Structural uncertainties in the projection and past simulation of Greenland ice sheet

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- Uncertainties in short-term $O(100\text{yr})$ projection
- (Uncertainties in long-term $O(10000\text{yr})$ simulation)

Demonstrate that each model aspect has some uncertainties, which accumulates enough to impact on the dispersion among ice-sheet model sensitivities
SeaRISE (Bindschadler et al., 2013)

SeaRISE (≡ Sea-level Response to Ice Sheet Evolution)
Intercomparison among 8 models; 10 future-scenario experiments (500 years);

$\Delta$ Volume computed relative to constant-climate run

$\leftarrow C^*$: Climate exp.
C1: A1B × 1.5  5.4 – 38.7 cm
C2: A1B × 2  7.2 – 79.8 cm
C3: A1B × 3  8.5 – 142.6 cm
($\Delta$ volume at 500 year)

$\leftarrow S^*$: Sliding exp.
S1: sliding × 2
S2: sliding × 2.5
S3: sliding × 3

$\leftarrow M^*$: Ocean melting exp.
M1: 2 m/a
M2: 20 m/a
M3: 200 m/a

$\leftarrow R8$: ~ RCP8.5 experiment
A1B × 1.5; sliding × 1.5; Transient marginal melting
⇒ volume changes 22 cm (100 yr); 53 cm (200 yr) s.l.eq

Large spreads over the results by individual models
<table>
<thead>
<tr>
<th>Characteristic (Model)</th>
<th>slide</th>
<th>Elmer/ice</th>
<th>UNISIM</th>
<th>ISSU</th>
<th>SICOPOLIS</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Model Type</strong></td>
<td></td>
<td>finite difference, Euleraian</td>
<td>finite element quadrilateral</td>
<td>finite element, arbitrary Lagrangian Euleraian</td>
<td>finite difference, Euleraian</td>
</tr>
<tr>
<td><strong>Grid</strong></td>
<td></td>
<td>H: uniform 10 km (vertically)</td>
<td>H: 2 km (in the interior)</td>
<td>H: 5 km (Greenland: 10 km in the interior)</td>
<td>H: 5 km (Greenland: 10 km in the interior)</td>
</tr>
<tr>
<td><strong>Time Step</strong></td>
<td></td>
<td>3 months</td>
<td>3 months</td>
<td>2 months</td>
<td>3 months</td>
</tr>
<tr>
<td><strong>Spin-up</strong></td>
<td></td>
<td>initial spin-up from the Euleraian through the last Earth period to match present-day velocity field</td>
<td>initial spin-up from the Euleraian through the last Earth period to match present-day velocity field</td>
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</tr>
<tr>
<td><strong>Ice Flow Mechanics</strong></td>
<td></td>
<td>shallow ice</td>
<td>shallow ice</td>
<td>shallow ice (Greenland: shallow shelf, Antarctica)</td>
<td>shallow ice (Greenland: shallow shelf, Antarctica)</td>
</tr>
<tr>
<td><strong>Surface Mass Balance</strong></td>
<td></td>
<td>positive degree-day (RSD)</td>
<td>mean annual temperature = 0.1°C (MAT)</td>
<td>surface mass balance from the Last Glacial Maximum (LGM)</td>
<td>surface mass balance from the Last Glacial Maximum (LGM)</td>
</tr>
<tr>
<td><strong>Basal Sliding</strong></td>
<td></td>
<td>Weertmann sliding law</td>
<td>Weertmann sliding law</td>
<td>viscous sliding law</td>
<td>viscous sliding law</td>
</tr>
<tr>
<td><strong>Basal Hydrology</strong></td>
<td></td>
<td>none</td>
<td>none</td>
<td>none</td>
<td>none</td>
</tr>
<tr>
<td><strong>Ice Shear Tongue</strong></td>
<td></td>
<td>no</td>
<td>no</td>
<td>no</td>
<td>no</td>
</tr>
<tr>
<td><strong>Advance/Retreat</strong></td>
<td></td>
<td>no</td>
<td>no</td>
<td>yes</td>
<td>yes</td>
</tr>
</tbody>
</table>

