The inclusion of ice model uncertainty in 3D Glacial Isostatic Adjustment modelling: a case study from the Arctic

Tanghua Li

li.tanghua@ntu.edu.sg

W.R. Peltier, Gordan Stuhne, Nicole Khan, Alisa Baranskaya, Timothy Shaw, Patrick Wu & Benjamin Horton

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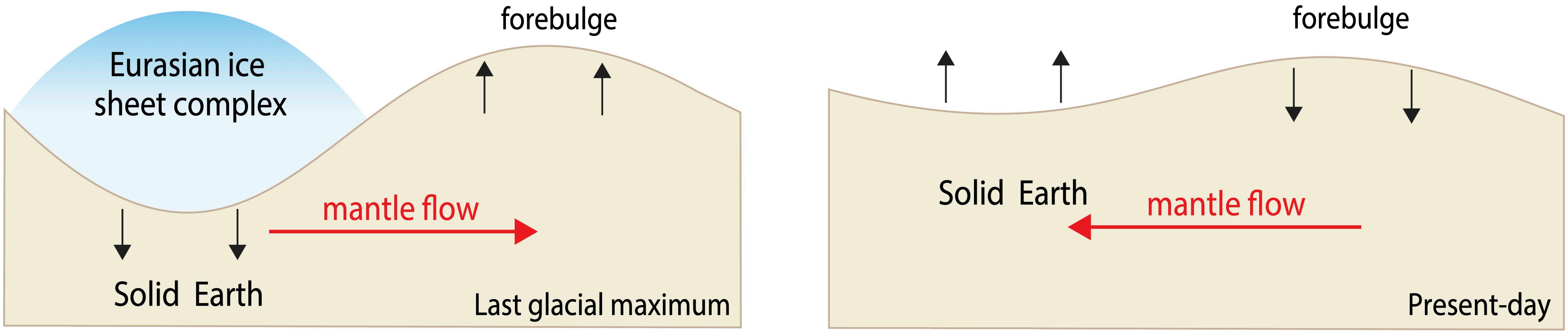
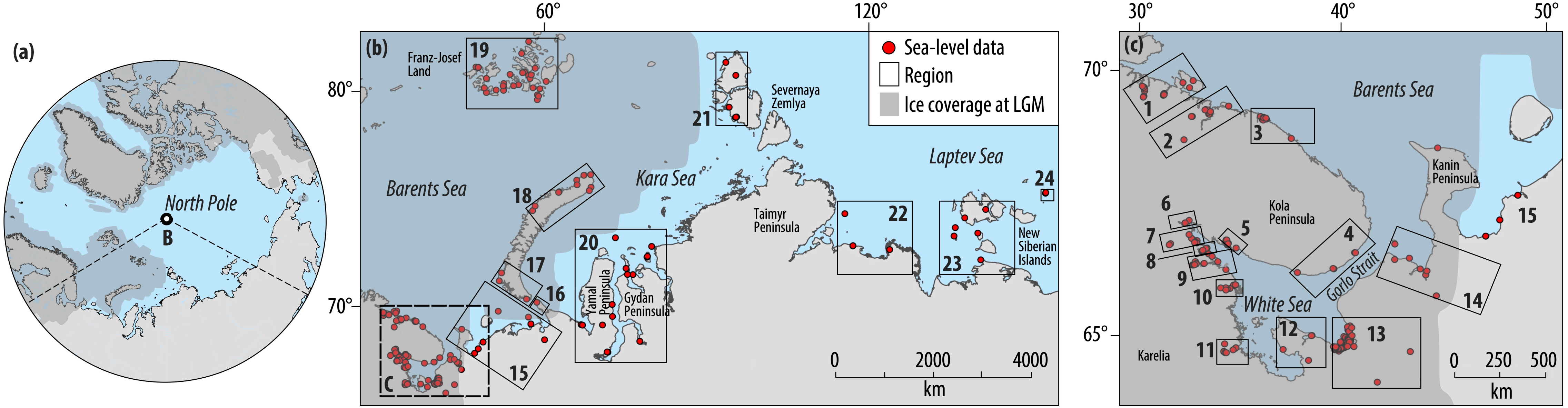
Glacial Isostatic Adjustment



The GIA process dominates the spatial pattern of sea-level change in the Arctic.

Relative sea-level database



359
Sea-level index points (SLIPs)

78
Marine limiting data

92
Terrestrial limiting data

-- Li et al., 2022

1D

Normal Mode Method | ICE-6G_C (VM5a) | ICE-7G_NA (VM7)

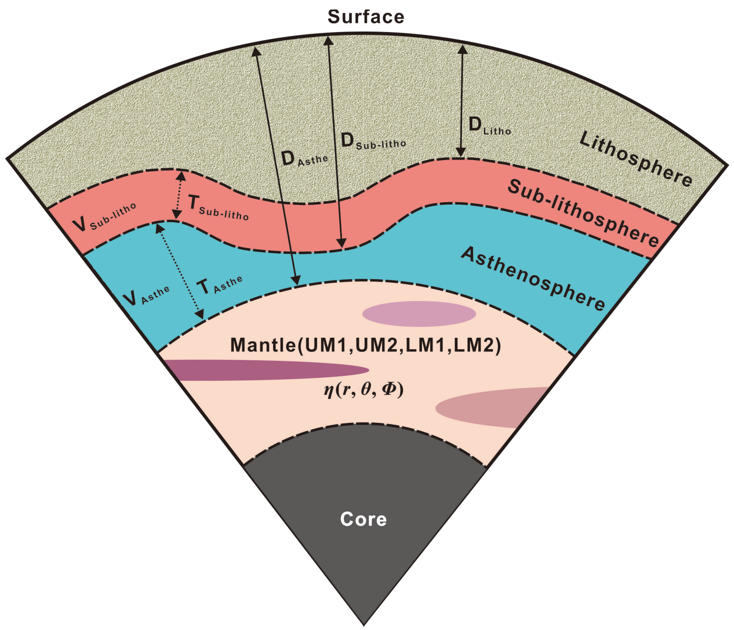
3D

Inputs	Model	Outputs
Earth Model (Density, Elastic properties, Viscosity)	Finite Element Model + Sea Level Equation + Rotational feedback of ocean & ice load	**Sea Levels** Surface Motion Gravity Field Earth Rotation
Ice history model e.g., ICE-6G_C		GIA Stress evolution

