Contrasting response of West and East Antarctic ice sheets to Glacial Isostatic Adjustment

Violaine Coulon, Kevin Bulthuis, Sainan Sun, Konstanze Haubner and Frank Pattyn

SUMMARY

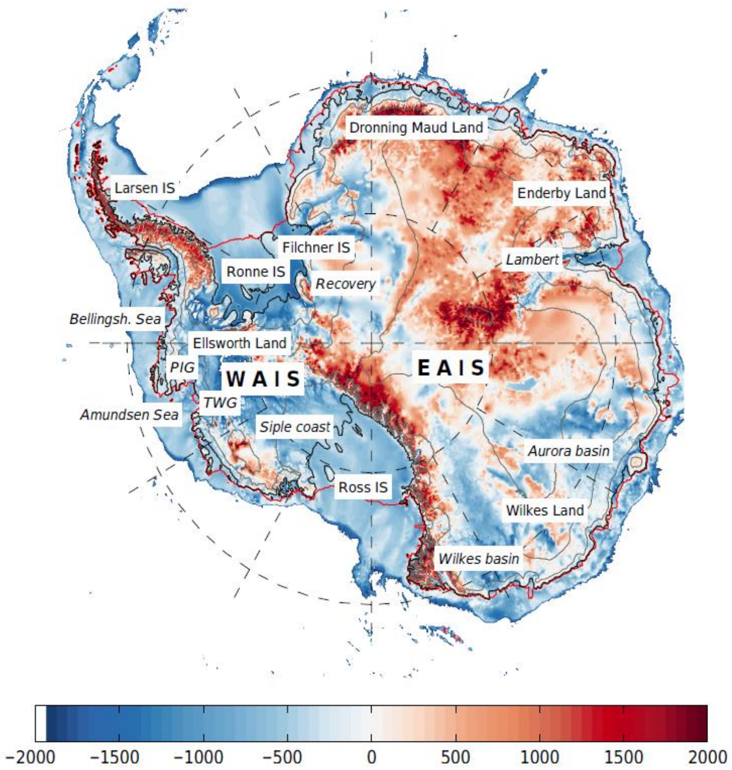
We explore the uncertainty range in Antarctic solid Earth characteristics in a probabilistic assessment. We use 2000 Monte Carlo samples spanning plausible Antarctic solid Earth structures to assess their impact on the response of the Antarctic ice sheet to future warming.

Compared to simulations that do not consider the lateral variability in Antarctic viscoelastic properties, our probabilistic projections show that:

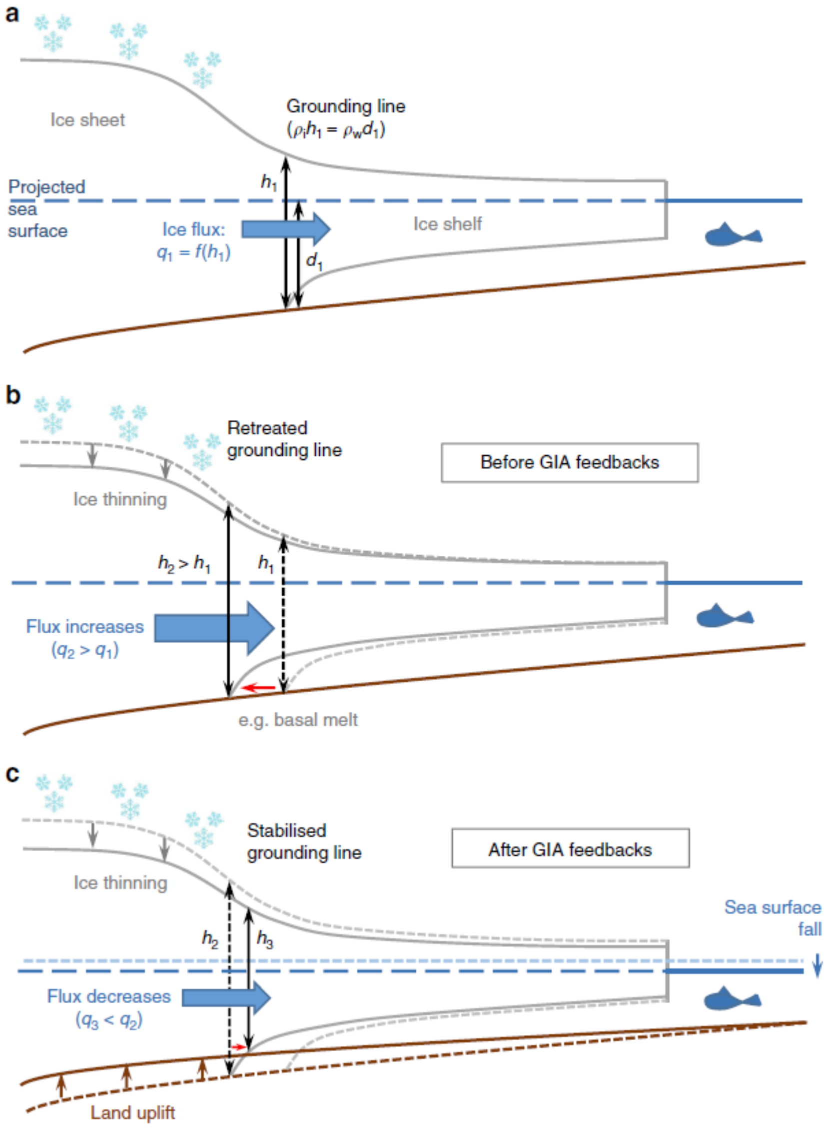
- On multicentennial-to-millennial timescales, Glacial Isostatic Adjustment (GIA) feedbacks significantly promote the stability of the West Antarctic ice sheet (WAIS).
- On millennial timescales, GIA feedbacks may facilitate mass loss in major marine basins of the East Antarctic ice sheet (EAIS).

