NANYANG TECHNOLOGICAL UNIVERSITY SINGAPORE

EARTH OBSERVATORY OF SINGAPORE
An institute of Nanyang Technological University

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

Tanghua Li & Benjamin P. Horton (Nanyang Technological University, Singapore)

Nicole Khan (University of Hong Kong, Hong Kong)

Simon Englehart (Durham University, UK)

Alisa Baranskaya (Lomonosov Moscow State University, Russia)

W.R. Peltier (University of Toronto, Canada)

Patrick Wu (University of Calgary, Canada)

EGU 2020 “Sharing Geoscience Online”, May 2020

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).

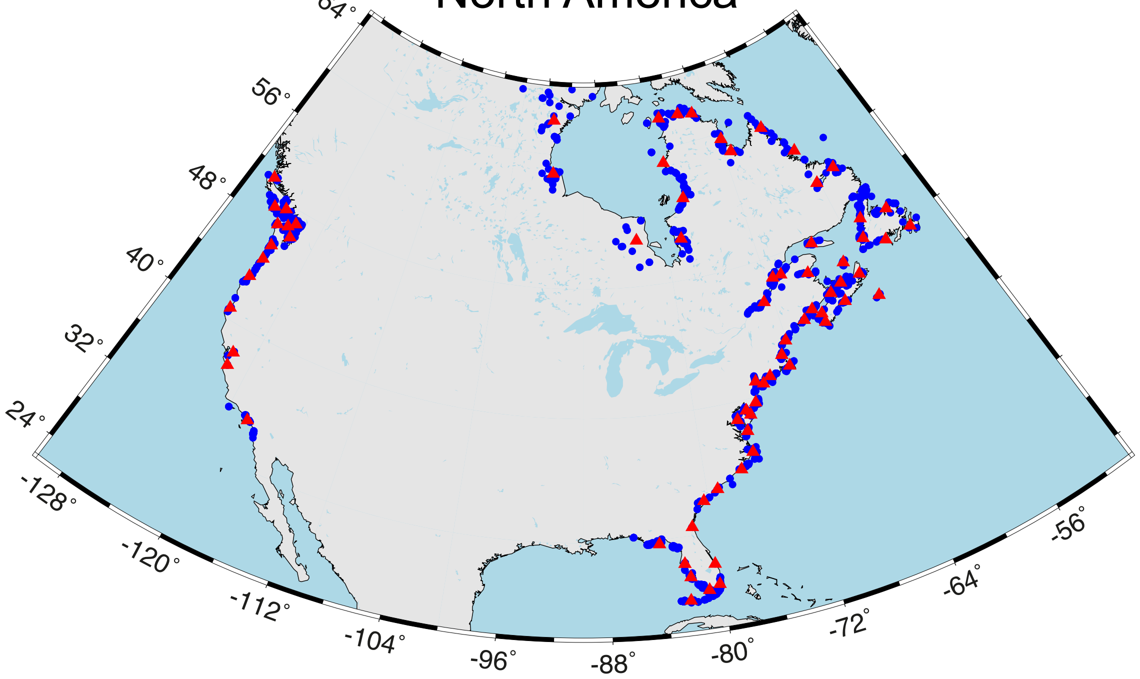
- Both the quality-controlled deglacial RSL databases in North America and Russian Arctic cover the near- and intermediate- fields.

- Investigate the influence of 3D viscosity structure both in North America and Russian Arctic.