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

3D Viscosity Structure | Background 1D Viscosity | Lateral Viscosity Perturbation

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

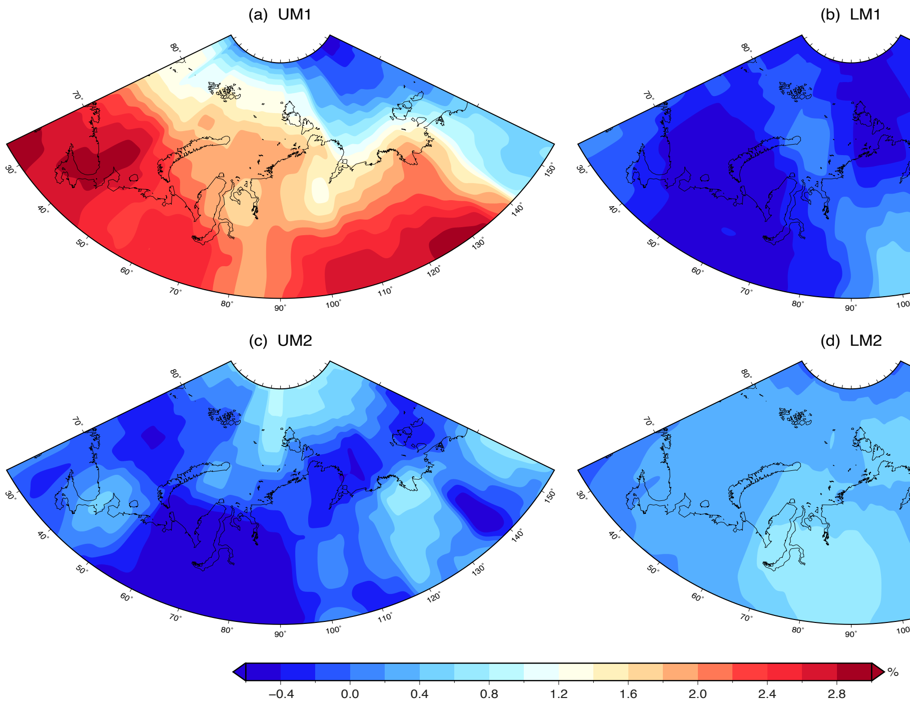


$$\log_{10}[\Delta\eta(r,\theta,\phi)] = K(R,p,T_0,E^*,V^*)\frac{\delta v_s}{v_s}\beta$$

Lateral Viscosity Perturbation

$\frac{\delta v_s}{v_s}$: Lateral shear velocity anomaly

$\beta \in [0,1]$, two different β values in the UM (β_{UM}) and LM (β_{LM}) are used.



Maps showing the $\frac{\delta v_s}{v_s}$ at four depth ranges in the mantle from seismic tomography model TX2011.

-- Karato, 2008; Li et al., 2022

RSL misfit χ-statistics

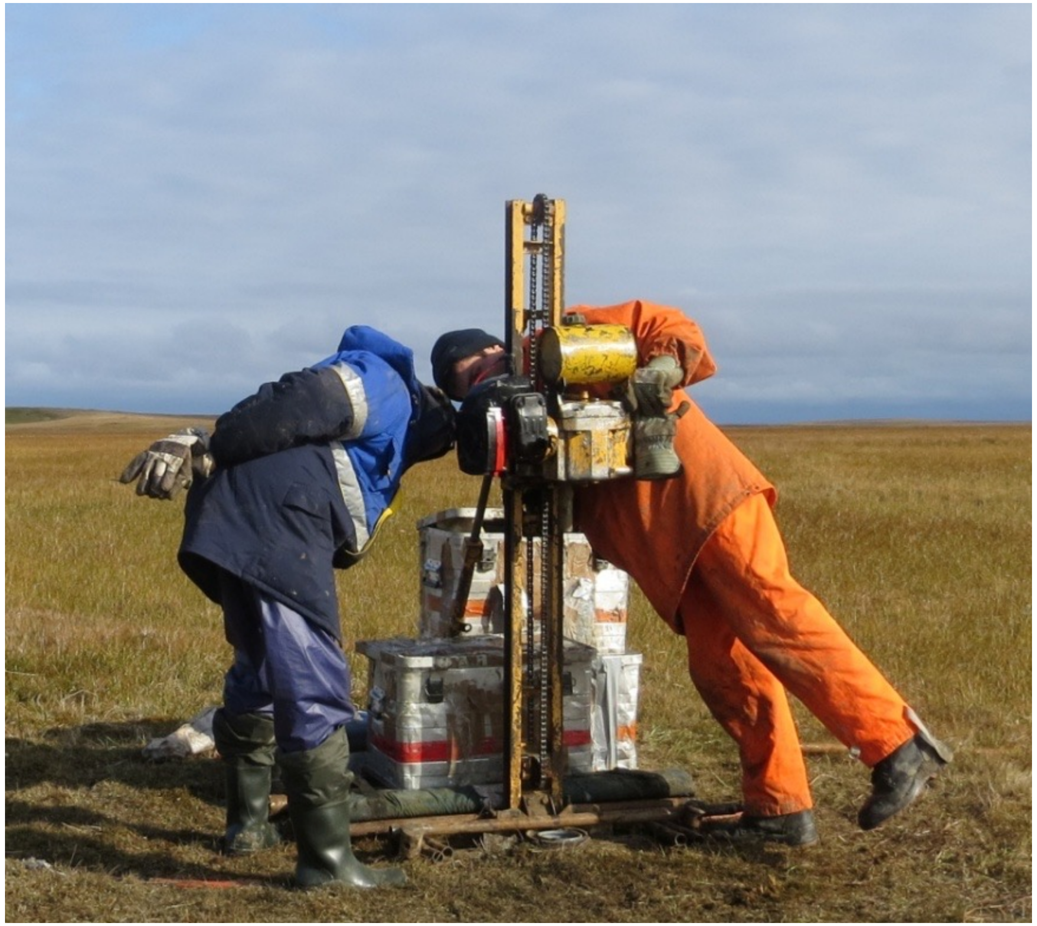
Calculate the χ-statistics to quantify the misfit between predictions and observations of RSL :

