Calibration of an ice-ocean model of West Antarctica

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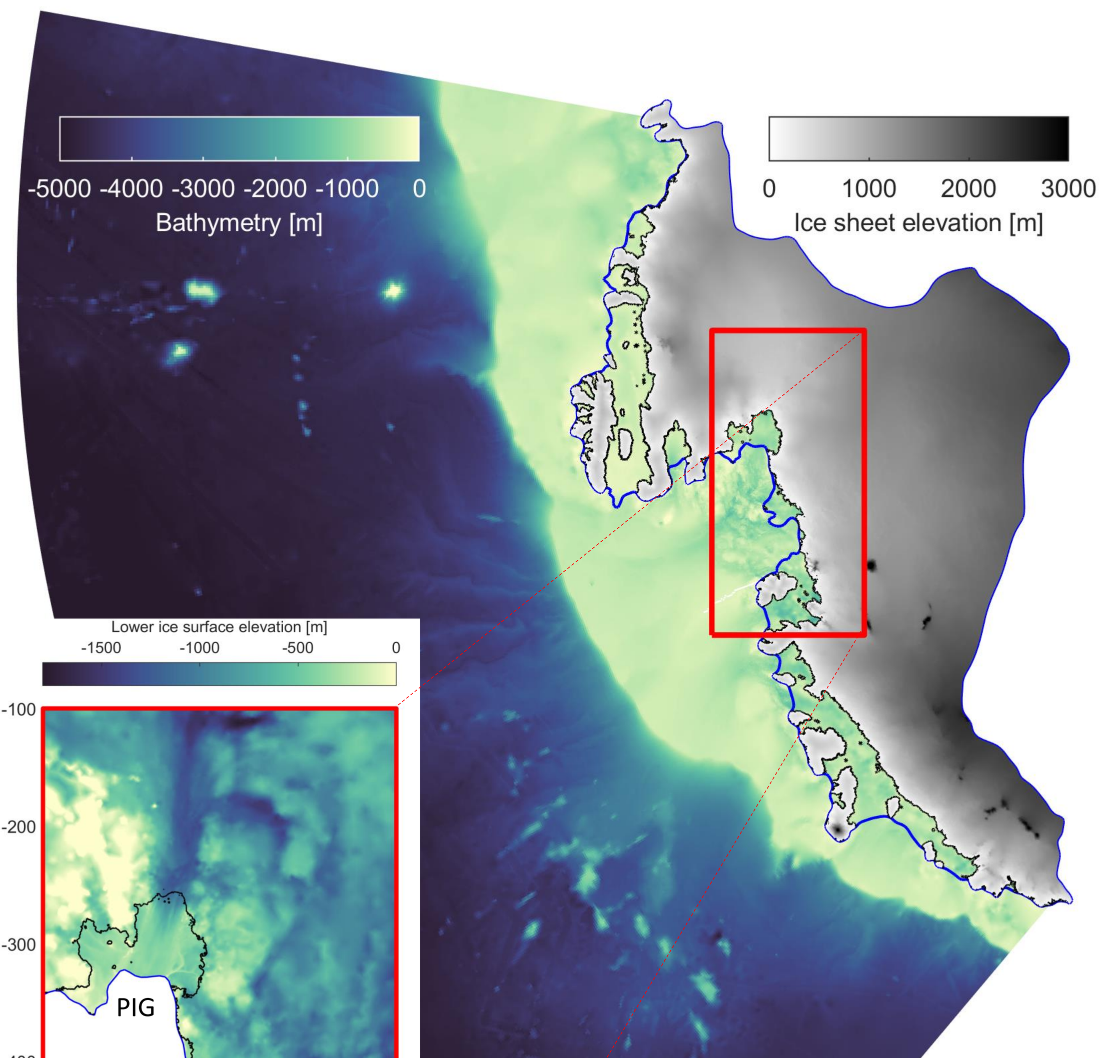