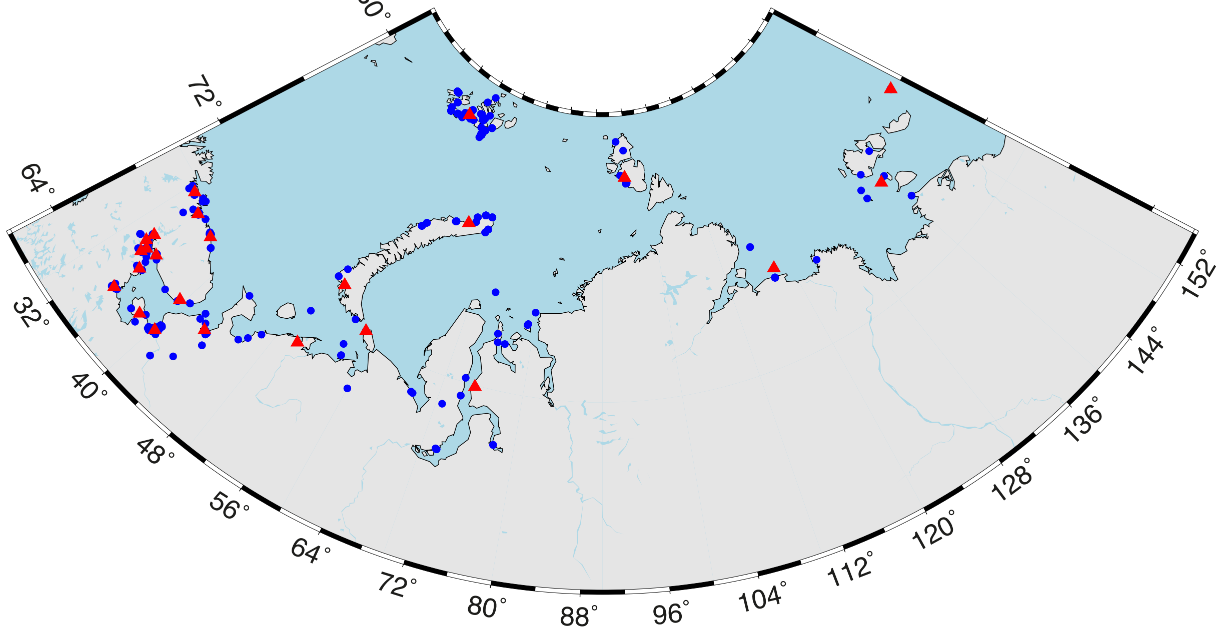
-- Argus et al., 2014; Baranskaya et al., 2018; Engelhart et al., 2015; Vacchi et al., 2018; Peltier et al., 2015; Roy & Peltier, 2015， 2017