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

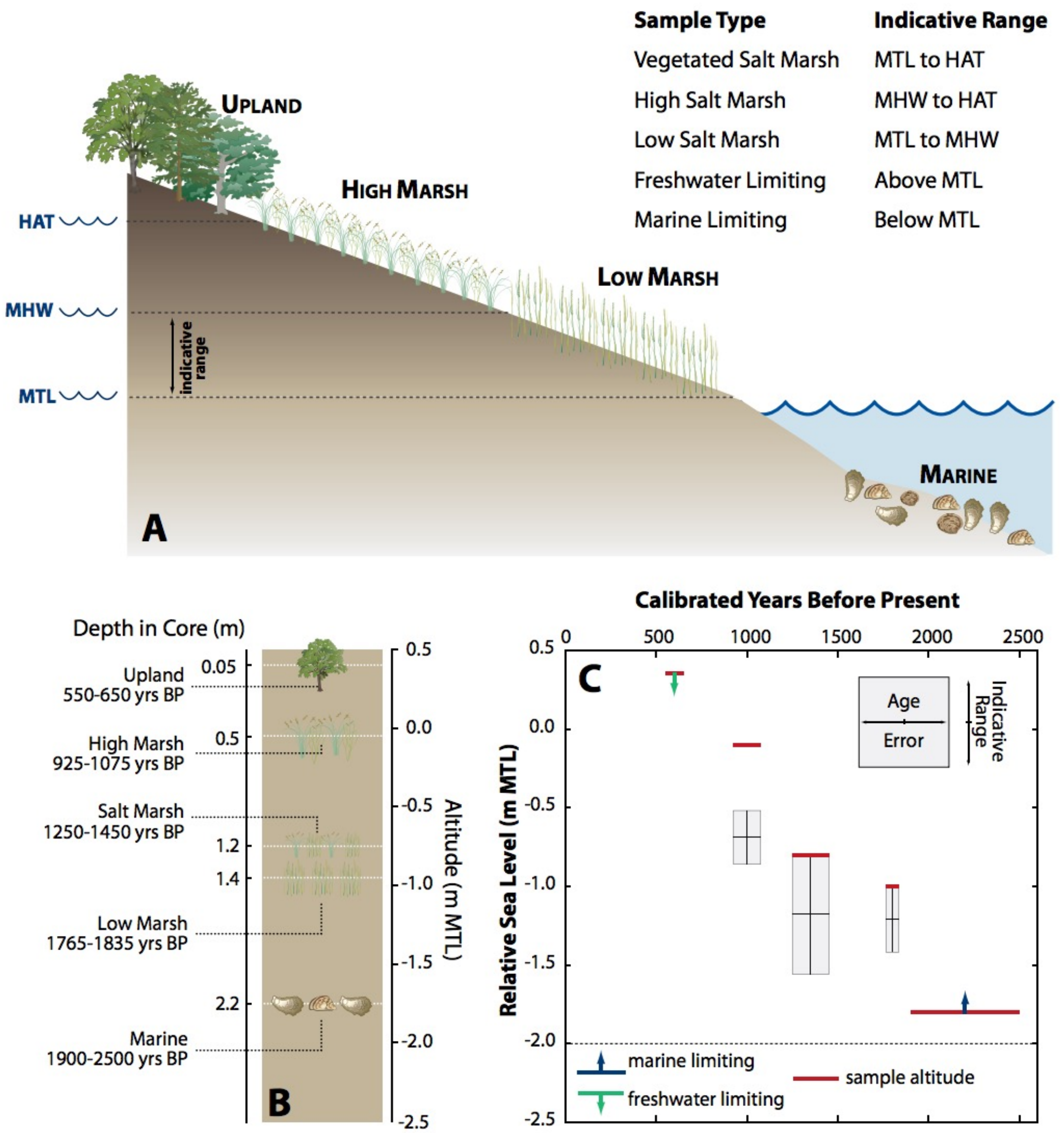
N: number of data.
o_i: ith observation with uncertainty Δo_i.
$p_i(m_j)$: the ith prediction for model m_j.
t: account for time uncertainty Δt.
$\left[\frac{o_i - p_i(m_j)}{\Delta o_i}\right](t)$: minimising $\left[\frac{o_i - p_i(m_j)}{\Delta o_i}\right]$.

