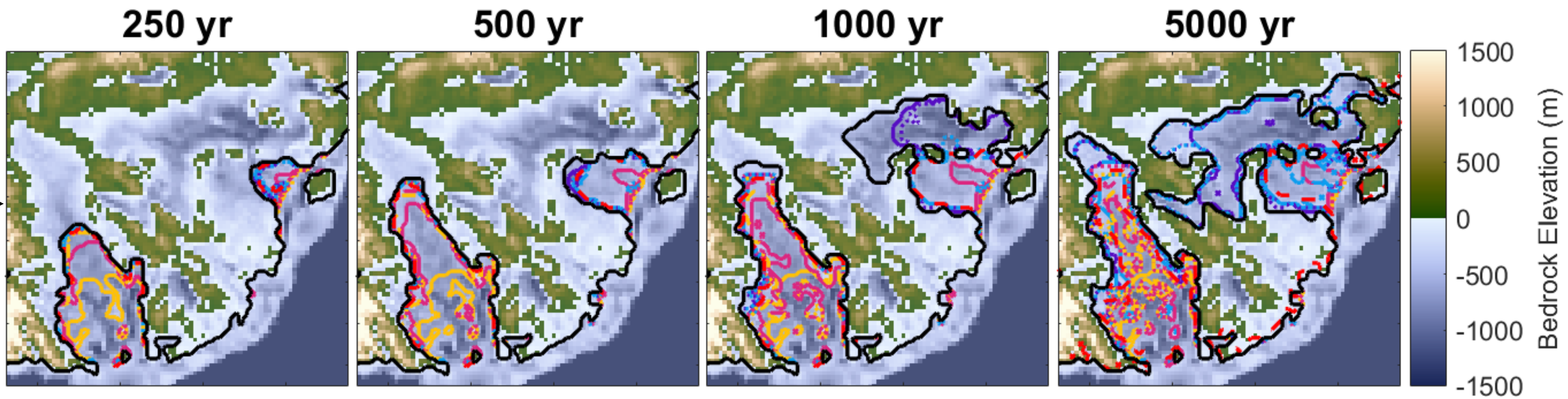
EXPERIMENT II: We apply an **extremely high constant melt** rate of 400 m a^{-1} underneath the ice shelves, leading to rapid loss of ice shelves and hence of buttressing (ABUM, Sun et al., 2020).

- Rapid (<100 yr) **WAIS collapse** occurs, **independently of the solid Earth configuration**.
- **Stronger East Antarctic Earth models,** inferred from relaxation time maps, **lead to significant increased mass loss**, essentially arising from the **Aurora basin** (up to >5 m SLE of increased mass loss compared to the UNIBED experiment).



Evolution of Antarctic grounded-ice volume for the different simulations from the ensemble.





Position of the grounding line in the Wilkes and Aurora marine basins after 250, 500, 1000 and 5000 yr of simulations for the different simulations from the ensemble, color-coded according to the legend above. The background represents observed present-day bedrock elevations.

SUMMARY

- **We designed an Elementary GIA model allowing to approximate near-field relative sea-level changes in a computationally-efficient way.**
  - Even though it does not consider the full complexity of the GIA signal, it is a **somewhat comprehensive model** of regional relative sea-level changes, **easy to implement** in a standalone ice-sheet model.
  - Useful if one seeks to use a **computationally-efficient model that captures the essential processes influencing grounding-line stability**, including the strong variability in Antarctic viscoelastic properties.
  - Allows for the realisation of **large ensembles of simulations and parameter exploration**, not envisageable with SVGEMs or models that include a 3-D Earth rheology.
- **We show that applying a spatially-variable Earth structure has a significant influence on the long-term stability of the Antarctic ice sheet.**
  - The **weak Earth structure** observed beneath the **WAIS** significantly **promotes its stability**, but WAIS collapse cannot be prevented under strong climate scenarios.
  - For **strong climate scenarios**, continent-wide mass loss projections may be underestimated because in **East Antarctica**, GIA feedbacks associated with **stronger Earth models** provide a **reduced stabilising effect compared with** simulations that use a **spatially-uniform Earth deformation model** (as typically considered in numerical ice-sheet models).

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