Quality-controlled deglacial RSL database

North America



Russian Arctic



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

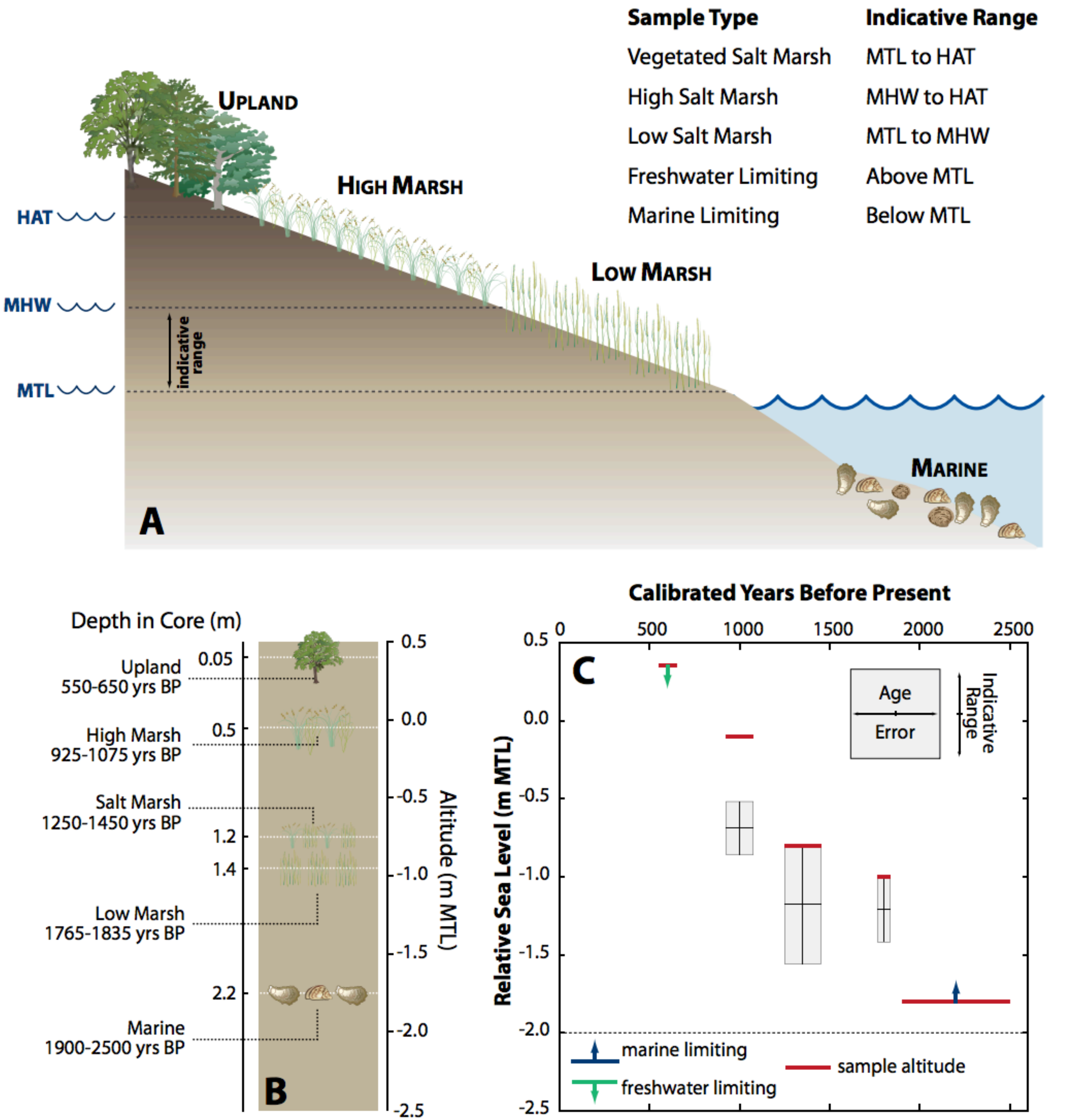
Sea-level reconstruction

Sea-level index points (SLIPs):

Altitude and indicative meaning constrain former RSL by: RSL= A – RWL ± 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.



Outline

- Introduction
- The GIA model
- Results: 1D and 3D GIA models
- Summary

GIA model

