Glacial Isostatic Adjustment with 3D Earth models: A comparison of case studies of deglacial relative sea-level records of North America and Russian Arctic

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Outline

• Introduction

• The GIA model

• Results: 1D and 3D GIA models

• Summary
Introduction: Motivation

• The published quality-controlled deglacial relative sea-level (RSL) database provide a good opportunity to validate the Glacial Isostatic Adjustment (GIA) model.

• The 1D GIA model show notable misfits when compared with the RSL data.

• Surface geology and seismic tomography show that Earth’s material properties are laterally heterogeneous (3D), rather than laterally homogeneous (1D).

• Both the quality-controlled deglacial RSL databases in North America and Russian Arctic cover the near- and intermediate- fields.

• Investigate the influence of 3D viscosity structure both in North America and Russian Arctic.
Quality-controlled deglacial RSL database

The blue dots indicate the location of each data and the red triangles represent the center of each sub-region.

1725 Sea-level index points (SLIPs).
847 Marine limiting data.
769 Terrestrial limiting data.

359 Sea-level index points (SLIPs).
78 Marine limiting data.
92 Terrestrial limiting data.

-- Baranskaya et al., 2018; Engelhart & Horton, 2012; Engelhart et al., 2015; Vacchi et al., 2018
Sea-level reconstruction

Sea-level index points (SLIPs):
Altitude and indicative meaning constrain former RSL by: \[ \text{RSL} = A - \text{RWL} \pm \text{Indicative Range}. \]

Marine limiting: Below MTL, so the RSL should be above the marine limiting data.

Terrestrial (freshwater) limiting: Above MTL, so the RSL should be below the terrestrial limiting data.
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GIA model

1D Normal Mode Method

ICE-6G_C (VM5a)

ICE-7G (VM7)

3D INPUTS

Ice history Model
ICE-6G_C

Earth Model
(Density, Elastic properties, Viscosity)
e.g. VM5a

MODEL

Finite Element Model +
Sea Level Equation +
Liouville’s Equation (Rotational feedback on sea level)

OUTPUTS

Crustal Uplift
Horiz Motion
Sea Levels
Gravity Field
Earth Rotation

GIA Stress evolution

-- Argus et al., 2014; Peltier et al., 2015; Roy & Peltier, 2017; Wu, 2004
3D mantle viscosity from Seismic Tomography Model

\[
\log_{10}[\eta(r, \theta, \phi)] = \log_{10}[\eta_o(r)] + \log_{10}[\Delta \eta(r, \theta, \phi)]
\]

**3D Viscosity Structure**  
**Background Viscosity**  
**Lateral Viscosity Perturbation**

\(\eta_o(r)\): VM5a and variations from VM5a in UM (0.05~0.5 \times 10^{21} \text{ Pa s})

\[
\log_{10}[\Delta \eta(r, \theta, \phi)] = \frac{-0.4343}{[\partial \ln \nu_s/\partial T]_{ah+an}} \frac{(E^* + pV^*)}{RT_0^2} \frac{\delta \nu_s}{\nu_s} \beta
\]

- \(E^*\): activation energy.
- \(V^*\): activation volume.
- \(p\): pressure.
- \(R\): gas constant.
- \(T_0\): background temperature profile.

\([\partial \ln \nu_s/\partial T]_{ah+an}\) includes both the effects of anharmonicity (ah) and anelasticity (an).

\(\frac{\delta \nu_s}{\nu_s}\): lateral shear velocity variations – TX2011 Seismic Tomo Model.

\(\beta\) = contribution of thermal effect to lateral shear velocity variations.

\(\beta \in [0,1]\)

Two different \(\beta\) values in the UM (\(\beta_{UM}\)) and LM (\(\beta_{LM}\)) are used.

\((\eta_o(r), \beta_{UM}, \beta_{LM})\) determines the 3D mantle viscosity.

--- Karato, 2008; Grand, 2002; Wu et al., 2012
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Calculate the $\chi$-statistics to quantify the misfit between predictions and observations of RSL:

$$
\chi = \sqrt{\frac{1}{N} \sum_{i=1}^{N} \left[ \frac{o_i - p_i(m_j)}{\Delta o_i} \right]^2 (t)}
$$

- $N$: number of data.
- $o_i$: $i$th observation with uncertainty $\Delta o_i$.
- $p_i(m_j)$: the $i$th prediction for model $m_j$.
- $t$: account for time uncertainty $\Delta t$.
- $\left[ \frac{o_i - p_i(m_j)}{\Delta o_i} \right] (t)$: minimising $\left[ \frac{o_i - p_i(m_j)}{\Delta o_i} \right]$.

Only calculate the $\chi$-statistics at each SLIP sample location, but use the limiting data to help check the results.
There is a trade-off between background viscosity ($\eta_{UM}$) and scaling factor ($\beta_{UM}$) in the upper mantle.

**HetM_\( \alpha \_ \beta_{UM} \_ \beta_{LM} \_ L140$, \( \alpha \) represents background viscosity in the upper mantle.

$$\eta_{UM} = \alpha \times 10^{21} \text{ Pa s.}$$

\( \eta_{LM} \): same as VM5a.

L140: Laterally varying lithosphere (Li & Wu 2018)

<table>
<thead>
<tr>
<th>Deglacial RSL data/( \chi )-statistics</th>
<th>ICE-6G C (VM5a)</th>
<th>ICE-7G NA (VM7)</th>
<th>ICE-6G C (Best-fit 3D model, red diamonds)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Whole North America</td>
<td>2.991</td>
<td>2.807</td>
<td>2.877</td>
</tr>
<tr>
<td>Whole North America with Pacific coast excluded</td>
<td>3.129</td>
<td>2.951</td>
<td>2.722</td>
</tr>
<tr>
<td>Russian Arctic</td>
<td>5.157</td>
<td>4.471</td>
<td>1.460</td>
</tr>
</tbody>
</table>
Results: 3D model improves the fit in North America

3D GIA model HetM\_0.2\_0.5\_0.6\_L140 fits better than the 1D models along eastern Canadian coast and U.S. Atlantic coast, but performs less well along the Pacific coast.
Results: 3D model improves the fit in Russian Arctic

3D GIA model HetM_0.1_0.8_0.6_L140 improves the fits significantly in White Sea.

Meanwhile, the 3D GIA model retains the good fits that 1D models achieved.
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- The ICE-7G (VM7) fits better than ICE-6G_C (VM5a) both in North America and Russian Arctic.
- The best-fit 3D GIA models (e.g. HetM_0.2_0.5_0.6_L140 and HetM_0.1_0.8_0.6_L140) improve the fits significantly and retain the good fits achieved by 1D models.
- The Russian Arctic database prefers a softer background viscosity model, but larger scaling factor than those preferred by the North America.
- There is a trade-off between the background viscosity ($\eta_{UM}$) and scaling factor ($\beta_{UM}$) in the upper mantle, with different combinations of $\eta_{UM}$ and $\beta_{UM}$ providing similar RSL predictions. This phenomenon is found both in North America and Russian Arctic.

Notice: For 3D GIA model search, here fixed with ICE-6G_C ice model, the uncertainty/error of the ice model is not considered.

With 1D viscosity model, changing the ice model may improve the fit as well.
Thank You!