3D Variations in Viscosity Reconcile the Strength of the Lower Mantle Inferred from Glacial Isostatic Adjustment and Mantle Convection

A. Bellas-Manley, K. Kang, T.W. Becker, & R.S. Nerem

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Background

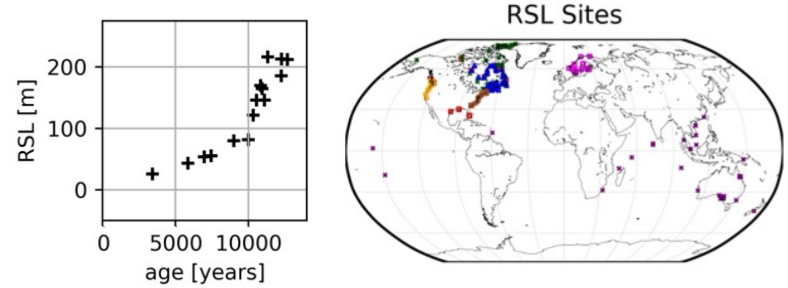
Glacial isostatic adjustment (GIA) is the solid Earth response to the last ice age, which is constrained by observations of

a) **relative sea level change at paleoshorelines (e.g., RSL records),**

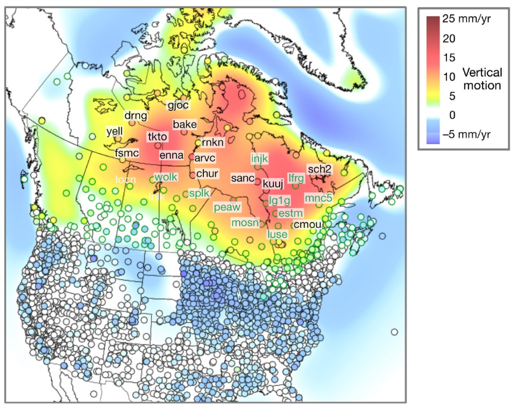
b) **present-day uplift (GNSS)**

c) changes in oblateness, $\dot{J}_2$ (SLR), and

d) polar motion (IERS)



RSL at a site in North America was much higher 10000 years ago because the land was depressed



Present-day snapshot of predicted and observed uplift rates (Argus et al., 2021)