Table 2. Characteristics of Models used in SeaRISE (additional capabilities of some models may not be indicated here if not used in SeaRISE experiments; details found in Appendix A)

There are many documented/undocumented differences among models. Some sensitivity tests are performed (e.g., Herzdorf et al., 2012; Greve & Herzfeld, 2013).
Variation in the Surface mass balance

SeaRISE provided future changes in
- the surface mass balance (→ one model)
- the surface temperature (→ the other models)

Computation of the surface mass balance varied among the models

Positive Degree-Day (PDD) method

\[ T_{\text{surf}}(x, y, t) = \Delta T(t) + T_{\text{ref}}(x, y) + \lambda h(x, y) \]
\[ M_{\text{surf}}(x, y, t) = f(T_{\text{surf}}) \]

ICIES uses Tarasov & Peltier (2002) for the SeaRISE submission, other models Huybrechts & de Wolde (1999), yet other models use …
Variation in the initialization

Either
- Using uniform fields (e.g., basal sliding coefficient) and historical spin-up
- Invert a field (e.g.,...) to match the present-day, without historical spin-up

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<thead>
<tr>
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</thead>
<tbody>
<tr>
<td>a,c</td>
<td>Free spin-up</td>
<td></td>
<td></td>
</tr>
<tr>
<td>d,h</td>
<td>Fixed topography spin-up</td>
<td></td>
<td></td>
</tr>
<tr>
<td>e</td>
<td>Free spin-up with flux adj.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>b</td>
<td>Enh. factor ‘inversion’</td>
<td></td>
<td></td>
</tr>
<tr>
<td>f,g</td>
<td>Basal sliding ‘inversion’</td>
<td></td>
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</tbody>
</table>

Figures from Bindschadler et al. (2013)
Sensitivity experiment (no inversion)

\[ \Delta \text{Volume computed relative to constant-climate run} \]

Left: Bindschadler et al. (2013)
Right: ICIES step-by-step replacement

- **2→3 Surface mass balance** method (Different PDD coefficients)
- **3→4 Initialization** method (Free to Fixed-topography spin-up)
  - fixed-topo: no changes in the topography during spin-up
- **4→5 Margin advance** treatment (Artificially prohibit margin advances)
  - smaller effect under warmer scenarios

Half of the spreads can be simulated by the replacement of surface mass balance, initialization, and the margin advance treatment
Demonstration of ‘Inversion’

Diff. in the surface elevation rel. to obs.
\[ \text{vb} \times 1 \quad \text{vb} \times 2 \quad \text{vb} \times 4 \quad \text{inv.} \]

Log. ratio of the coeff. rel. to vb×2 case

‘Inversion’ (or relaxation) following Pollard & DeConto (2012)
- Initial guess of the basal sliding coeff.
- 2kyr free evolving thickness run
- Adjust basal sliding coefficient field according to the error in the thickness
- Repeat, and run 100 kyr totally
- Need to adjust enh. factor as 1 (default 3)
Sensitivity to the non-uniform basal sliding coeff.

Simulated volume change under SeaRISE/C1 (A1B) scenario rel. to those under SeaRISE/C0 (control, no warming) scenario

$v_1, v_2, v_4$: uniform coeff; $v_m$: inverted

- Large coefficient enhances ice-sheet melting
- Inverted coefficient: larger near margin; smaller in interior — smaller response than $v_1$ case

Enh. factor adjusted to 1

$ICIES$ can perform like the ‘least impact’ model
— SeaRISE spreads MAY be explained by

- Non-uniform basal sliding coeff (and/or initialization)
- Surface mass balance
- (secondary) margin advance treatment
Summary and prospects

Climate warming experiment in SeaRISE for Greenland is revisited, in order to separate impact of different formulation of models. Major (potential) sources are:

- difference in the initialization method
  - Non-uniform basal sliding coefficient field to match the present-day ice sheet
- difference in the surface mass balance method

This is not proof, just a potential explanation

- If all the models repeat this study, then more valid explanation can be expected
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