Antarctic ice sheet ensemble studies to better quantify uncertainties in sea level rise

Mira Berdahl, Nathan Urban, Bill Lipscomb, Gunter Leguy
Sub-shelf melting

- Ice melt in Antarctica happens primarily from below
- There is a lot of uncertainty in the ocean melt rates
  - Multi-model uncertainty in CDW
  - Ocean eddy heat transport unresolved
  - Ice-fracture mechanics
Sub-shelf melting

- Ice melt in Antarctica happens primarily from below
- There is a lot of uncertainty in the ocean melt rates
  - Multi-model uncertainty in CDW
  - Ocean eddy heat transport unresolved
  - Ice-fracture mechanics

- Reduced statistical models (Kopp, Keller, LeBars)
- Less mechanistic empirical or expert elicitations (Kopp, Little, Bamber)
- SLR UQ modeling (Bulthuis, Edwards, Schlegel) – study the origin propagation and interplay of sources of uncertainty
**Global mean temperature increase**

- **Enhanced basal ice-shelf melting**
- **Dynamic ice sheet response**
- **Sea level rise**

**Southern Ocean warming**

- **Idealized ocean melt rates**

**Uncertainties throughout**

**Project overview: The big picture**

- Run large ensemble of ice sheet simulations driven to the year 2200 by idealized basin-specific ocean basal melt rate trajectories
- Build ice sheet emulator that provides ice retreat as a function of heat applied at the coastal shelves
- Propagate uncertainties from ocean warming through the ice system to produce an envelope of SLR uncertainties
Emulating instead of simulating

**Problem:** Models are time consuming, can’t fully explore parameter space.

**Solution:** Emulate what the model “would have simulated” at parameter settings we don’t have time to check.

**Advantages:**

- Permits efficient resampling of the modeled ice sheet response under different probability distributions for future Antarctic basal melt rates
  - New oceanographic information, competing expert assumptions, intentionally sampled-scenarios
- More “effective” Monte Carlo samples than is possible from a few CMIP models -> a more accurate characterization of any desired distribution
Emulating instead of simulating

**Problem:** Models are time consuming, can’t fully explore parameter space.

**Solution:** Emulate what the model “would have simulated” at parameter settings we don’t have time to check.

**Advantages:**

- Permits efficient resampling of the modeled ice sheet response under different probability distributions for future melt rates
  - new oceanographic information, competing expert assumptions, intentionally sampled-scenarios
- More “effective” Monte Carlo samples than is possible from a few CMIP models -> a more accurate characterization of any desired distribution
Emulating instead of simulating

**Problem:** Models are time consuming, can’t fully explore parameter space.

**Solution:** Emulate what the model “would have simulated” at parameter settings we don’t have time to check.

**Advantages:**

- Permits efficient resampling of the modeled ice sheet response under different probability distributions for future melt rates
  - new oceanographic information, competing expert assumptions, intentionally sampled-scenarios
- More “effective” Monte Carlo samples than is possible from a few CMIP models -> a more accurate characterization of any desired distribution
CISM spin-up with inversion

**Goal:** Obtain an ice sheet in steady state with modern forcing (SMB from RACMO model), with ice extent and thickness close to observed values.

**Method:** Spin up the model for 40 kyr, nudging toward the observed thickness by adjusting basal friction parameters beneath grounded ice and basal melt rates beneath floating ice. (4 km resolution)
Goal: Obtain an ice sheet in steady state with modern forcing (SMB from RACMO model), with ice extent and thickness close to observed values.

Method: Spin up the model for 40 kyr, nudging toward the observed thickness by adjusting basal friction parameters beneath grounded ice and basal melt rates beneath floating ice. (4 km resolution)

Result: Excellent agreement with observed surface velocity, ice thickness, and ice shelf extent, with little drift.
Design an ocean-only CISM ensemble

Inform these with ocean model projections
There's not much ocean melt rate 'data' out there
Fitting melt rates with a sigmoidal function
Fitting melt rates with a sigmoidal function

\[ M(t) = \frac{M_{\text{max}}}{(1 + e^{xx})} - Y \]

Where \[ xx = (-1 \times \frac{(t-t_0)}{\tau}) \]

\[ Y = \frac{M_{\text{max}}}{1 + e^{t_0/\tau}} \]
Fitting melt rates with a sigmoidal function

\[ M(t) = \frac{M_{\text{max}}}{1 + e^{xx}} - Y \]

Where

\[ xx = (-1 \times \frac{(t - t_0)}{\tau}) \]

\[ Y = \frac{M_{\text{max}}}{1 + e^{t_0/\tau}} \]
Fitting melt rates with a sigmoidal function

\[ M(t) = \frac{A}{1 + e^{xx}} - B \]