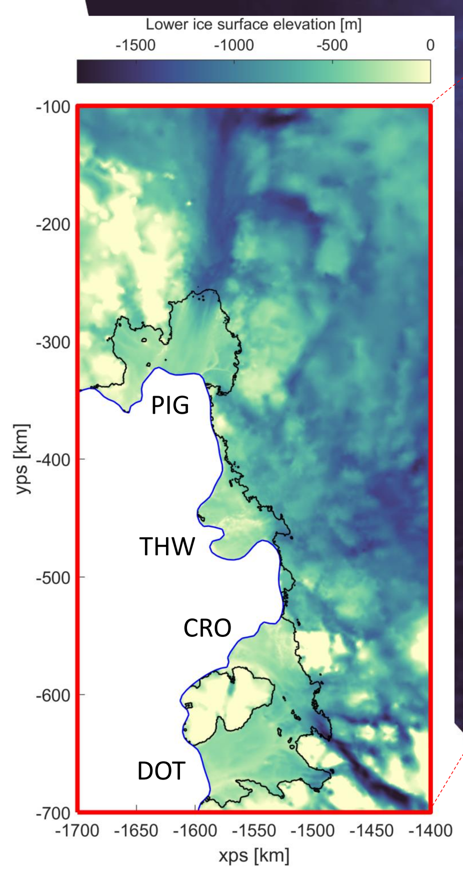


Figure: Lower ice surface elevation of Pine Island, Thwaites, Crosson and Dotson ice shelves and grounded basins. The grounding line is shown in black and the fixed ice front in thick blue.

Figure: Coupled model domain showing the BedMachine ocean bathymetry and ice sheet elevation that is input to both models. The grounding line is shown in black and the fixed ice front in thick blue. The red box shows the location of the three major basins.

Background

The **West Antarctic Ice Sheet** has been losing mass in recent decades[1], with widespread acceleration[2], thinning[3] and retreat[4].

This has led to concerns about the **stability**[5] of the region, which if destabilized, could raise global mean sea level by several meters[6].

Mass loss is predominantly driven by **basal melting**[7] along the Amundsen Sea coast, where vulnerable ice shelves are exposed to warm ocean waters.

Internal **ice dynamics** also plays a significant role in how the ice sheet responds to ocean-induced melting[8].

To understand the ice sheet evolution, we must consider changes in both the ice and ocean systems and how they affect each other.

Coupled Ice-Ocean Model Setup

Ice: Úa[9] - finite element, SSA, Weertman sliding (m=3), Glen's flow law (n=3), adaptive mesh refinement (50m at GL/high strain, 10km slow moving areas). Input: BedMachine, RACMO, MEaSUREs. Two-stage inversion using observations of ice velocities[10] and thickness changes[11].

Ocean: MITgcm - regional configuration (Abbot to Getz), continental shelf, break and deep ocean. Sea ice and ice shelf thermodynamics. Resolution: Hor = 1/10° (~3 to 5 km), Vert = 50 levels (10m shallow, 300m deep).

Coupling: Úa and MITgcm exchange ice geometry and melt rates, respectively, offline at 1 month intervals. Each model run on their own grid and interpolation between nodes.

Forcing: ERA5 atmospheric reanalysis (climatology: 2000-2010).
ICs/BCs: WOA18 (temperature, salinity) and B-SOSE (other variables).