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

Fieldwork in the Arctic

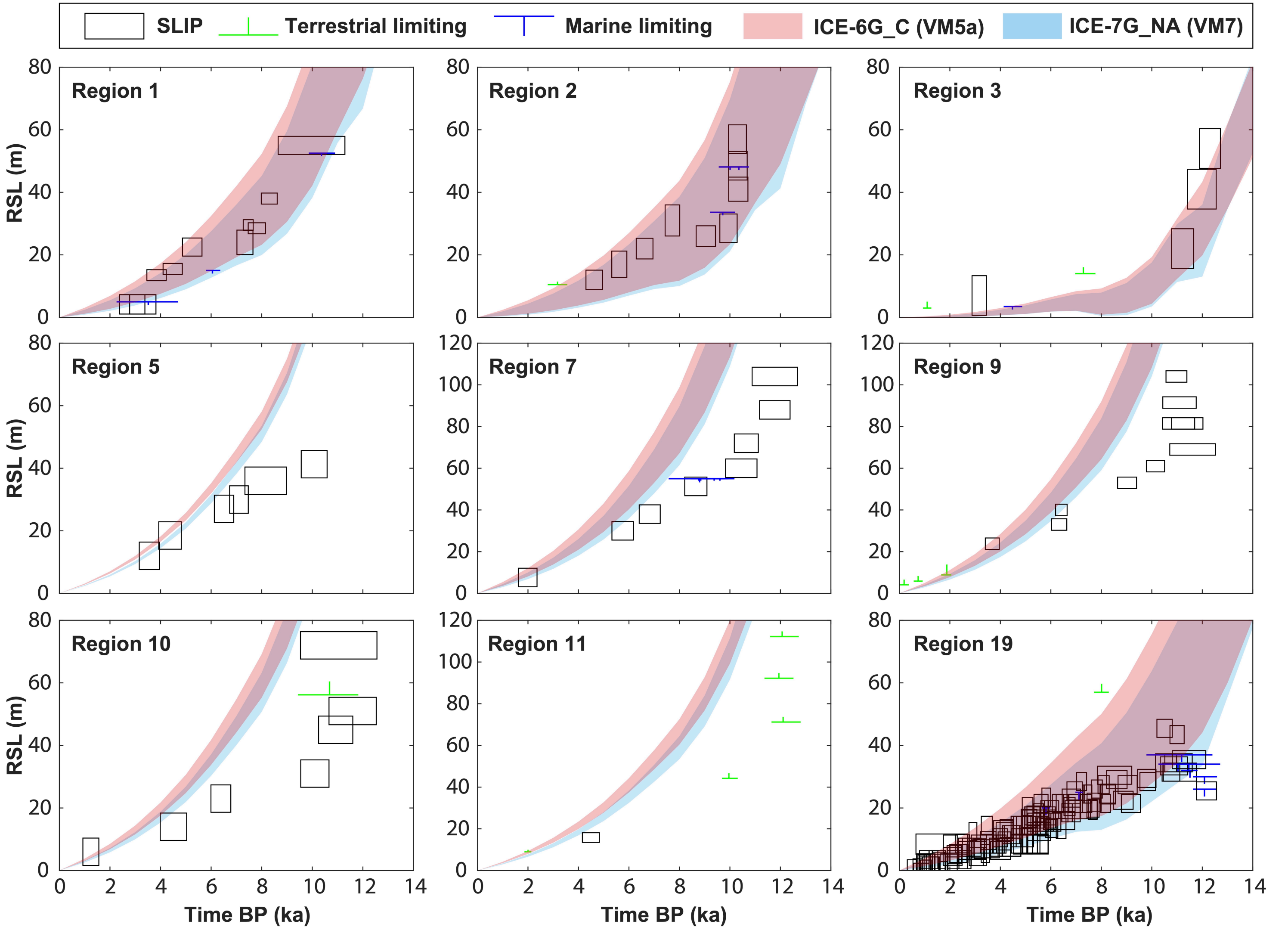


Sea level reconstruction

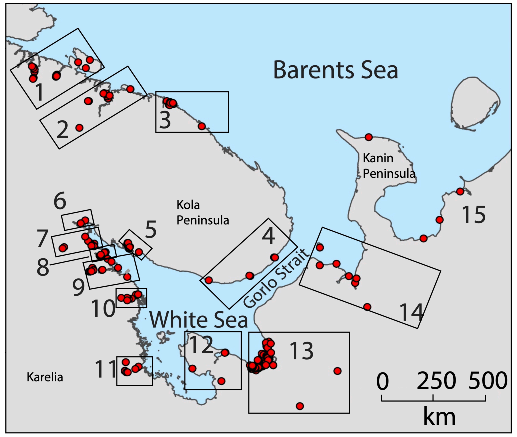


- Sea-level index points (SLIPs): Altitude and indicative meaning constrain former RSL by: RSL= Elevation – RWL.
- Marine limiting: Below MTL, so the RSL should be above the marine limiting data.
- Terrestrial (freshwater) limiting: Above MTL, so the RSL should be below the terrestrial limiting data.

-- Shennan & Horton, 2002; Englehart & Horton, 2012



RSL predictions from 1D GIA models ICE-6G_C (VM5a) and ICE-7G_NA (VM7) at 9 selected regions compared with deglacial RSL data.



- The RSL misfit statistics for ICE-6G_C (VM5a) and ICE-7G_NA (VM7) are 5.23 and 4.53, respectively.
- We attribute the better fit of ICE-7G_NA (VM7) to the Earth model change from VM5a to VM7.
- Both ICE-6G_C (VM5a) and ICE-7G_NA (VM7) show notable misfits (up to 53 m at 10 ka BP) in the White Sea region (region 5).