1D Normal Mode Method ICE-6G_C (VM5a) ICE-7G (VM7)

3D

INPUTS	MODEL	OUTPUTS
Ice history Model ICE-6G_C	Finite Element Model + Sea Level Equation + Liouville's Equation (Rotational feedback on sea level)	Crustal Uplift Horiz Motion Sea Levels Gravity Field Earth Rotation
Earth Model (Density, Elastic properties, Viscosity) e.g. VM5a		GIA Stress evolution

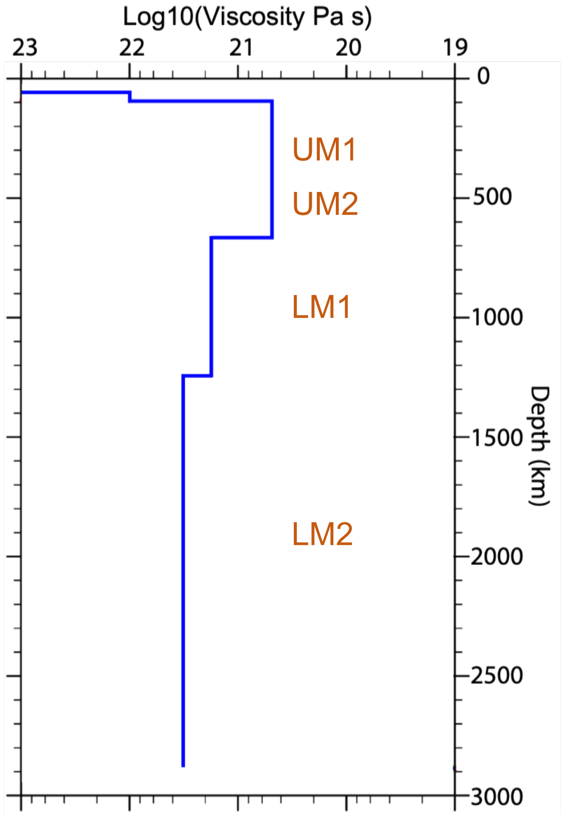
-- Argus et al., 2014; Peltier et al., 2015; Roy & Peltier, 2017; Wu, 2004