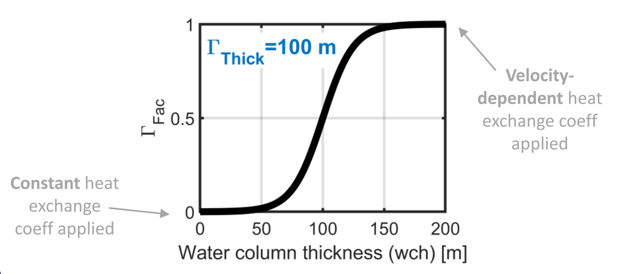
MITgcm basal melt parameterization

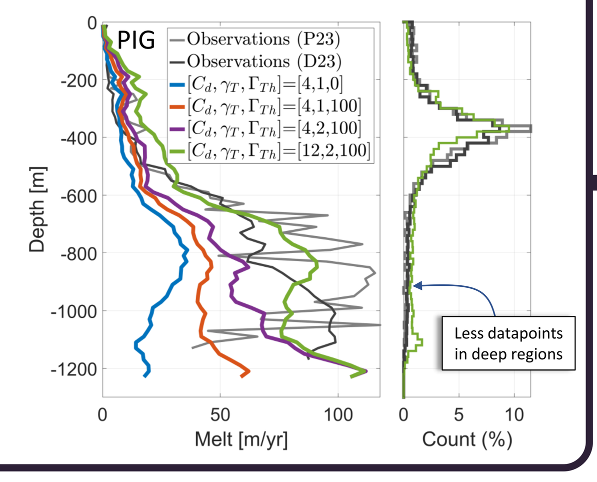
- In MITgcm, melt rates beneath the ice shelf are calculated using the three-equation model[12]. This parameterization accounts for ice-ocean interaction by evaluating the heat and salt fluxes into and out of the boundary layer.
- The turbulent exchange between the boundary layer and ocean is velocity dependent, with heat and salt exchange coefficients:

$$\underbrace{\gamma_{T,S}}_{\text{Heat/salt exchange coeff.}} = \frac{u_*}{\underbrace{\Gamma_{Turb}}_{\text{Turbulent exchange}} + \underbrace{\Gamma^{T,S}_{Mol}}_{\text{Molecular diffusion}}} \quad \text{where} \quad \underbrace{u_*^2}_{\text{Friction velocity}} = \underbrace{C_d}_{\text{Drag coeff.}} \underbrace{U_M^2}_{\text{Mixed layer velocity}}$$

- But, modelled velocities (and therefore melt rates) are **not well represented** in regions of thin water column and coarse vertical resolution **near the grounding line**
- To overcome this, we taper from a **velocity-**dependency to a **constant** exchange coefficient, based on water column thickness:

$$\gamma_{T*} = \underbrace{\Gamma_{Fac}}_{\text{Taper function}}\gamma_T + (1-\Gamma_{Fac})\underbrace{\gamma_{T0}}_{\text{Constant heat exchange coeff.}}$$





Hindcast experiment setup

Ocean **spinup** (20 years) → Ocean model (5 years) → Coupled ice-ocean model (5 years)

Model runs	# Runs	Model	Time (yrs)	Forcing	MITgcm melt parameters
Ocean Spinup	1	MITgcm (fixed ice)	20	ERA5 climatology (2000-2010)	$C_d = 8\times10^{-3}$ γ_{T0} = N/A Γ_{Thick} = 0 m
Ocean sensitivity	80	MITgcm (fixed ice)	5	ERA5 climatology (2000-2010)	Varied (see below)
Coupled sensitivity	80	UaMITgcm (evolving ice)	5	ERA5 climatology (2000-2010)	Varied (see below)