Marine basins of Antarctica are sensitive to **Marine Ice Sheet Instability** (MISI)…

Glacial Isostatic Adjustment has the potential to **stabilise** a marine ice sheet **undergoing MISI**.



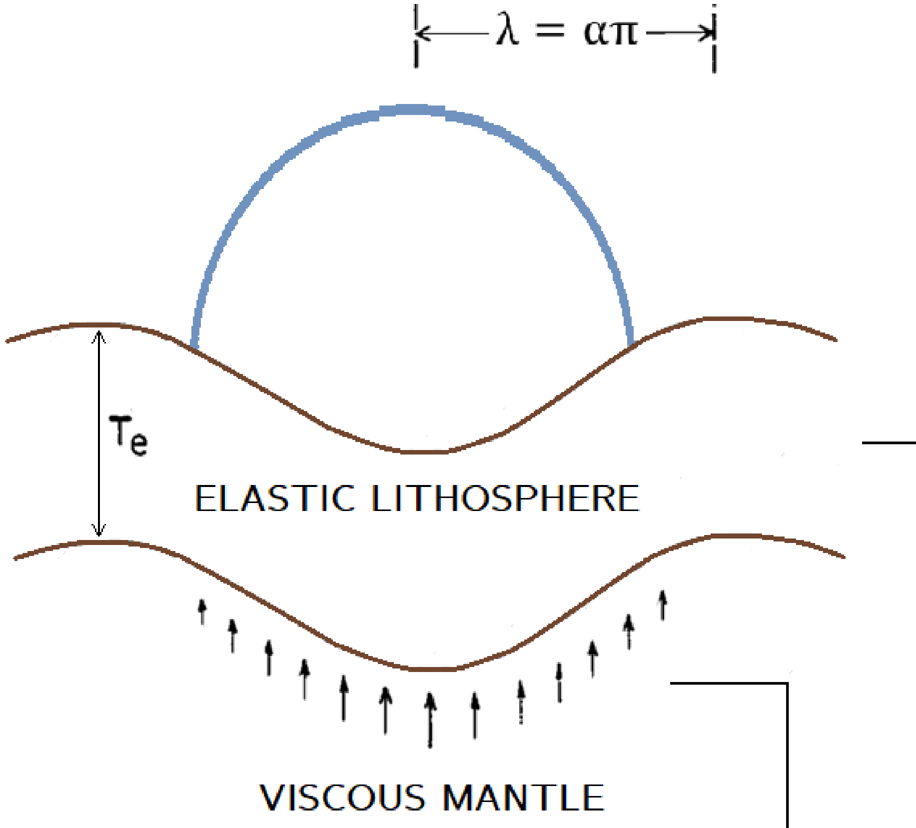
Bedrock topography (Fretwell et al., 2013) of the Antarctic ice sheet, Grounding lines are shown in black; ice shelf edges are shown as a red line.
[From Pattyn, The Cryosphere, 2017]



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

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

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



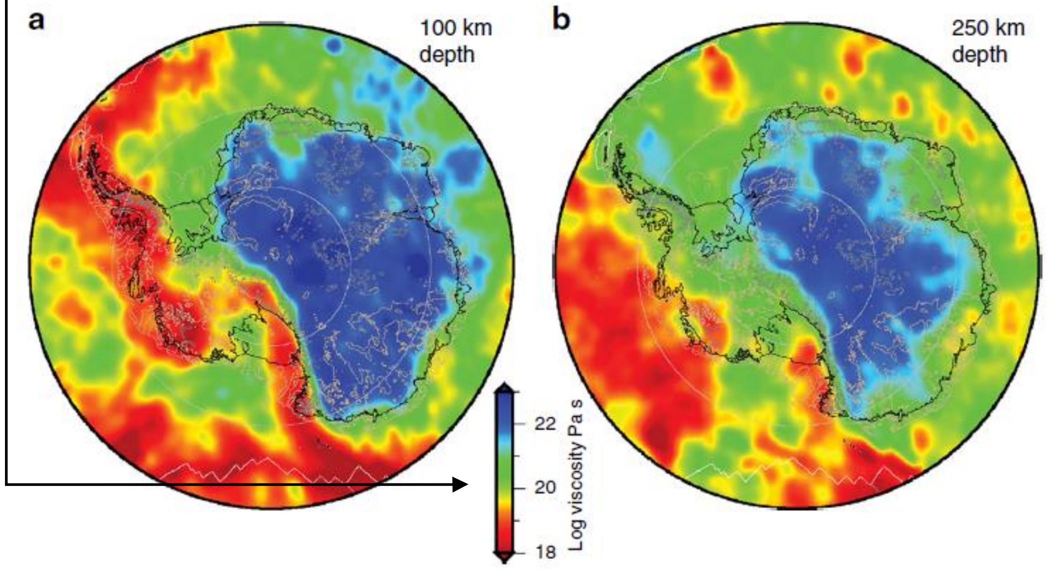
The pattern of the deformation depends on the thickness of the lithosphere: the thinner the lithosphere, the more local the deformation (λ↘).