Motivation

1. Studies of GIA indicate that present-day uplift rates require a *weak** lower mantle

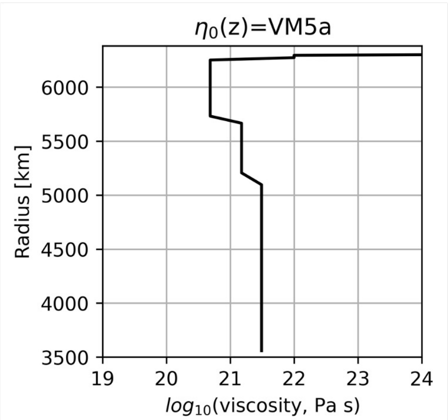
**6x more viscous than upper mantle*

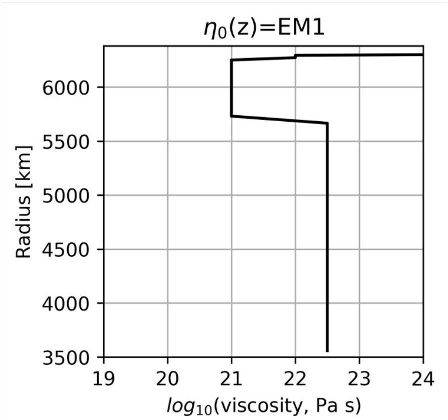
Cathles, 1971; *Peltier et al.*, 2015

2. Studies of mantle circulation and seismic tomography indicate that the static geoid requires a *strong** lower mantle

**30-100x more viscous than upper mantle*

Hager, 1984; *Mao & Zhong*, 2021



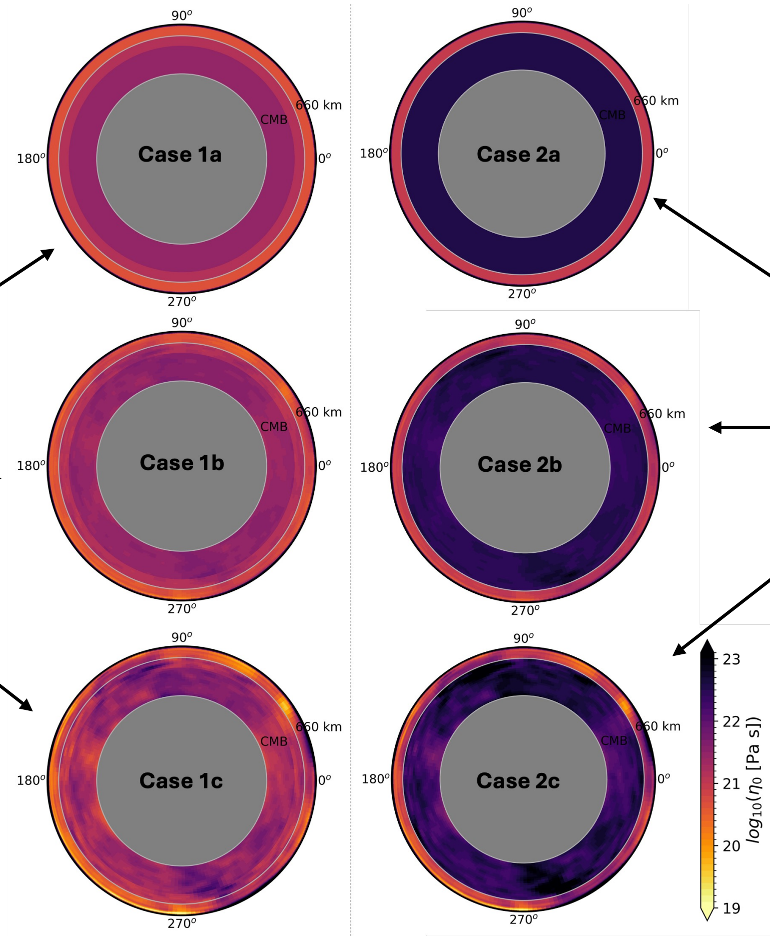


Can accounting for 3D viscosity in GIA models reconcile this discrepancy?