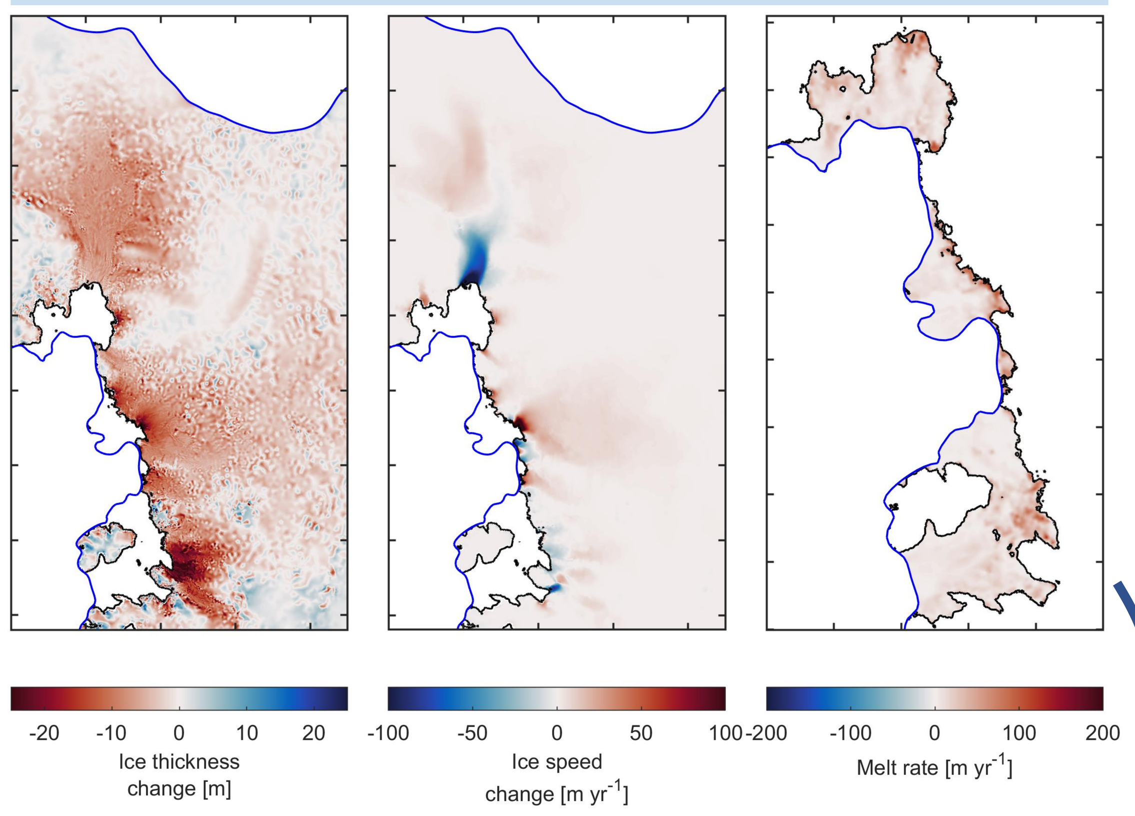
Coupled model run with different melt parameter values →

MITgcm melt parameters:

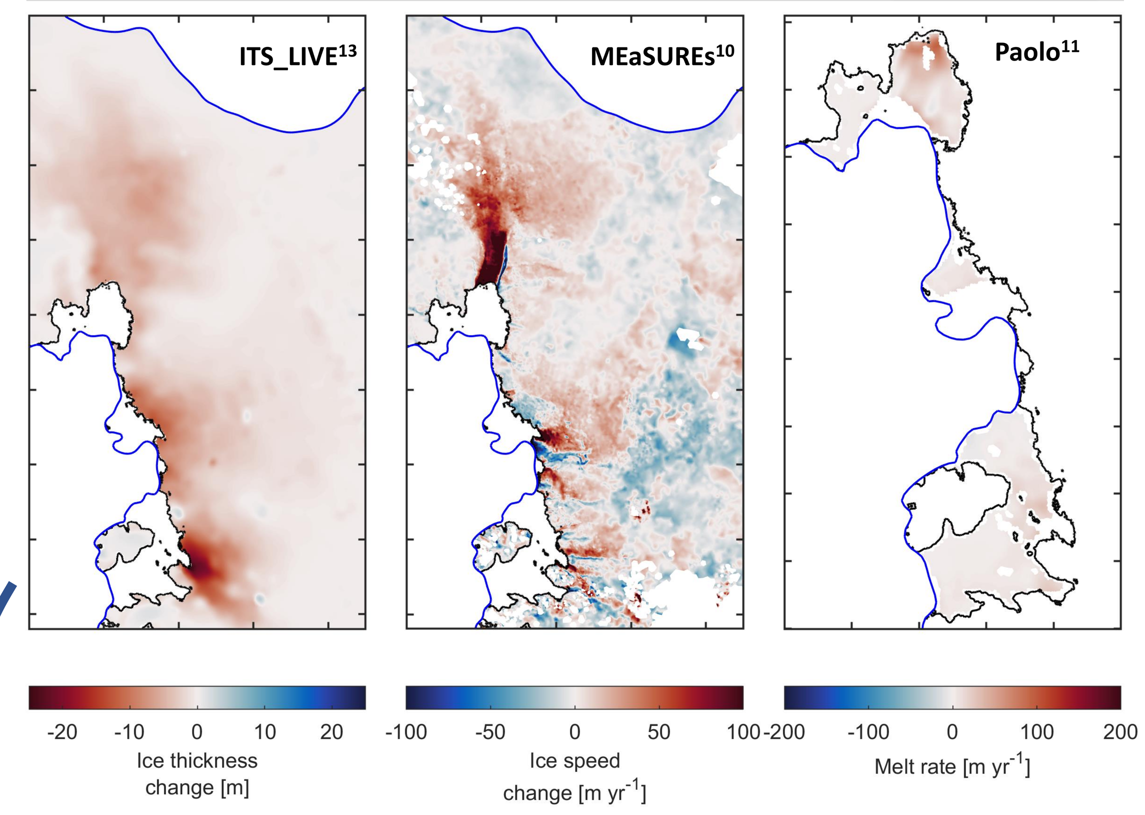
- $C_d \in \{1, 4, 8, 12\} \times 10^{-3}$
- $\gamma_{T0} \in \{1, 2, 4, 8\} \times 10^{-4}\ \mathrm{m\ s^{-1}}$
- $\Gamma_{Thick} \in \{0, 50, 100, 150, 200\}$ m