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

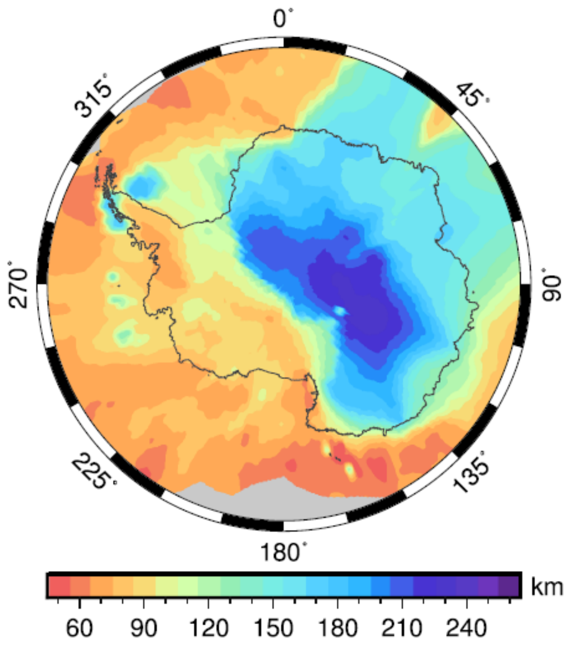
The Antarctic solid Earth displays **strong lateral variations in viscoelastic Earth structure**...

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

Uniform upper mantle value typically considered in the literature:
2×10^{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...

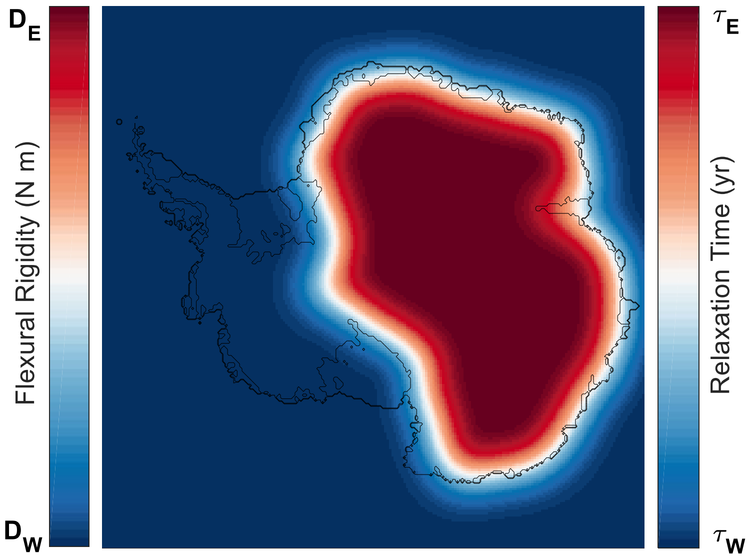
We would like to assess the influence of uncertainties in Antarctic viscoelastic properties on the response of the Antarctic ice sheet to future warming.

- Using a simple Elastic Lithosphere Relaxing Asthenosphere (ELRA) model, we run an ensemble of **2000 Monte Carlo experiments** spanning **plausible solid Earth configurations** for both **West** and **East Antarctica**.

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 (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 DW, W, DE and E are sampled from the table below.