-- Li et al., 2022

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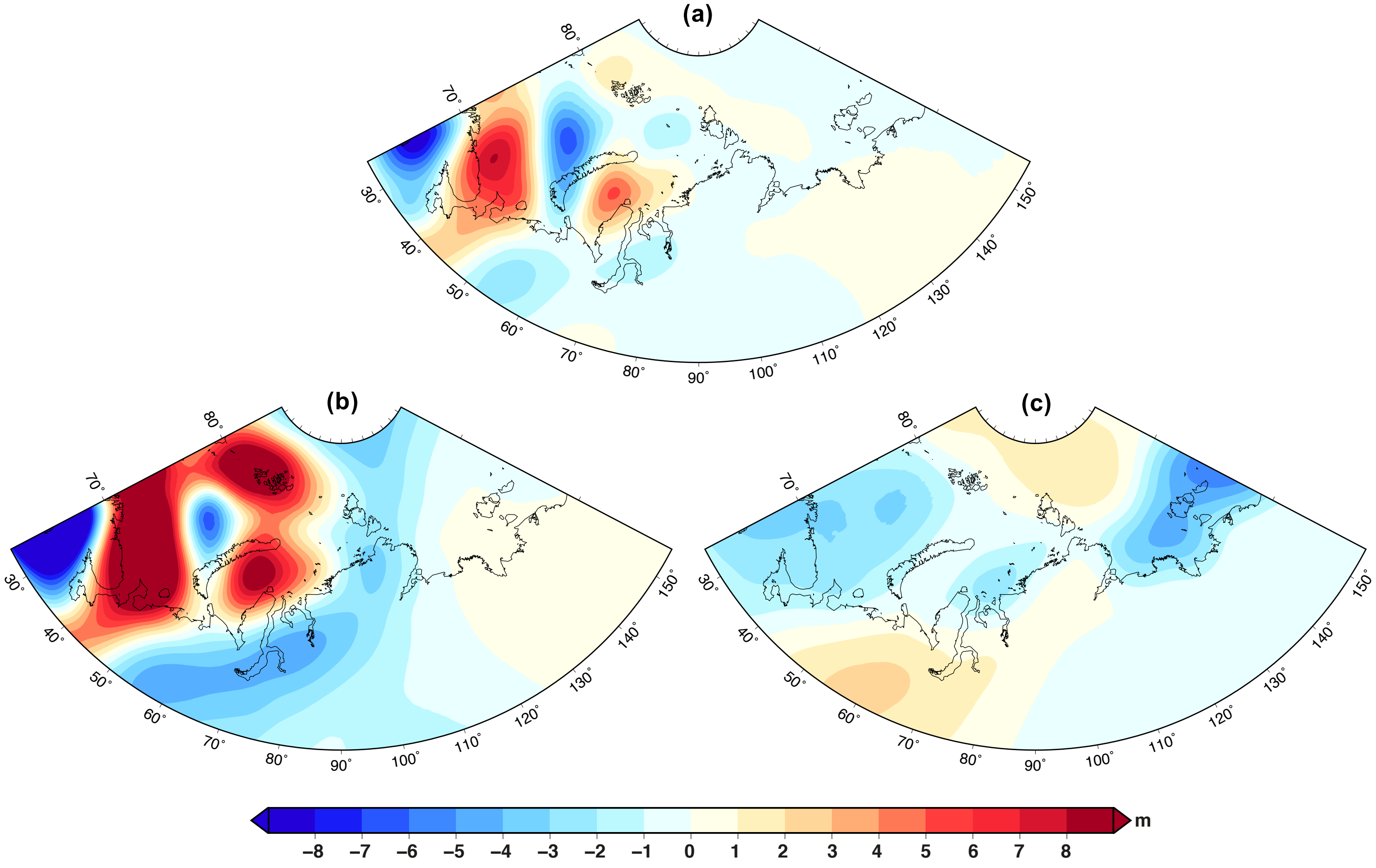
RSL sensitivity to 3D parameters