How to score coupled runs with different parameter values?

Coupled model result (1 of 80 runs)



Observations (3 independent observation datasets)



All 80 **coupled** runs are assigned a likelihood score

$$\mathcal{L}_{i,j}(\mathcal{P},\mathcal{O}) = \prod_{i=1}^{3} \frac{1}{N} \exp\left[-\frac{1}{2\mathcal{A}} \int \left(\frac{\left(\mathrm{mod}_{i,j} - \mathrm{obs}_i\right)^2}{\mathrm{modErr}^2_{i,j} - \mathrm{obsErr}^2_i}\right) d\mathcal{A}\right]$$

Number of observations: 3; Model parameters: $C_d, \gamma_{T0}, \Gamma_{Thick}$; Observation data: dhdt, dvdt, melt; Normalizing factor: N; Total model area: $\mathcal{A} = \int d\mathcal{A}$; Model errors: dhdt, dvdt, melt; Observation errors: dhdt, dvdt, melt

Using both **ice** dynamics and **ocean** forcing observations in the calibration

To **calibrate** the coupled ice-ocean model we use the above normalized **likelihood score** which measures model-observation misfit for each of the model simulations

Which MITgcm melt rate parameters give the best ice sheet response?

This melt parameterization (Γ_{Thick} = 0m) is typically used ...

... but this gives low melt near the grounding line and a poor ice sheet response compared with observations

Top 10 runs and **bottom 10 runs** when using **melt**, ice **thickness** and ice **speed** changes in calibration