Relaxation time τ

ELRA parameter representative of **upper mantle viscosity**

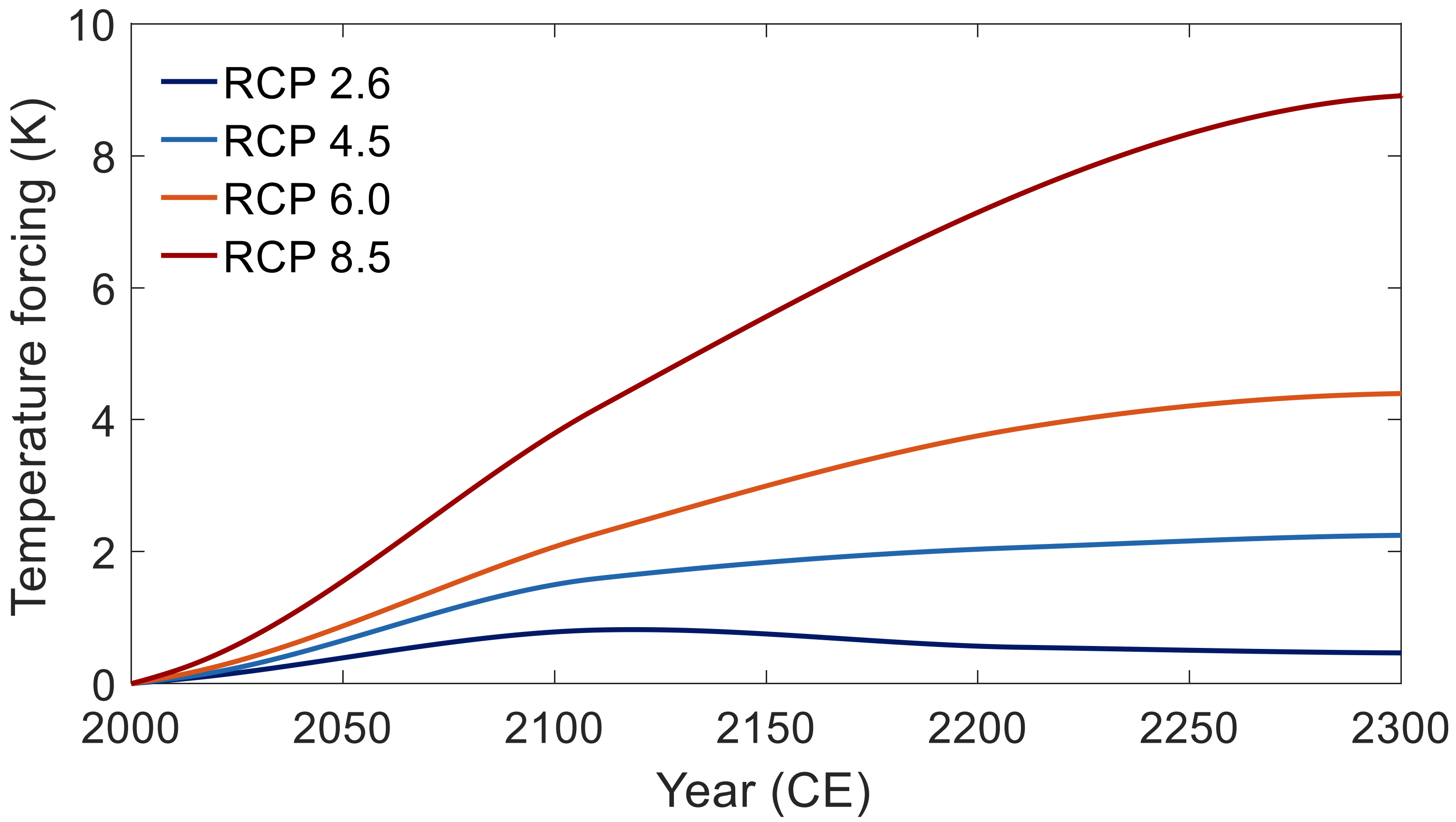
Uniform τ value typically considered in the literature:
3000 years

ELRA parameter	Uncertainty range
τ_{WEST}	[3 – 3 x 10^3] yr
τ_{EAST}	[3 x 10^3 - 3 x 10^4] yr
D_{WEST}	[10^{21} – 5 x 10^{23}] N m
D_{EAST}	[5 x 10^{23} - 10^{25}] N m

Solid-Earth parameters in the ELRA model with associated uncertainty range (determined in order to be representative of observations-based inferences of 3D Earth structure in Antarctica).

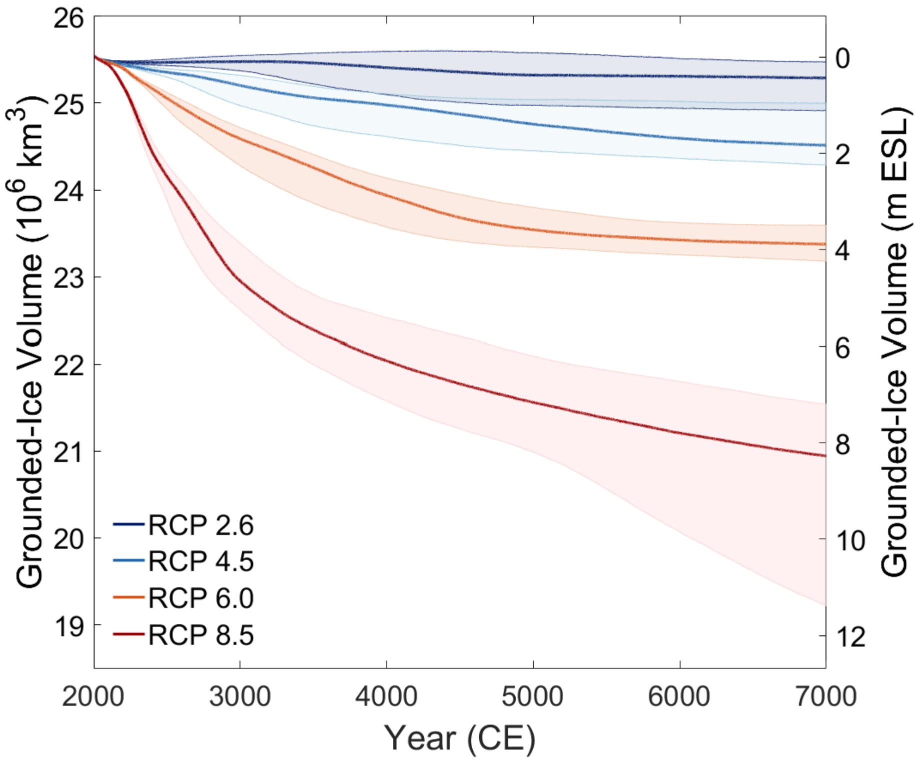
We would like to assess the influence of uncertainties in Antarctic viscoelastic properties on the response of the Antarctic ice sheet to future warming.

