Simulating the Greenland Ice sheet over two glacial cycles:

*Sensitivity to sub-shelf melting and relative sea level*

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Aim 1: GrIS contribution to Eustatic Sea Level

Last Interglacial

GrIS: 0.6-3.5m

Dutton et al, Science, 2015
Aim 1: GrlS contribution to Eustatic Sea Level?

Last Interglacial
GrIS: 0.6-3.5m

Dutton et al., Science, 2015

Last Glacial Maximum
GrIS: 5m

Clark + Tarasov, PNAS, 2014
Aim 2: How large was the sheet at glacial maximum?
Aim 3: When did the Ice sheet retreat?

- < 9 kyr
- < 10.8 kyr
- < 10.9 kyr
- < 15 kyr
- ~12.2 kyr
- ~ 7.4 kyr
- ~ 17.2 kyr
- > 15 kyr
Method

• Use a SIA-SSA Ice sheet model ‘IMAU-ICE’
• Simulate the GrIS from 238 kyr BP to PD

Investigate

• parameterisation for sub shelf melting related to changes in palaeo water depth
• Offline RSL forcing – GIA model – palaeo water depth

• Suite of ~ 300 simulations
• 11 final viable combinations

Can we address the 3 proposed questions
Background: Ice sheet – Ice shelf model

Hb and Sea Surface Height
Calculate with GIA model

Sea Surface/Geoid height

‘Grounding line’

‘Flotation criterion’

\[ \left( \frac{\rho_i}{\rho_w} \right) \times H_i \leq \text{Sea Surface height} - H_b \]
Background: Ice sheet – Ice shelf model

Sub shelf melting – parameterised based on changes in water depth

Ice sheet
Grounded

‘Grounding line’

H_i

ρ_i

ρ_w

Sub Shelf Melting

Tidal motion of floating ice shelf

Calved iceberg

Sea Surface/Geoid height

Ice shelf floating

H_b

www.AntarcticGlaciers.org
General model setup

Input: topography and ice sheet thickness – Bamber et al, 2013
Input: Climate parameters – adapted from the Racmo2 dataset
Surface Air Temperature Forcing – Helsen et al, 2013

Vostok Ice core $\delta D$
Grip $\delta^{18}O$ Ice core
General model setup

Input topography and ice sheet thickness – *Bamber et al, 2013*

Input Climate parameters – adapted from the Racmo2 dataset

Surface Air Temperature Forcing - *Helsen et al, 2013*

- Ran 20x20km
- Each simulation ran for 100 kyr to reach equilibrium: match to present day observations
- SMB – influence of topo on SMB - SMB-gradient method *Helsen et al, 2013*

- ‘Weertman-type sliding law’ relates $\nu_b$ - basal velocity to $\tau_b^p$ basal shear stress

$$\nu_b = A_s \frac{\tau_b^p}{Zq}$$

$A_s : 0.04 \times 10^{-10}$ and $1.8 \times 10^{-10}$ m$^8$N$^{-3}$yr$^{-1}$. 
Sub Shelf Melt Parameterisation

- Looked into four different parameterisation

- Increase in palaeo water depth – increase in ssm
Method 4: Exponential ssm

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Method 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A_s$ (m$^8$ N$^{-3}$ yr$^{-1}$)</td>
<td>0.04 - 1.2 × 10$^{-10}$</td>
</tr>
<tr>
<td>ssm1 (m/yr)</td>
<td>0.25 - 10</td>
</tr>
<tr>
<td>ssm2 (m/yr)</td>
<td>10 - 150</td>
</tr>
<tr>
<td>WD1 (m)</td>
<td>300 - 600</td>
</tr>
<tr>
<td>WD2 (m)</td>
<td>1000</td>
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</tbody>
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Increasing sub shelf melting

Water depth (WD) (m)
Method 4: Exponential ssm

Sub shelf melting (m/yr)

Water Depth (m)
Relative Sea Level forcing

Glacial

Interglacial

Relative Sea Level = Geoid – Solid Earth
Relative Sea Level forcing

\[ S(\theta, \psi, t) = G_T (\theta, \psi, t) - R_T (\theta, \psi, t) \]