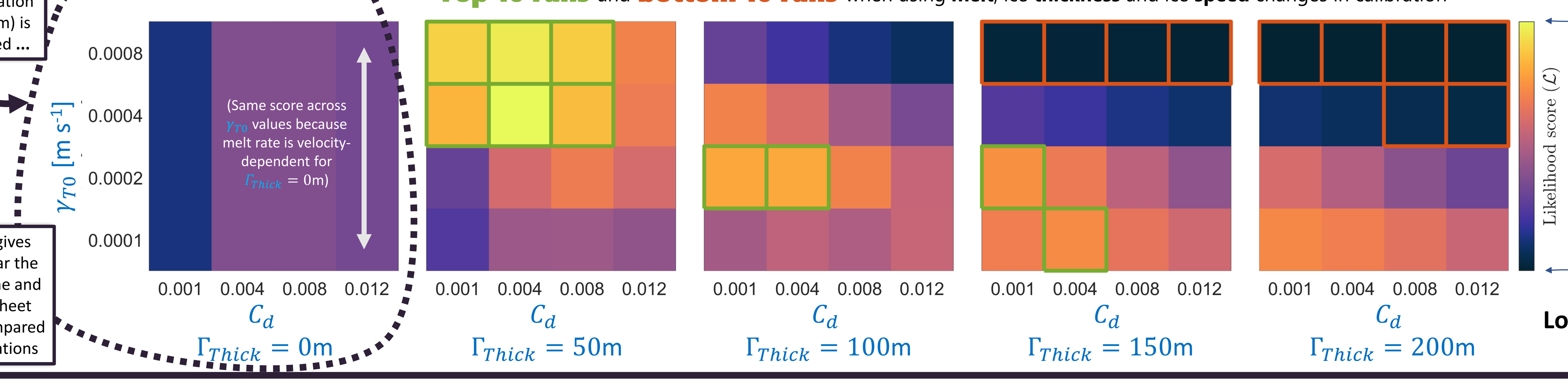


Figure: Likelihood scores for all 80 coupled simulations (4 C_d values, 4 γ_{T0} values, 5 Γ_{Thick} values). The higher (best) scores in lighter colours represent runs which have a smaller misfit with observations.

DISCUSSION

- ❑ We introduce the first step in the **calibration** of a new **coupled ice-ocean** model of West Antarctica.
- ❑ Results shown here are from testing of the ocean model **melt rate parameters**. We assess the ice sheet response to **three** parameters that control how much melting is near the grounding line.
- ❑ Typically, ocean model melt parameters are tuned only to indirect (satellite) or some direct observations of melt rate but here we also use **changes in ice sheet thickness and speed** in a coupled model to constrain the model parameters.
- ❑ This coupled ice-ocean model will be used to estimate future sea level contribution from this rapidly changing region of Antarctica.

We find the **best ice sheet response (smallest model-data misfit)** when:

- ✓ Calibrating the coupled ice-ocean model with **ice dynamic** data in addition to melt rates.
- ✓ Using parameters that increase melt near the **grounding line**.
- ✓ Drag coefficient (C_d): 1 to 8x10^{-3} and a water column thickness parameter (Γ_{Thick}): 50m to 150m.

Challenges:

- ❖ Lack of direct melt observations; satellite derived estimates not reliable near the grounding lines.

Next steps:

- Include more observations (e.g., integrated melt) into the calibration.
- Calibration of **ice sheet model** parameters (**see Jan De Rydt poster:** EGU25-1718 Session CR2.1 Thu, 01 May, 14:00–15:45)

Sensitivity of coupled model to MITgcm melt rate parameters

Top 10 runs and **bottom 10 runs** when using **melt**, ice **thickness** and ice **speed** changes in calibration