3D mantle viscosity from Seismic Tomography Model

$$\mathrm{Log}_{10}[\eta(r,\theta,\phi)] = \mathrm{Log}_{10}[\eta_o(r)] + \mathrm{Log}_{10}[\Delta\eta(r,\theta,\phi)]$$

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

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



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

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

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

$\frac{\delta v_s}{v_s}$: lateral shear velocity variations – TX2011 Seismic Tomo Model.

β = contribution of thermal effect to lateral shear velocity variations.

$\beta \in [0,1]$

Two different β values in the UM (β_{UM}) and LM (β_{LM}) are used.

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

-- Karato, 2008; Grand, 2002; Wu et al., 2012

Outline

- Introduction
- The GIA model
- Results: 1D and 3D GIA models
- Summary

RSL misfit χ-statistics calculation

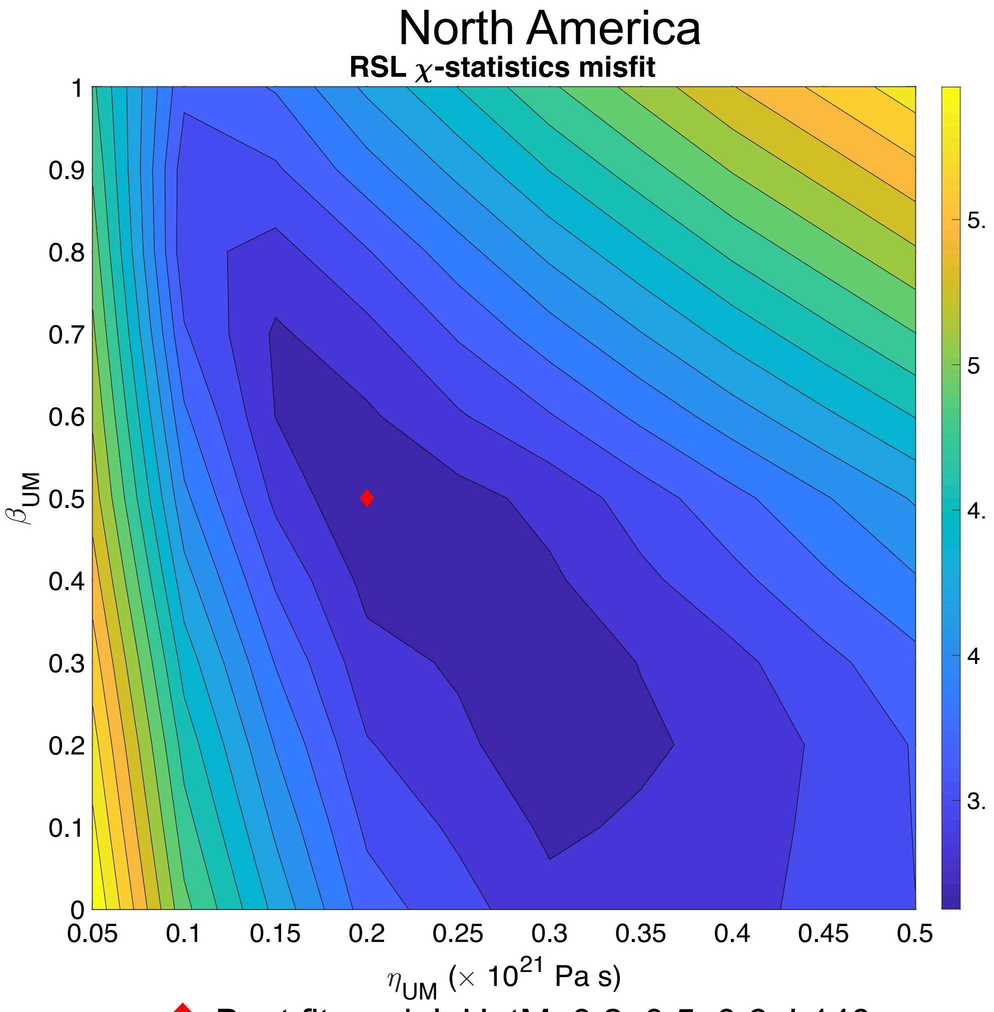
Calculate the χ-statistics to quantify the misfit between predictions and observations of RSL:

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

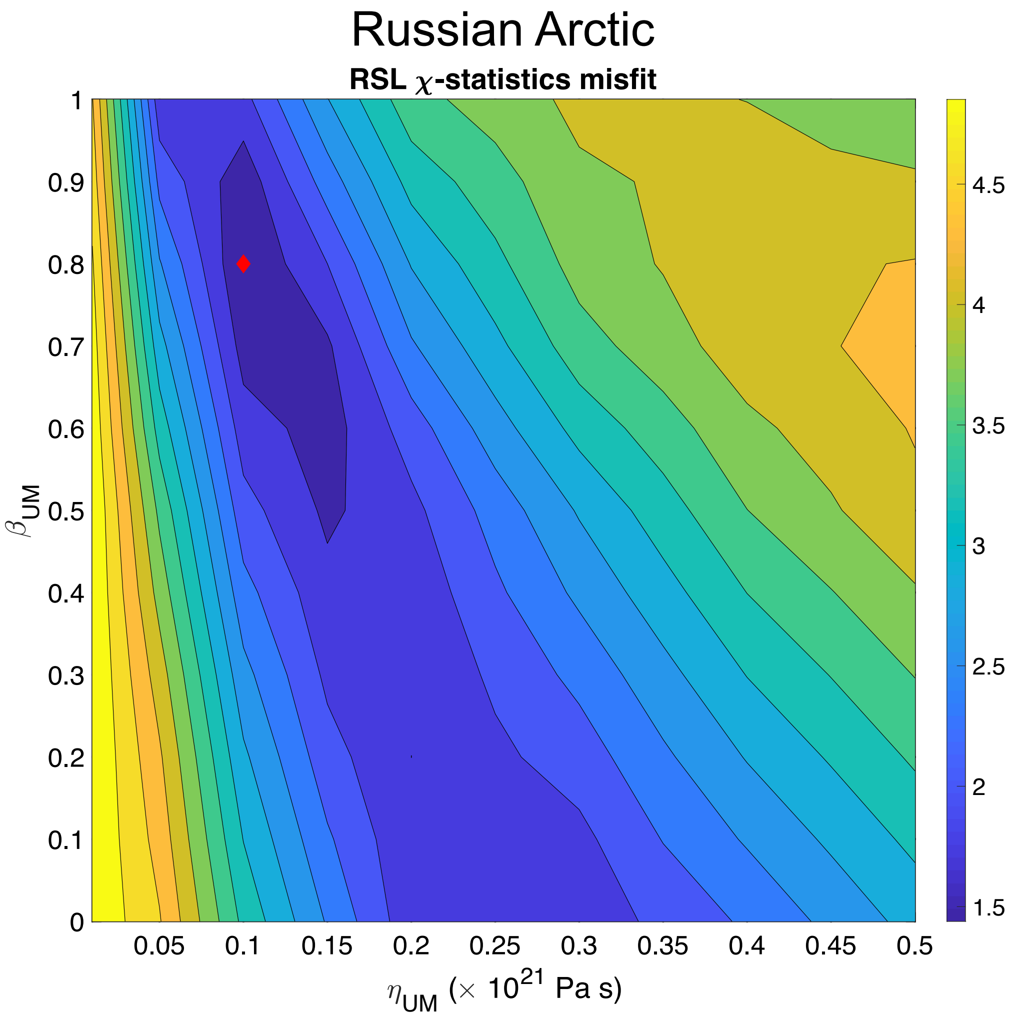
N: number of data.
o_i: ith observation with uncertainty Δo_i.
$p_i(m_j)$: the ith prediction for model m_j.
t: account for time uncertainty Δt.
$\left[\frac{o_i - p_i(m_j)}{\Delta o_i}\right](t)$: minimising $\left[\frac{o_i - p_i(m_j)}{\Delta o_i}\right]$.