- For each of the 2000 Monte Carlo configurations:
  - **f.ETISh model** (Pattyn, 2017)
  - **5000-yr simulations** from present-day configuration at 25km resolution
  - **Extended RCP scenarios** (Golledge et al., 2015)

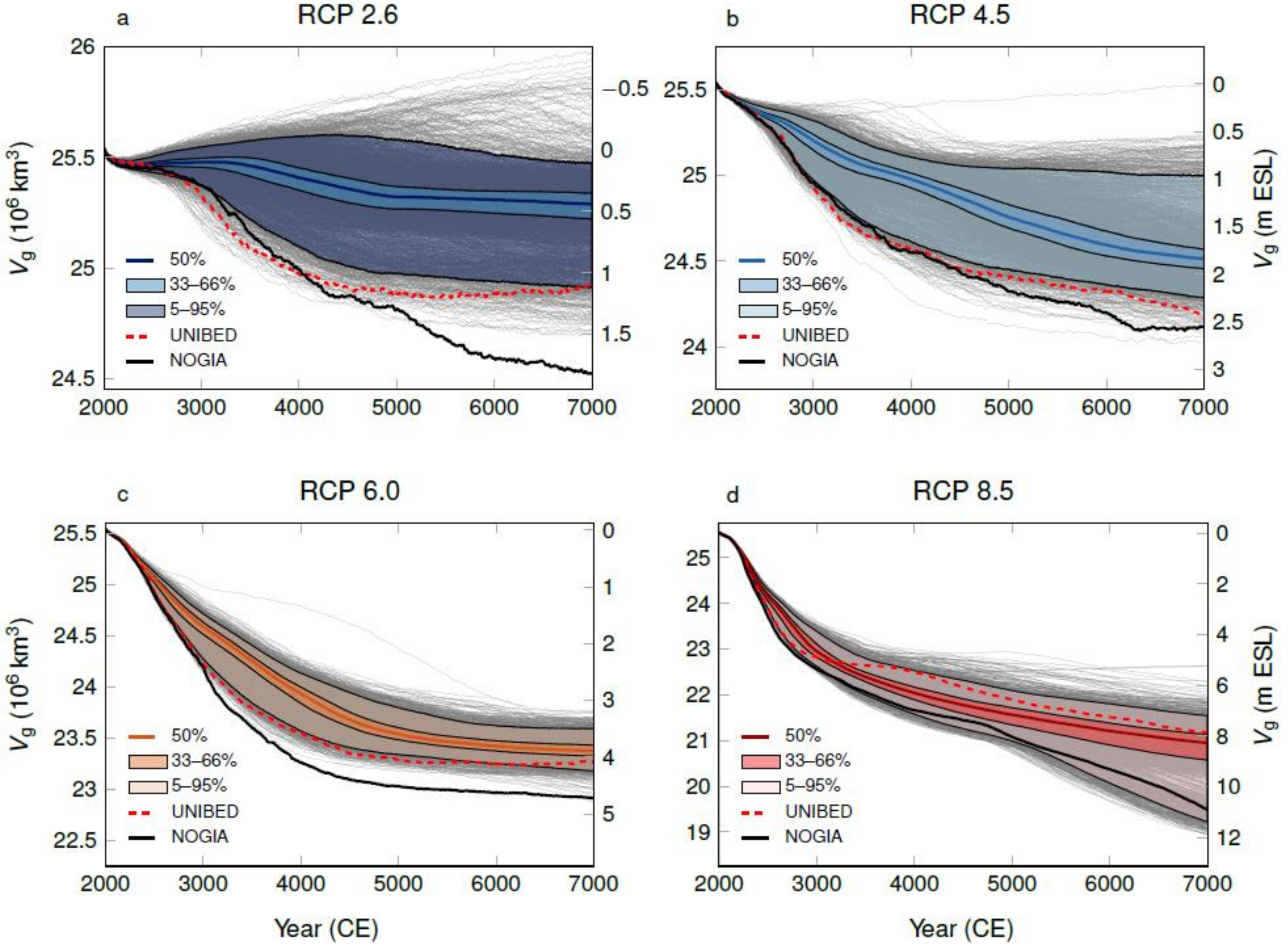


Long-term RCP temperature scenarios (Golledge et al., 2015) for Antarctica based on the CMIP5 data at 2100 CE and extended to 2300 CE. Temperatures are held constant after 2300 CE.

When compared to spatially-uniform ELRA simulations, our probabilistic projections show a stabilising effect, except under RCP 8.5 at longer timescale.