Melt rate

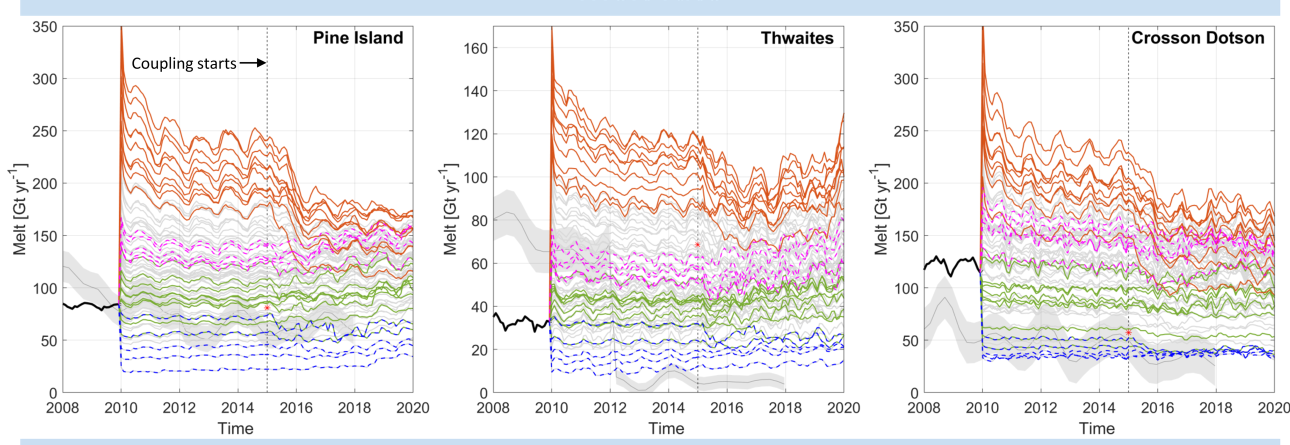


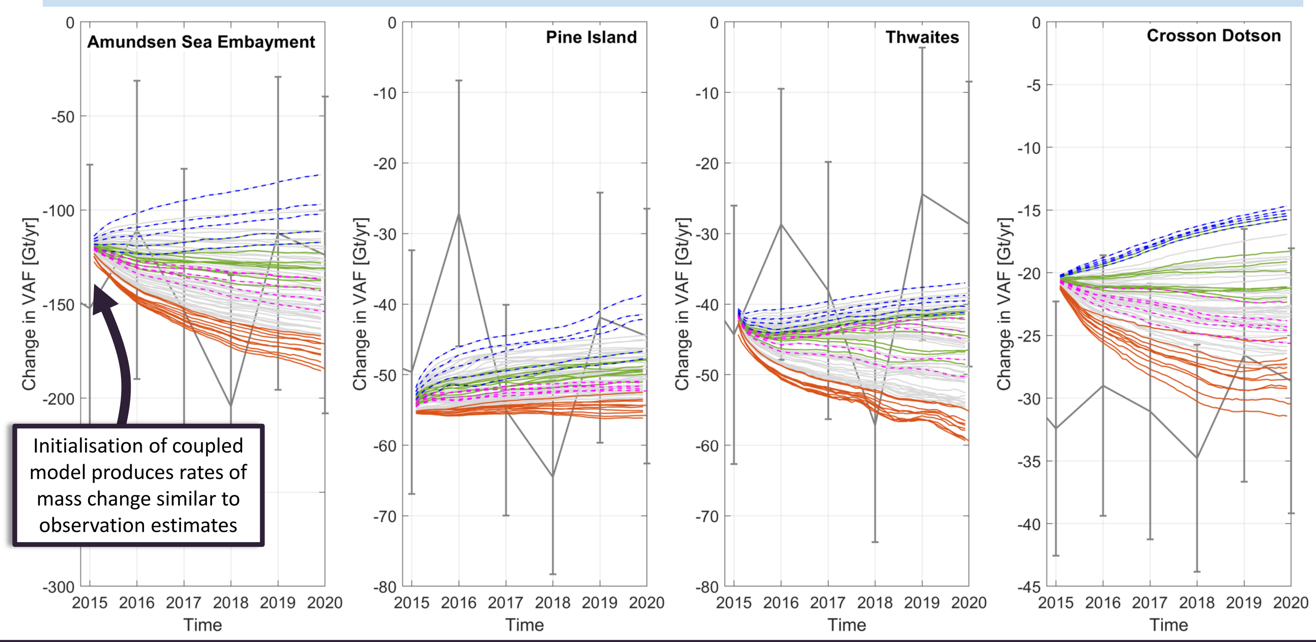
Figure: Integrated melt rates for the three main ice shelves. Ocean-only spinup is shown in thick black, with just the last two years visible. All 80 ocean-only and coupled runs are shown as light grey lines, with coupling starting in 2015. Satellite-derived melt rates[11] are shown in dark grey, with their associated errors in the surrounding shaded area. The ice model balance melt rate is shown as a red star in 2015.