Only calculate the χ-statistics at each SLIP sample location, but use the limiting data to help check the results.

3D GIA Models



◆ Best fit model: HetM_0.2_0.5_0.6_L140



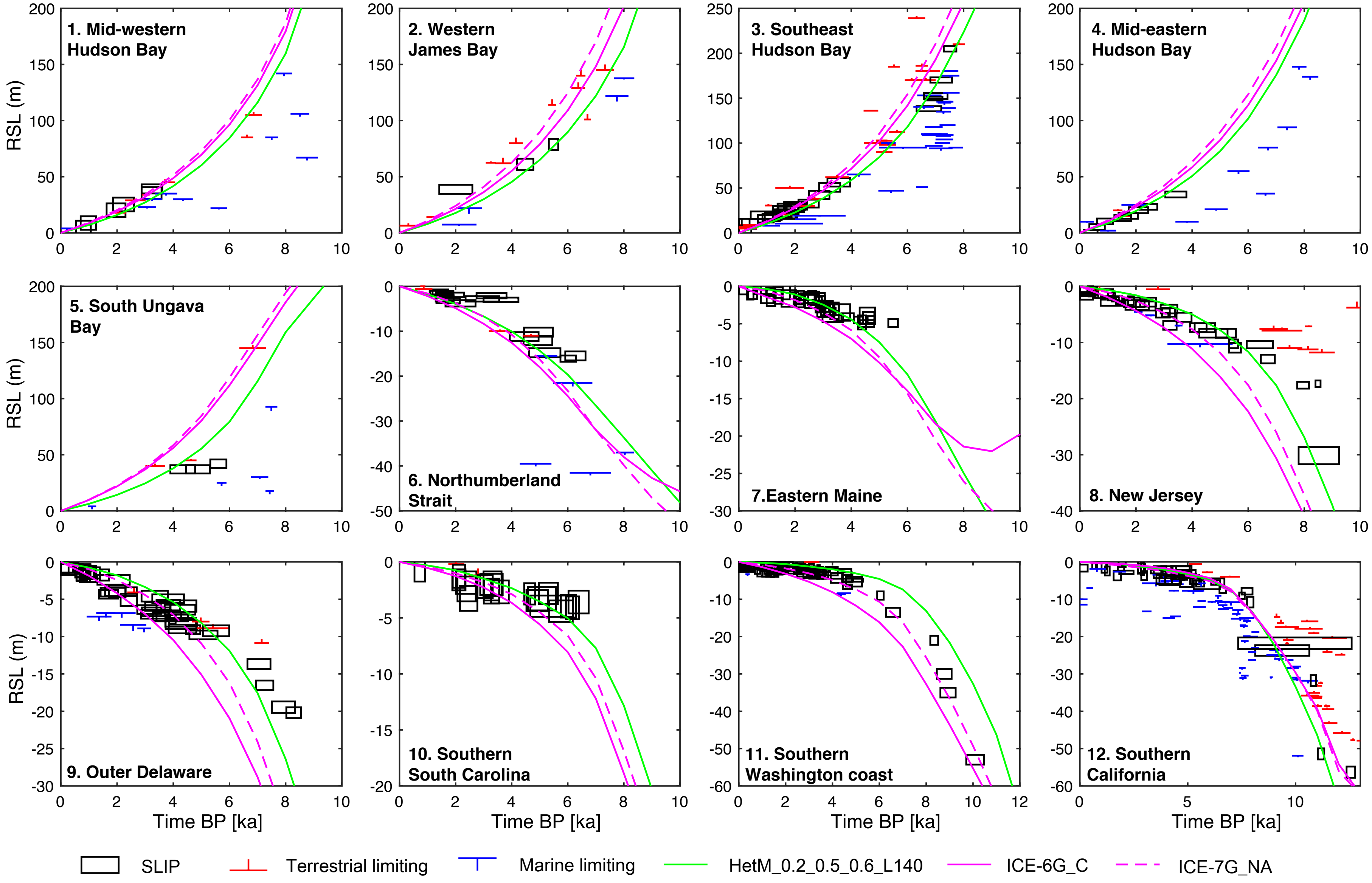
◆ Best fit model: HetM_0.1_0.8_0.6_L140

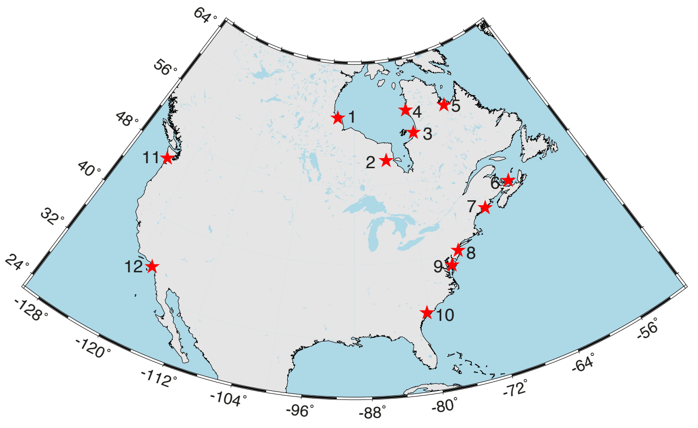
HetM_α_ β_{UM}_ β_{LM}_L140, α represents background viscosity in the upper mantle.
$\eta_{UM} = \alpha \times 10^{21}$ Pa s.
η_{LM}: same as VM5a.
L140: Laterally varying lithosphere (Li & Wu 2018)

There is a trade-off between background viscosity (η_{UM}) and scaling factor (β_{UM}) in the upper mantle.

Deglacial RSL data/χ-statistics	ICE-6G_C (VM5a)	ICE-7G_NA (VM7)	ICE-6G_C (Best-fit 3D model, red diamonds)
Whole North America	2.991	2.807	2.877
Whole North America with Pacific coast excluded	3.129	2.951	2.722
Russian Arctic	5.157	4.471	1.460