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,



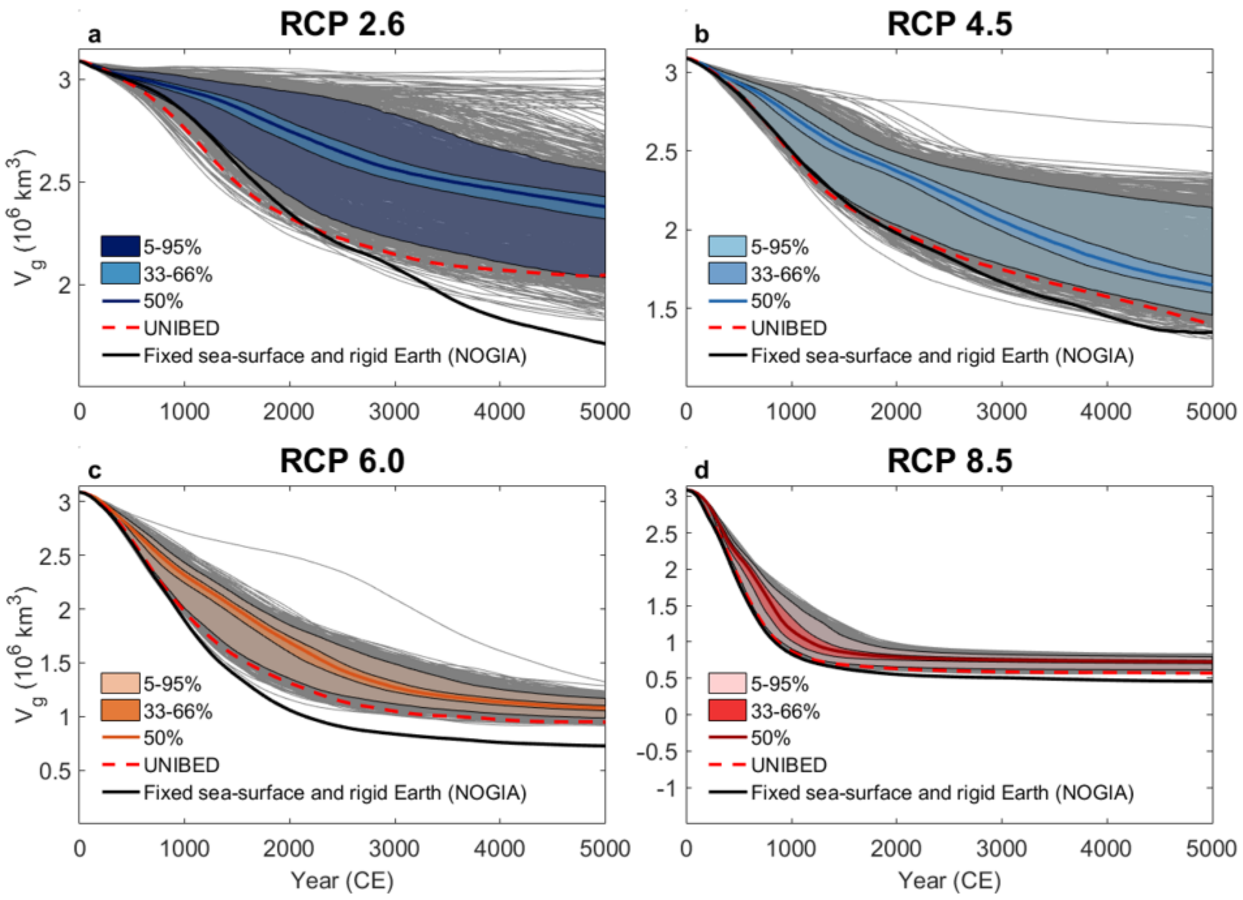
Antarctic grounded-ice volume (Vg) projections considering uncertainty in Antarctic viscoelastic properties under different RCP scenarios. Colored solid lines are the median projections while shaded areas are the 33-66% and 5-95% probability intervals that represent the uncertainty in grounded-ice volume projections due to uncertainty in ELRA parameters. Black lines correspond to control simulations in which both bedrock and sea-level adjustments are not 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.

Projections from the ensemble are **compared to** simulations considering **spatially-uniform** values of **ELRA** parameters commonly used is the literature:
$\mathbf{D = 10^{25}\ N\ m}$ **&** $\boldsymbol{\tau} \mathbf{= 3000\ yrs}$ (Le Meur & Huybrechts, 1996)