\( G_T (\theta, \psi, t) \)  
Vertical perturbation of the geoid

\( R_T (\theta, \psi, t) \)  
Vertical perturbation of the solid earth surface
Relative Sea Level = Sea Surface – Solid Earth

Total Signal

\[ S_T = G_T - R_T \]
Relative Sea Level forcing

\[ S(\theta, \psi, t) = (G_L(\theta, \psi, t) + G_{NL}(\theta, \psi, t)) - (R_L(\theta, \psi, t) + R_{NL}(\theta, \psi, t)) \]

Separate into:

- **LOCAL component** - due to GrIS
  \[ G_L(\theta, \psi, t) \quad R_L(\theta, \psi, t) \]

- **NON-LOCAL component** - primarily due to Laurentide Ice sheet
  \[ G_{NL}(\theta, \psi, t) \quad R_{NL}(\theta, \psi, t) \]

- To calculate the NON-LOCAL component – use GIA model
Relative Sea Level = Sea Surface – Solid Earth

Non–Local
Relative Sea Level forcing

\[ S(\theta, \psi, t) = \left( G_L(\theta, \psi, t) + G_{NL}(\theta, \psi, t) \right) - \left( R_L(\theta, \psi, t) + R_{NL}(\theta, \psi, t) \right) \]

- **NON-LOCAL** – derived from GIA model
- **LOCAL** component - GrIS == IMAU-ICE model

\[ G_L(\theta, \psi, t) \quad R_L(\theta, \psi, t) \]
Relative Sea Level forcing

For the LOCAL signal: IMAU-ICE: calculate \( R_L(\theta, \psi, t) \) - ‘ELRA’ method.

\[
S(\theta, \psi, t) = \left(G_{NL}(\theta, \psi, t)\right) - \left(R_L(\theta, \psi, t) + R_{NL}(\theta, \psi, t)\right)
\]

- Still missing the LOCAL Geoid signal
- No mechanism in IMAU-ICE to calculate
Relative Sea Level forcing:

\[ S(\theta, \psi, t) = (G_{NL}(\theta, \psi, t)) - (R_L(\theta, \psi, t) + R_{NL}(\theta, \psi, t)) \]
Results: Present day extent
Results:
Recap:

Aim 2: How large was the sheet at glacial maximum?

Aim 3: When did the Ice sheet retreat?
Results

- **LGM IV**: 2.61m
- **PD IV**: $3.31 \times 10^{15}$ m$^2$
- 19.9 to 14.9 minimal change

South
- Retreat – readvance – retreat
- Timings related to SAT

North
- One period of retreat
- Sensitive to choice of ssm
- Highly variable timings
Summary Points

• Reconstruct GrIS over two glacial cycles

Q1 – Eustatic Sea Level (ESL) contribution
• LIG ESL = 1.5m, decrease ~ 0.5m relative to SIA only
• LGM ESL = 2.6m, increase of 1.5 m

Q2 – Simulate a large GrIS
• Extends out onto continental shelf and across the Nares Strait
• Mismatch to the observations still remain

Q3 – Timing of Retreat
• SW Retreat – driven primarily by SAT, secondary ssm
• NW – retreat driven by RSL and ssm- sensitive to the timing of the LIS deglaciation
What drives the Spatial Variation in the retreat?
Between 14.7 and 13.9 - RETREAT

- Rise in SAT: 0.24 m
- Fall GIV: 1
1 kyr stillstand
Between 12.9 and 11.5 kyr BP READVANCE

GIW (Grounded Ice Volume ($10^{15}$ m$^3$))

SAT (Surface Air Temperature °C)
From 11.5 kyr BP RETREAT

GIV (Grounded Ice Volume ($10^{15} \text{ m}^3$))

SAT (Surface Air Temperature °C)

Time (kyr BP)
From 11.5 kyr BP: North West Margin

- Retreat between 7.9 and 6.9 kyr BP
- Timing – variable depending on ssm and RSL forcing
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