Top 5 runs if calibration only uses **ice speed** changes

Top 5 runs if calibration only uses **melt** rates

These runs have **advancing** grounding lines, **slowing** and **thickening** glaciers – not consistent with observations

Rate of ice mass change



Initialisation of coupled model produces rates of mass change similar to observation estimates

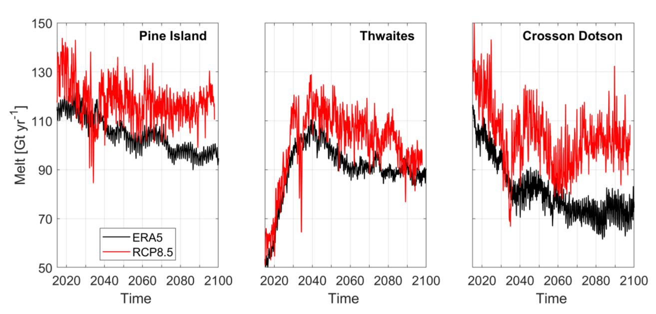
Top 5 runs if calibration only uses **ice speed** changes

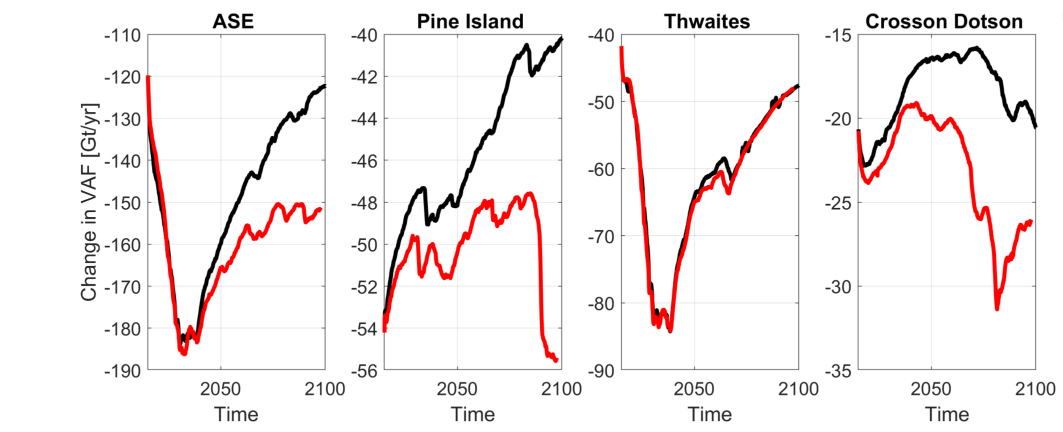
Figure: Rate of change in volume above floatation (VAF) (i.e., ice mass) for the whole domain (Amundsen Sea Embayment) and the three main basins. Satellite-derived mass changes[14] are shown in dark grey, with their associated error bars.

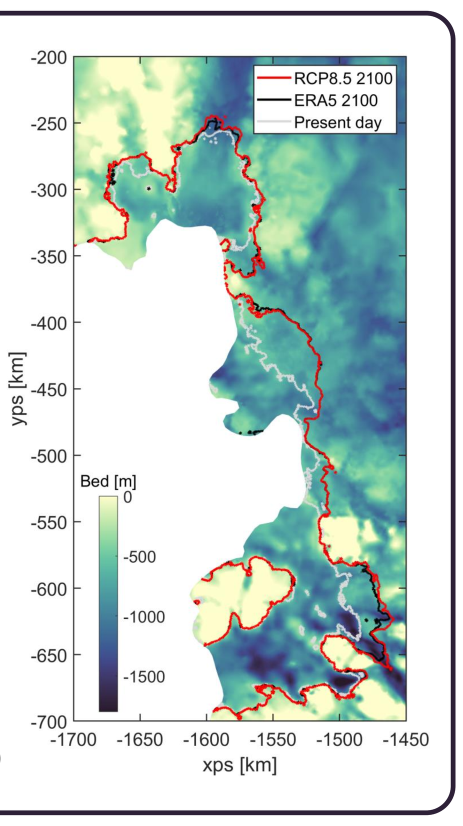
Projections

Coupled ice-ocean simulations run to 2100, for **present-day (ERA5)** forcing and **RCP8.5** forcing using MITgcm melt rate parameters:

C_d = 0.004
γ_{T0} = 0.0002 ms^{-1}
Γ_{Thick} = 150 m







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