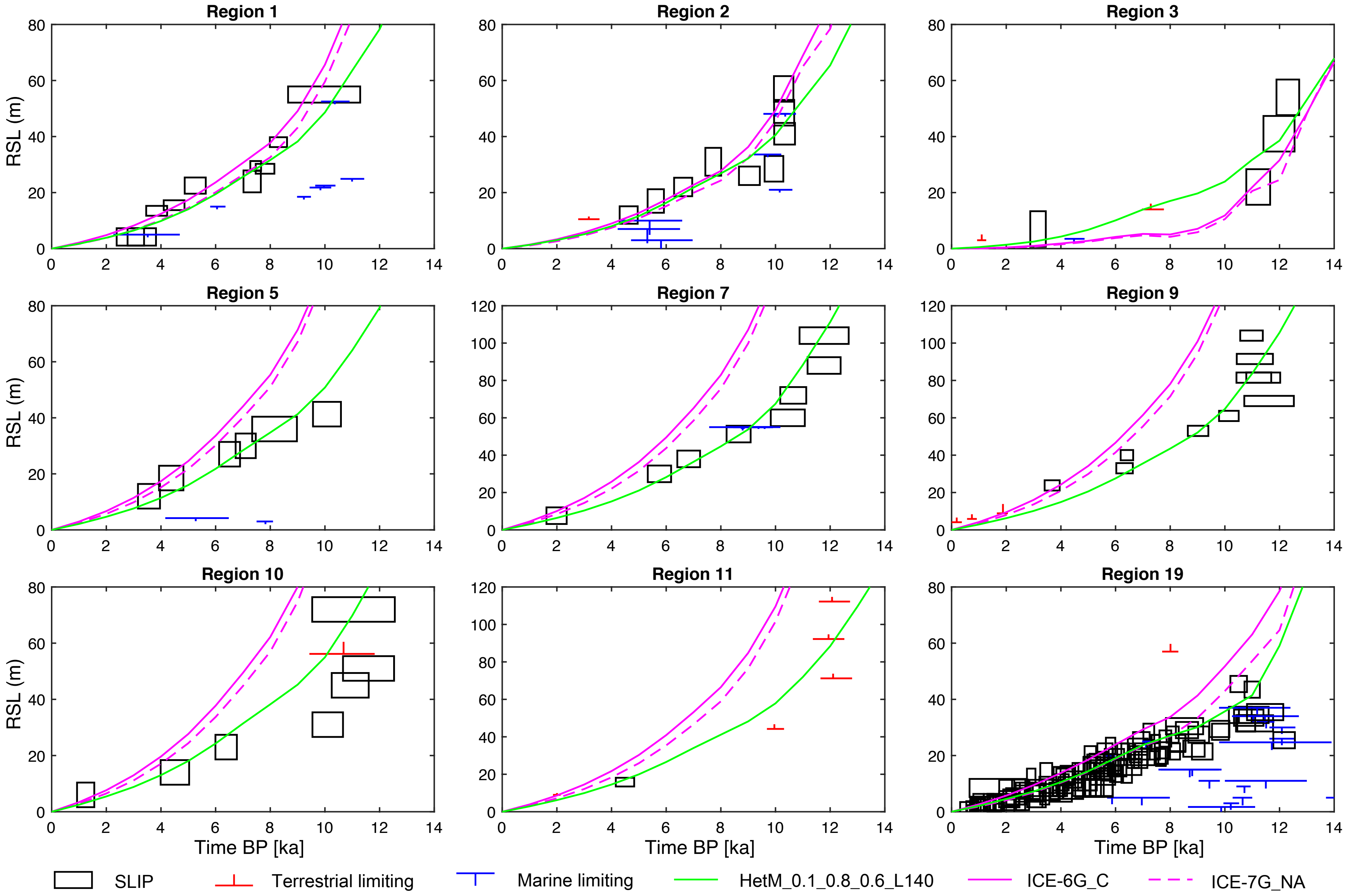
Results: 3D model improves the fit in North America

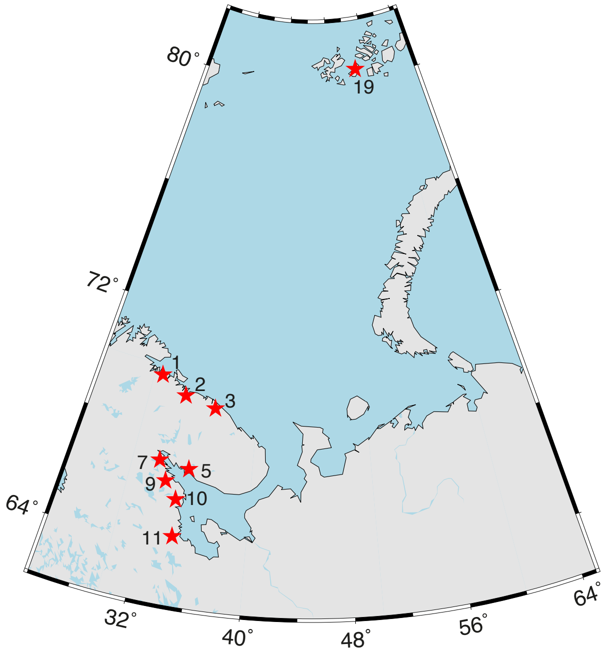




3D GIA model HetM_0.2_0.5_0.6_L140 fits better than the 1D models along eastern Canadian coast and U.S. Atlantic coast, but performs less well along the Pacific coast.

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.

Outline

- Introduction
- The GIA model
- Results: 1D and 3D GIA models
- Summary

Summary

- 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 (η_{UM}) and scaling factor (β_{UM}) in the upper mantle, with different combinations of η_{UM} and β_{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!