Where \( xx = (-1 \times \frac{(t-t_0)}{\tau}) \)

\[ A = \frac{K}{K-1} \times M_{2200} \]

\[ B = A/K \]
Fitting melt rates with a sigmoidal function

\[ M(t) = \frac{A}{1 + e^{xx}} - B \]

Where

\[ xx = (-1 \times \frac{t - t_0}{\tau}) \]

\[ A = \frac{K}{K - 1} \times M_{2200} \]

\[ B = A/K \]

\[ \tau = [10:75] \]

\[ t_0 = [100:225] \]

\[ M_{2200} = [0:1] \]
Sobol’ Sequence space-filling design

Advantages of Sobol’

- reduces the likelihood of clustering whilst ensuring a "uniform" coverage over parameter space
- parameters cover the full space reasonably when terminated at any point

Image Credit: extremelearning.com
Ensemble design

\[ \tau = [10:75] \]
\[ t_0 = [100:225] \]
\[ M_{2200} = [0:1] \]
Ensemble design

- We can make as many sigmoidal trajectories as we want and scale their values at M2200 per basin based on literature values.
- We allow M2200 to be 2x the maximum found in the literature.

Basal melt rate trajectories [m/yr]

Basal melt rate trajectories [m/yr]
Design an ocean-only CISM ensemble

500 ensemble members

Introduction          Model Configuration       Ensemble Design       Ensemble Results       Emulator Validation       Simple

Example
CISM Ensemble Results

NB: uniform priors on the melt parameters shouldn’t be considered physically meaningful.
Emulating instead of simulating

- We build an emulator to interpolate SLR (in 2100 & 2200) across a 15-dimensional input space to build a response surface. (15 = 5 regions x 3 sigmoid parameters)
Emulating instead of simulating

- We build an emulator to interpolate SLR (in 2100 & 2200) across a 15-dimensional input space to build a response surface. (15 = 5 regions x 3 sigmoid parameters)

example of simple Gaussian process model (https://en.wikipedia.org/wiki/Kriging)

Interpolating property + probabilistic nature
Emulator Validation

- Holding out 20% of the points for validation
- Correlate at 0.98 & 0.99
- For 2100, 8% of hold-out validation points lie outside the 2-sigma predictive intervals, which is plausible (one would expect 5%)
Prior Distributions: A1B Scenario

Introduction       Model Configuration      Ensemble Design       Ensemble Results      Emulator Validation

Simple Example
Corresponding sigmoids
Sample Uncertainty Propagation

Emulated 2100 SLR (peak of PDF) $\sim 7.5$ mm
Summary

We have:

- Designed and run a 500 member CISM ocean-only ensemble, perturbing basal melt rates for 200 years with projections that can be mapped back to ocean models.
- Built an ice sheet emulator that provides ice retreat as a function of heat applied at the coastal shelves. Can sample very wide range of possible forcings, including tails.
- Shown how one can propagate uncertainty through the emulator with a simple example.
Summary

We have:

- Designed and run a 500 member CISM ocean-only ensemble, perturbing basal melt rates for 200 years with projections that can be mapped back to ocean models
- Built an ice sheet emulator that provides ice retreat as a function of heat applied at the coastal shelves. Can sample very wide range of possible forcings, including tails.

Ongoing:

- Shown how one can propagate uncertainty through the emulator with a simple example
- Generate more priors & produce envelope of SLR uncertainties given CMIP priors
- Tie in high resolution ocean models like ROMS b/c GCMs lack important transport processes
Summary

We have:

- Designed and run a 500 member CISM ocean-only ensemble, perturbing basal melt rates for 200 years with projections that can be mapped back to ocean models
- Built an ice sheet emulator that provides ice retreat as a function of heat applied at the coastal shelves. Can sample very wide range of possible forcings, including tails.

Ongoing:

- Shown how one can propagate uncertainty through the emulator with a simple example
- Generate more priors & produce envelope of SLR uncertainties given CMIP priors
- Tie in high resolution ocean models like ROMS b/c GCMs lack important transport processes

Other ideas:

- Build impulse response model with CISM
- Increase resolutions, include better melt parameterizations, fast-ice uncertainties etc
- Include emulator into larger SLR/coastal flooding integrated assessment
Thanks!
ROMS

- Based on 4-day averages between July 1991 and June 1994, where ROMS is forced by MAR-ACCESS1.3.

- Surface velocity magnitude (blue to yellow): 0-1.2 m2/s2

- Sub-ice shelf melt (red scale): 0-4m/year

- Sea ice cover (0-1)

- So far: The first run was done over the 20 years of historical (1980-2004) period forced by ACCESS1.3 (downscaled by MAR)