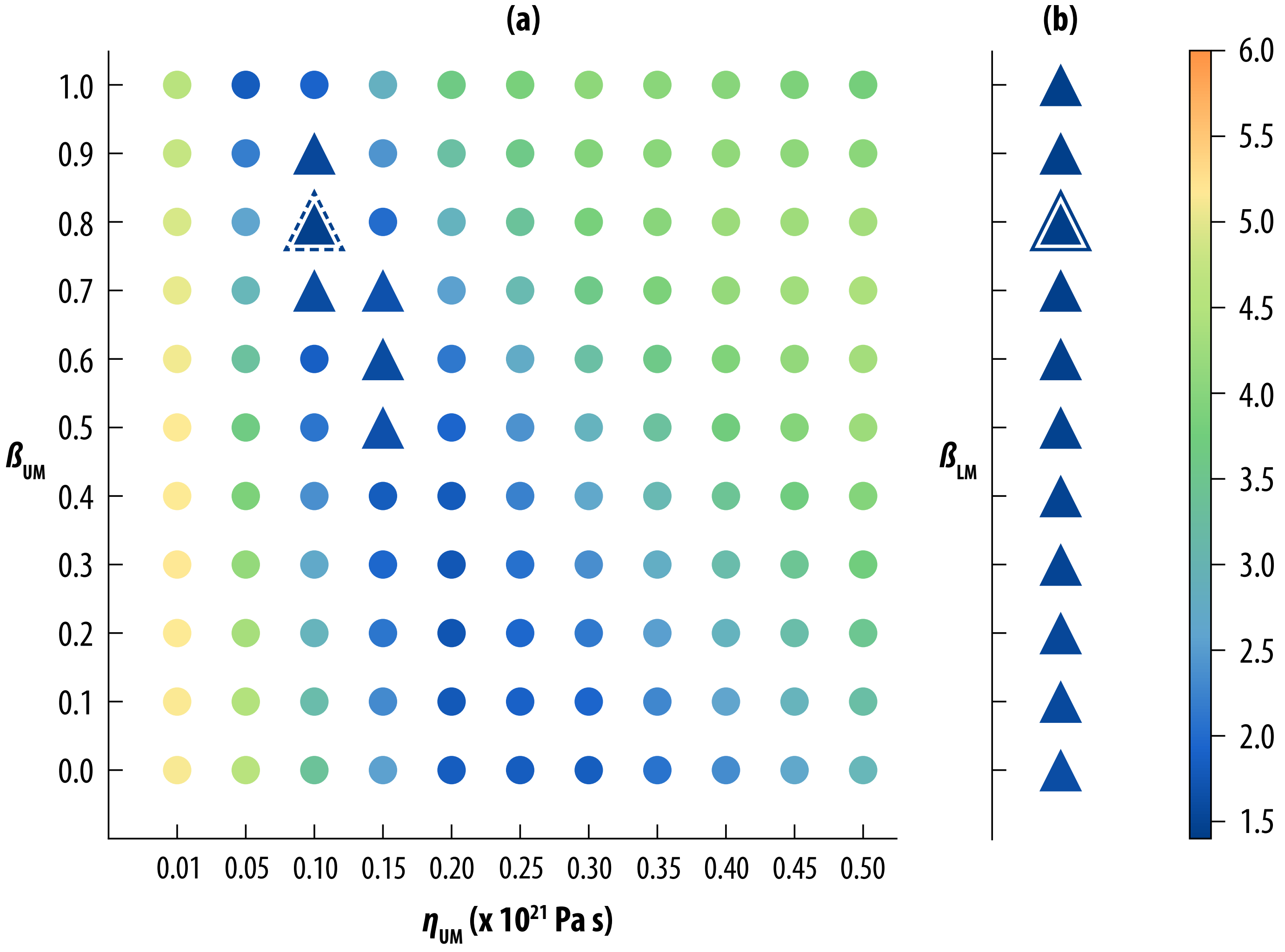


- RSL in the western part is sensitive to lateral thickness varying lithosphere and 3D viscosity structure in the upper mantel.
- RSL is less sensitive to the 3D viscosity structure in the lower mantle.

RSL sensitivity to (a) laterally varying lithosphere and 3D viscosity structures in (b) the upper mantle and (c) the lower mantle at 4 ka BP.