6 Models

Compute the GIA response of 6 viscoelastic Earth models to ICE-6G

Equatorial slice of the viscosity field



VM5a

VM5a with moderate LVVs

VM5a with strong LVVs

EM1

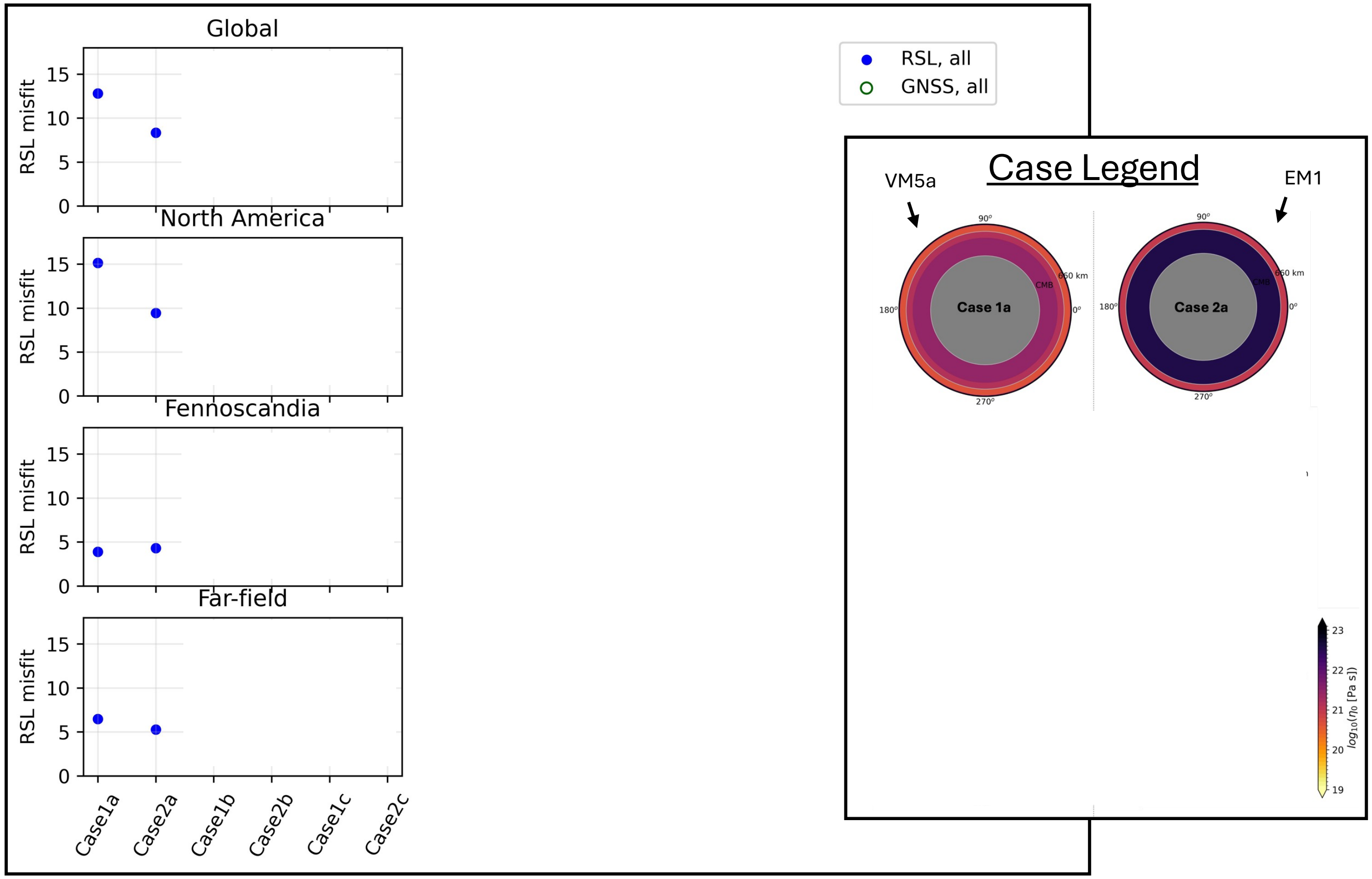
EM1 with moderate LVVs

EM1 with strong LVVs

**LVVs = lateral viscosity variations*

Results

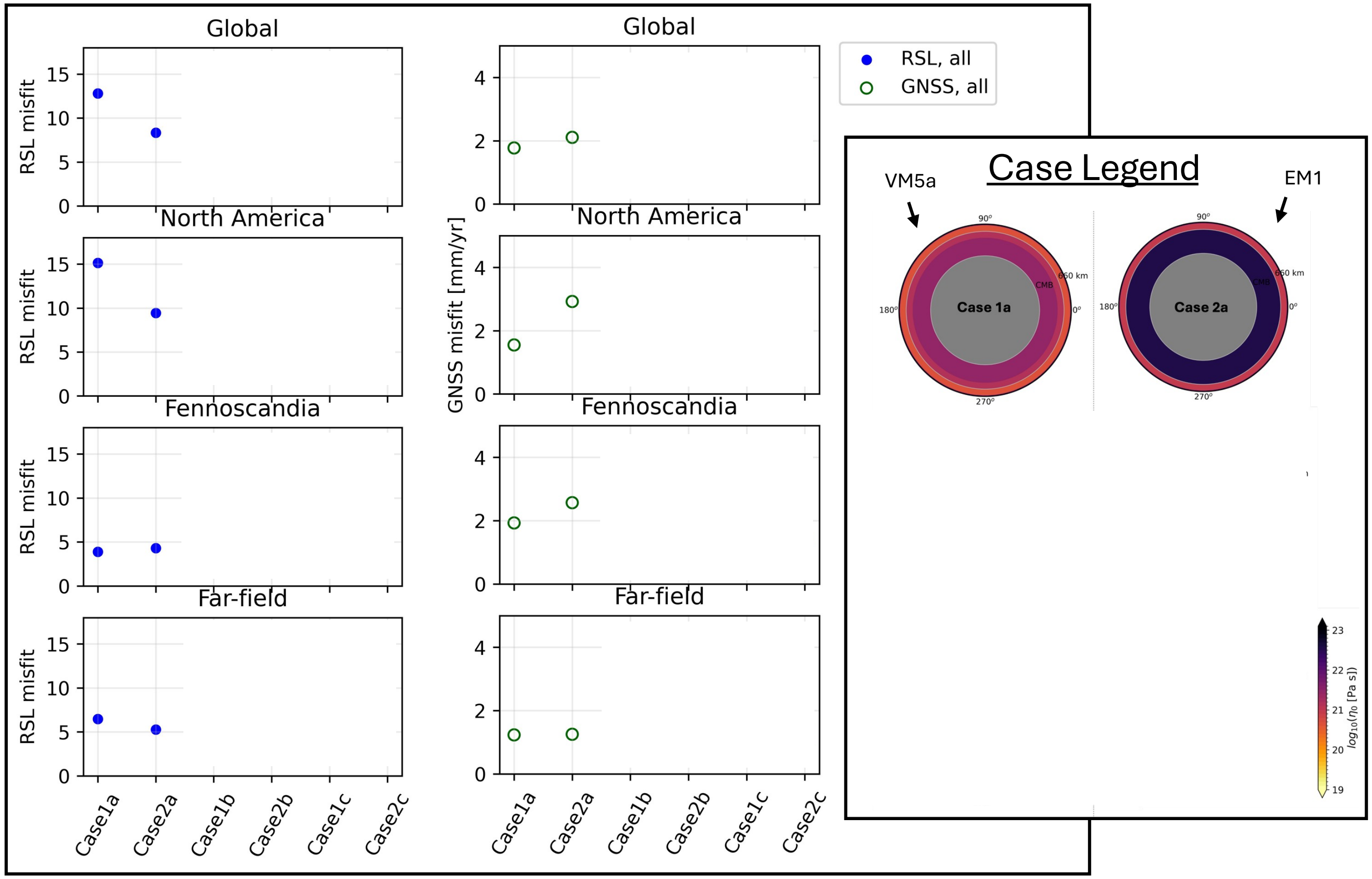
1. The misfit to global RSL records is reduced by ~40% for models with a strong lower mantle vs. those with a weak lower mantle like VM5a