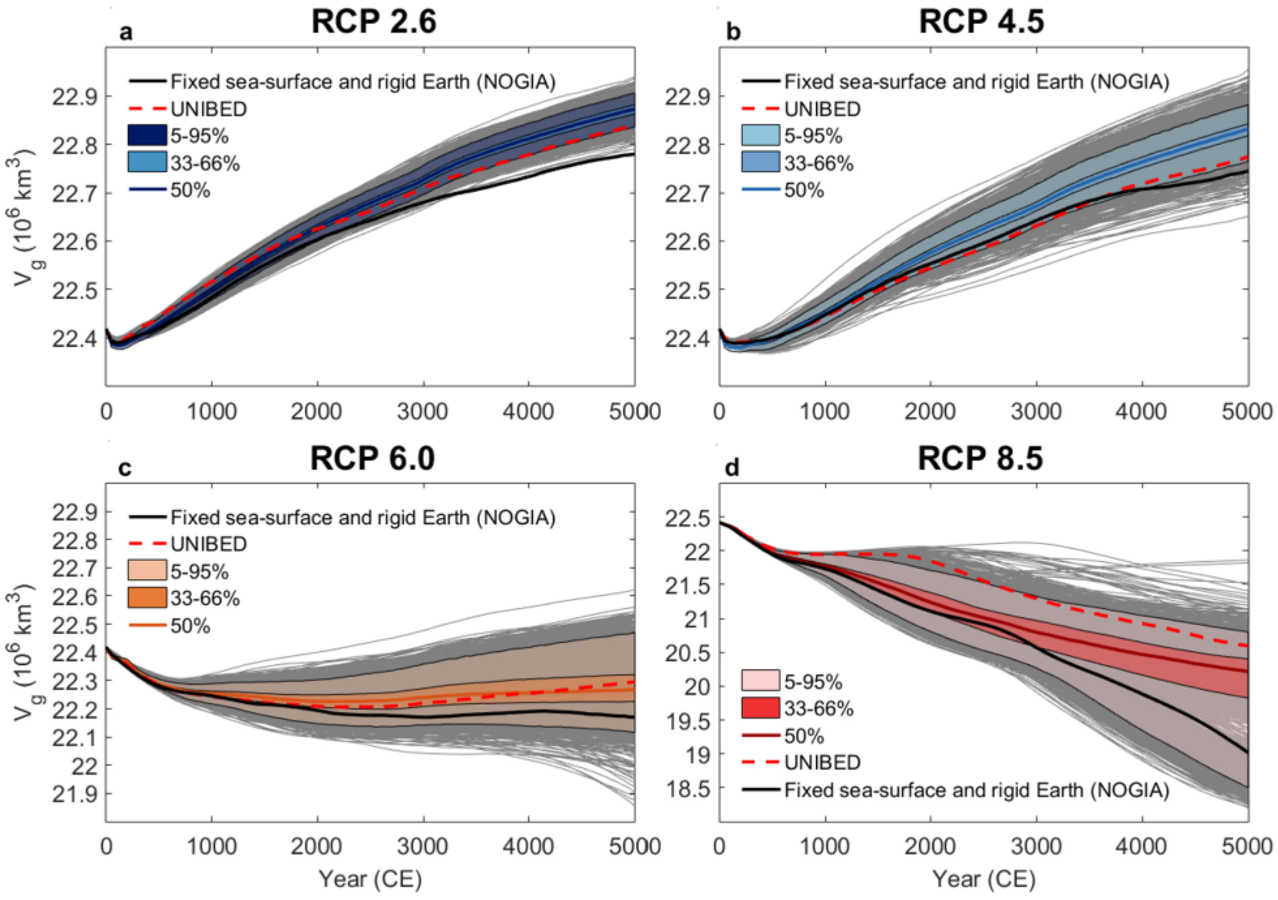
Spatial variations in viscoelastic properties VS spatially-uniform ELRA model:

- WAIS: GIA feedbacks promote stability.
- EAIS: potential re-enforcement of climate forcing.

What if we look at West and East Antarctic ice sheets separately?



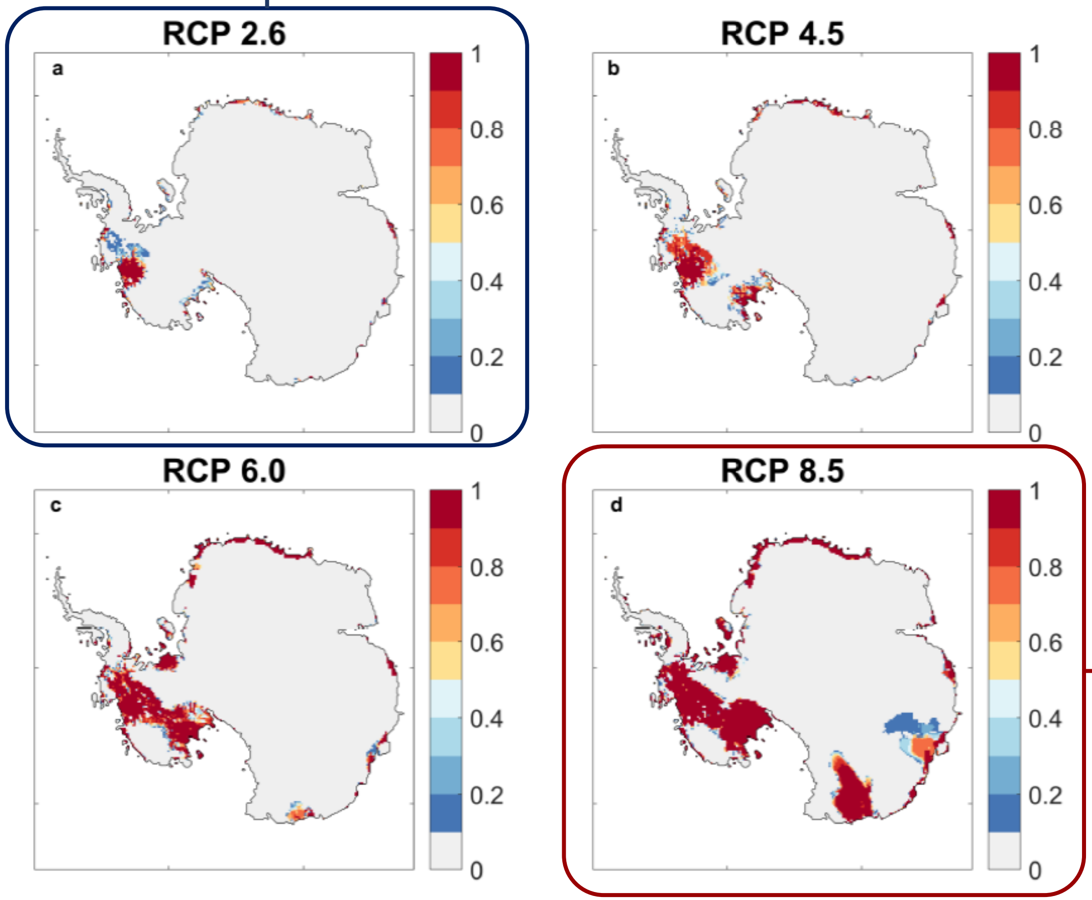
West Antarctic grounded-ice volume (Vg) projections considering uncertainty in Antarctic viscoelastic properties under different RCP scenarios.