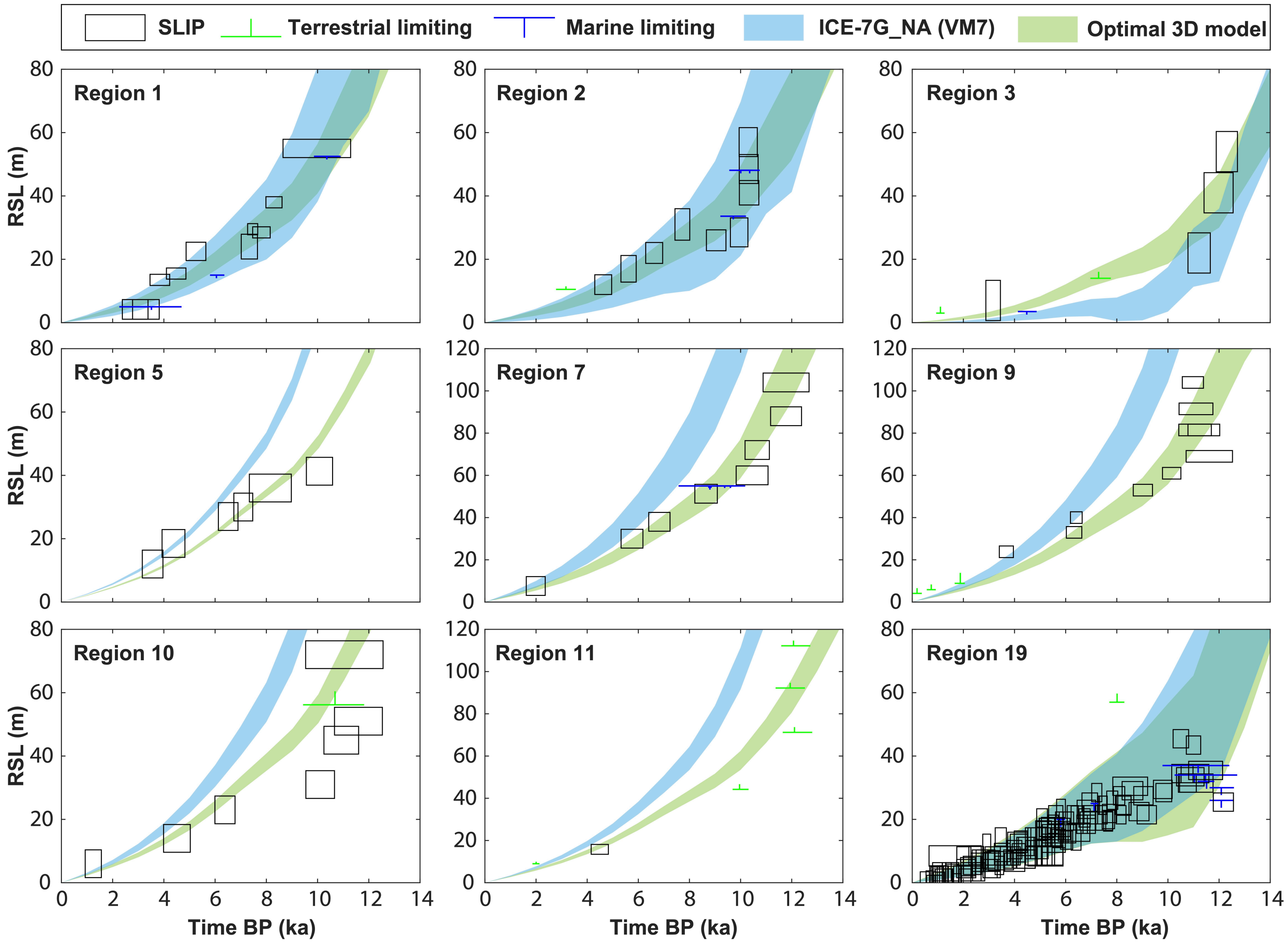
-- Li et al., 2022

The optimal 3D GIA model

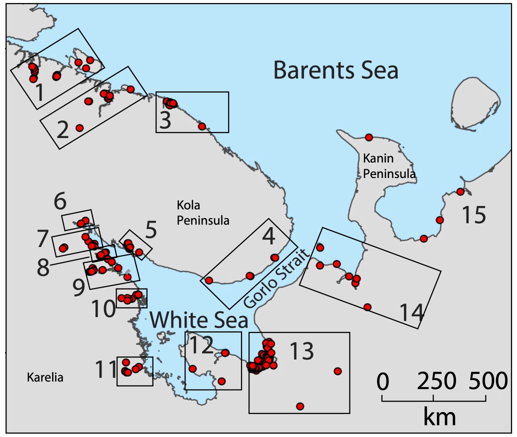


(a) RSL misfit χ-statistics with varying upper mantle background viscosity (η_{UM}) and scaling factor (β_{UM}). The triangle with dashed outline in (a) represents the smallest χ in (a). (b) χ statistics with varying scaling factor in the lower mantle (β_{LM}) fixed with the optimal parameters of the triangle with dashed outline in (a) in the upper mantle. The triangle with solid outline in (b) represents the smallest χ in (b).

-- Li et al., 2022



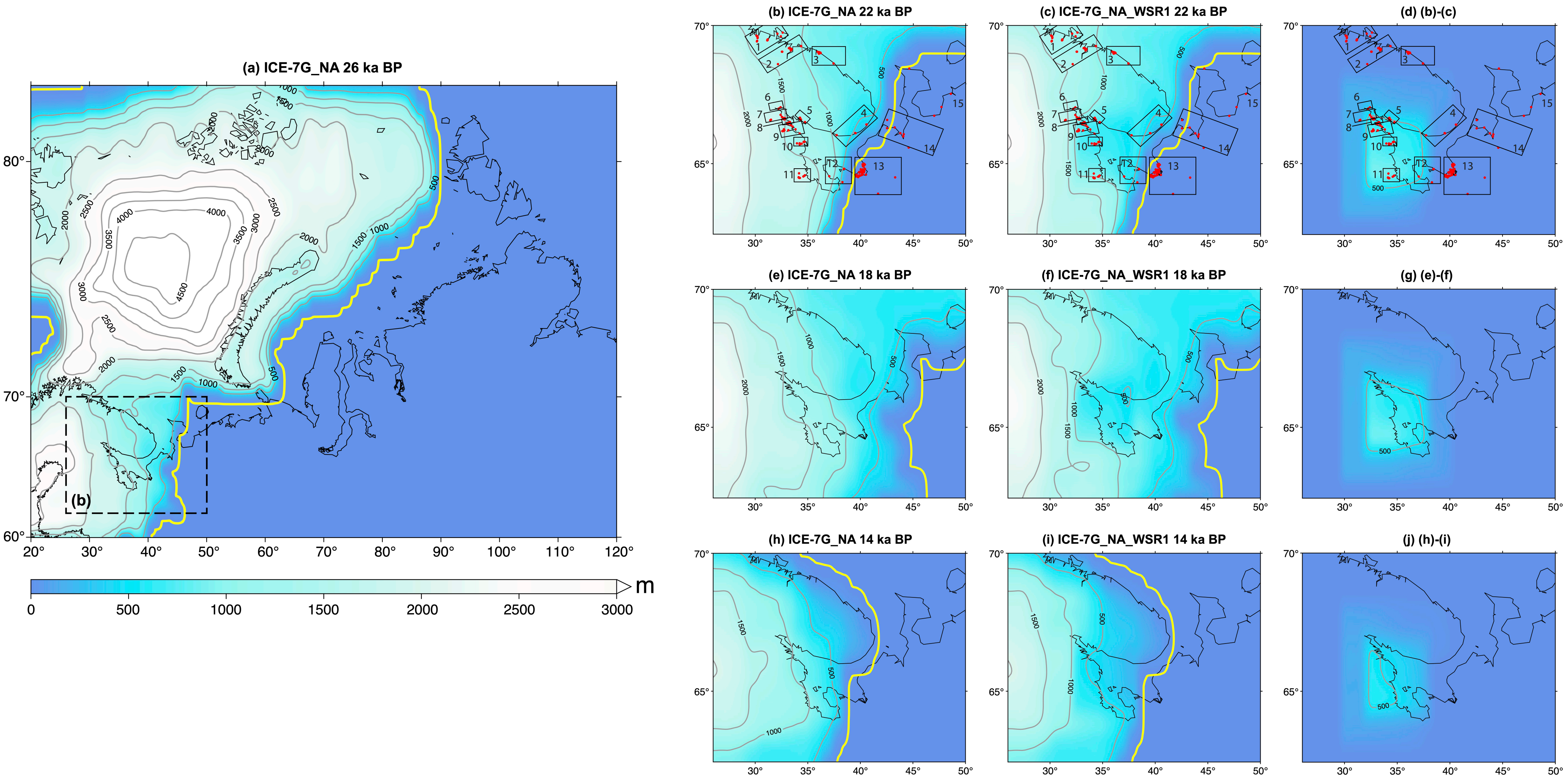
RSL predictions from 1D GIA model ICE-6G_C (VM5a) and the optimal 3D model at 9 selected regions compared with deglacial RSL data.



- The optimal 3D model retains the good fits 1D models achieved along the southern coast of Barents Sea and around the Franz-Josef-Land.
- The optimal 3D model significantly improves the fit around the White Sea, where 1D models show notable misfits.
- The remaining misfits imply that ICE-6G_C around White Sea needs to be refined.

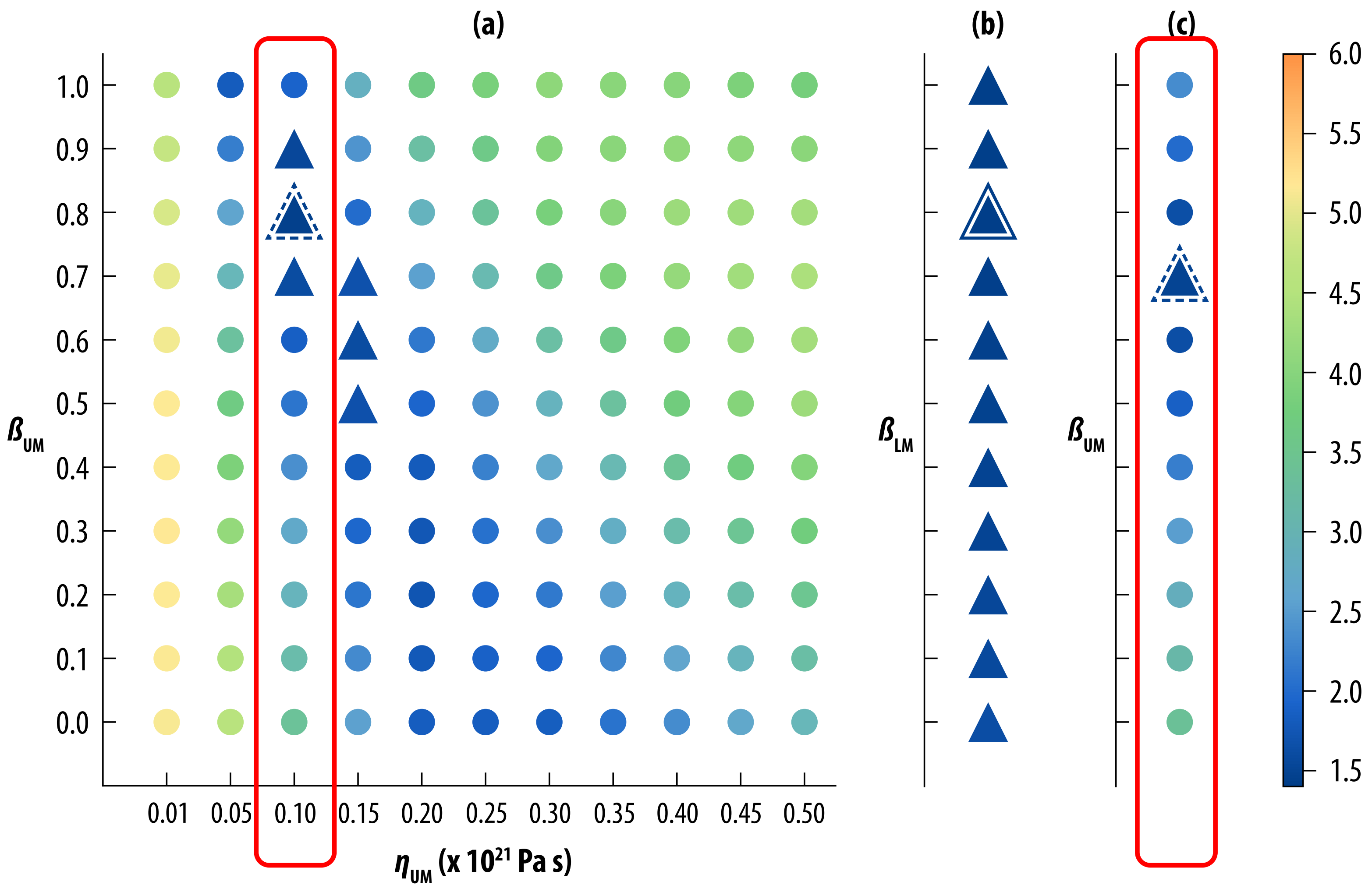
-- Li et al., 2022

ICE model modification



-- Li et al., 2022

The optimal 3D model with modified ice model



(a) RSL misfit χ-statistics with varying upper mantle background viscosity (η_{UM}) and scaling factor (β_{UM}). The triangle with dashed outline in (a) represents the smallest χ in (a). (b) χ statistics with varying scaling factor in the lower mantle (β_{LM}) fixed with the optimal parameters of the triangle with dashed outline in (a) in the upper mantle. The triangle with solid outline in (b) represents the smallest χ in (b). (c) χ statistics with varying scaling factor (β_{UM}) in the upper mantle with $\eta_{UM} = 0.1 \times 10^{21}$ Pa s and $\beta_{LM} = 0.8$ when fixed with the modified ice model. The triangle with dashed outline in (c) represents the smallest χ in (c).

-- Li et al., 2022

Summary

The ICE-6G_C (VM5a) and ICE-7G (VM7) 1D models show notable misfits in several regions (e.g. White Sea) where the RSL histories are well-constrained.

The 3D GIA models (e.g. HetM_0.1_0.8_0.8_L140) retain the good fits achieved by 1D models and significantly improve the fits in White Sea region. Local modification of the ice history in the White Sea region decreases the optimal β_{UM} by 13% from 0.8 to 0.7.

There is a slight 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.

RSL in the western part is more sensitive to lateral lithospheric thickness variation and 3D upper mantle, whereas RSL is less sensitive to 3D lower mantle.

-- Li, T., Khan, N. S., Baranskaya, A. V., Shaw, T. A., Peltier, W. R., Stuhne, G. R., ... & Horton, B. P. (2022). Influence of 3D Earth Structure on Glacial Isostatic Adjustment in the Russian Arctic. Journal of Geophysical Research: Solid Earth, 127(3), e2021JB023631.

Thank You!

Q&A