East Antarctic grounded-ice volume (Vg) projections considering uncertainty in Antarctic viscoelastic properties under different RCP scenarios.

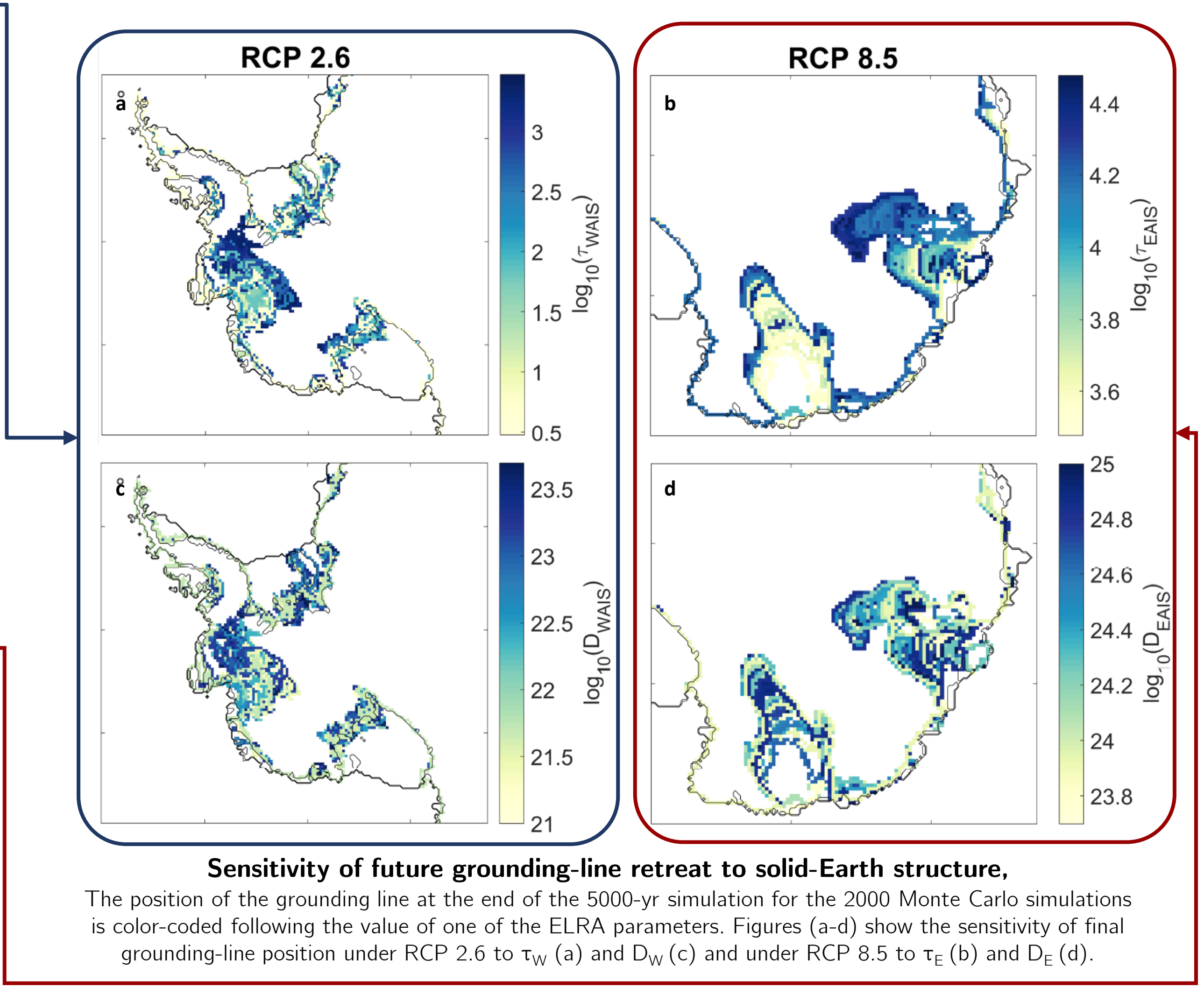
- Weak solid Earth structures (low D and τ) are able to delay or even prevent WAIS collapse under weak forcing.
- Retreat in Wilkes and Aurora basins under RCP 8.5 at longer timescales.
- Retreat in Aurora basin is strongly GIA-dependent.

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).

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).

CONCLUSIONS

- On multicentennial-to-millenial timescales, UNIBED projections systematically overestimate the sea-level contribution from the Antarctic ice sheet
  - solid-Earth deformation plays significant role in promoting WAIS stability.
  - However, GIA feedbacks cannot prevent WAIS collapse under high-emissions climate scenarios.
- At longer timescales and under unabated climate forcing, future mass loss may be underestimated because in East Antarctica, GIA feedbacks have the potential to re-enforce the influence of climate forcing as compared with a spatially-uniform GIA model.
  - Mainly in Wilkes and Aurora marine basins.

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