*RSL records from Peltier et al. (2015), Lambeck et al. (2017) Engelhart et al. (2012, 2015), Vacchi et al. (2018)
*GNSS uplift from Hammond et al (2016), Schumacher et al. (2018), Argus et al. (2021)

Results

1. The misfit to global RSL records is reduced by ~40% for models with a strong lower mantle vs. those with a weak lower mantle like VM5a
2. If LVVs are neglected or moderate, then a strong lower mantle significantly degrades the fit to GNSS uplift rates (especially in North America)



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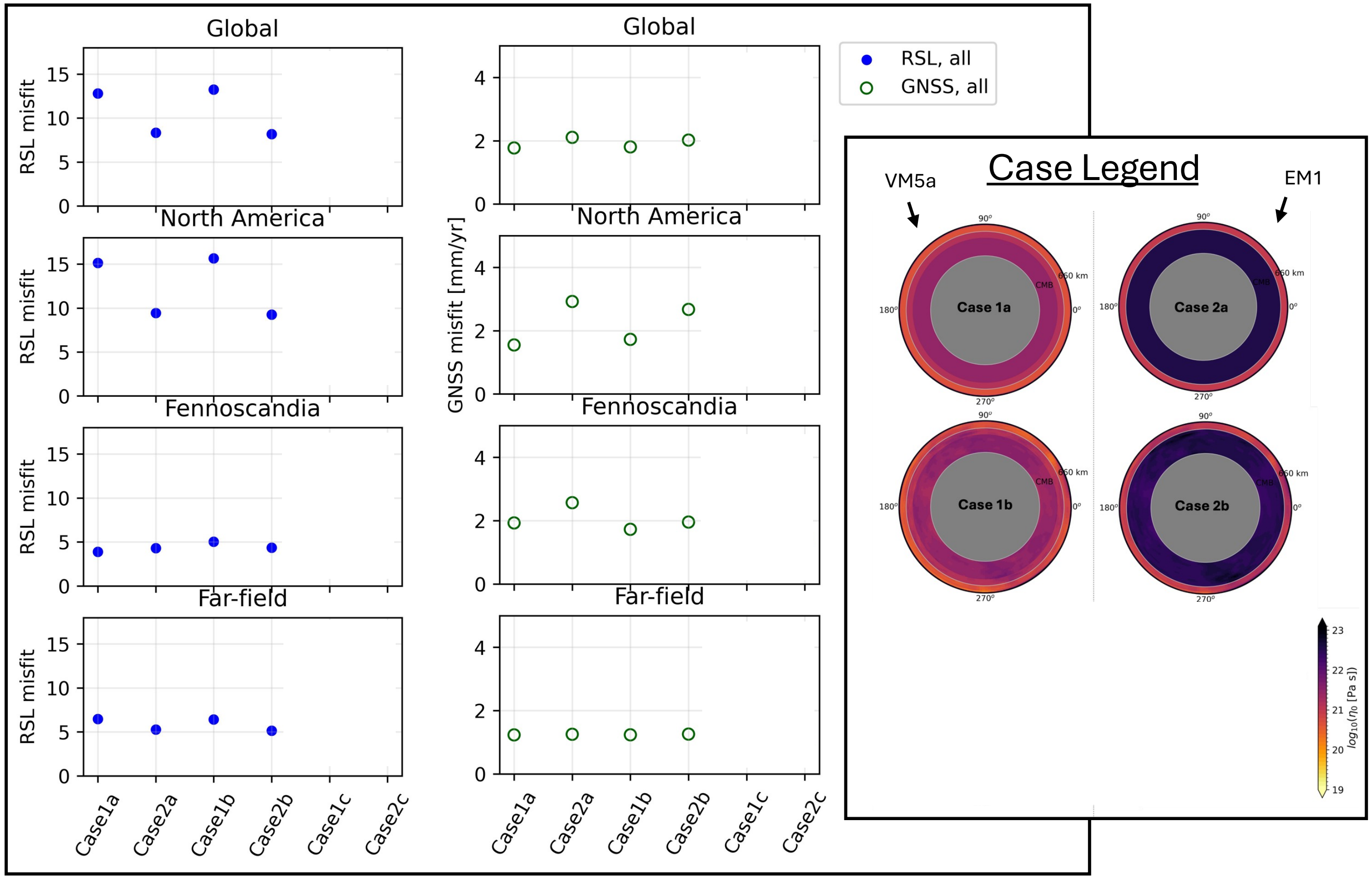

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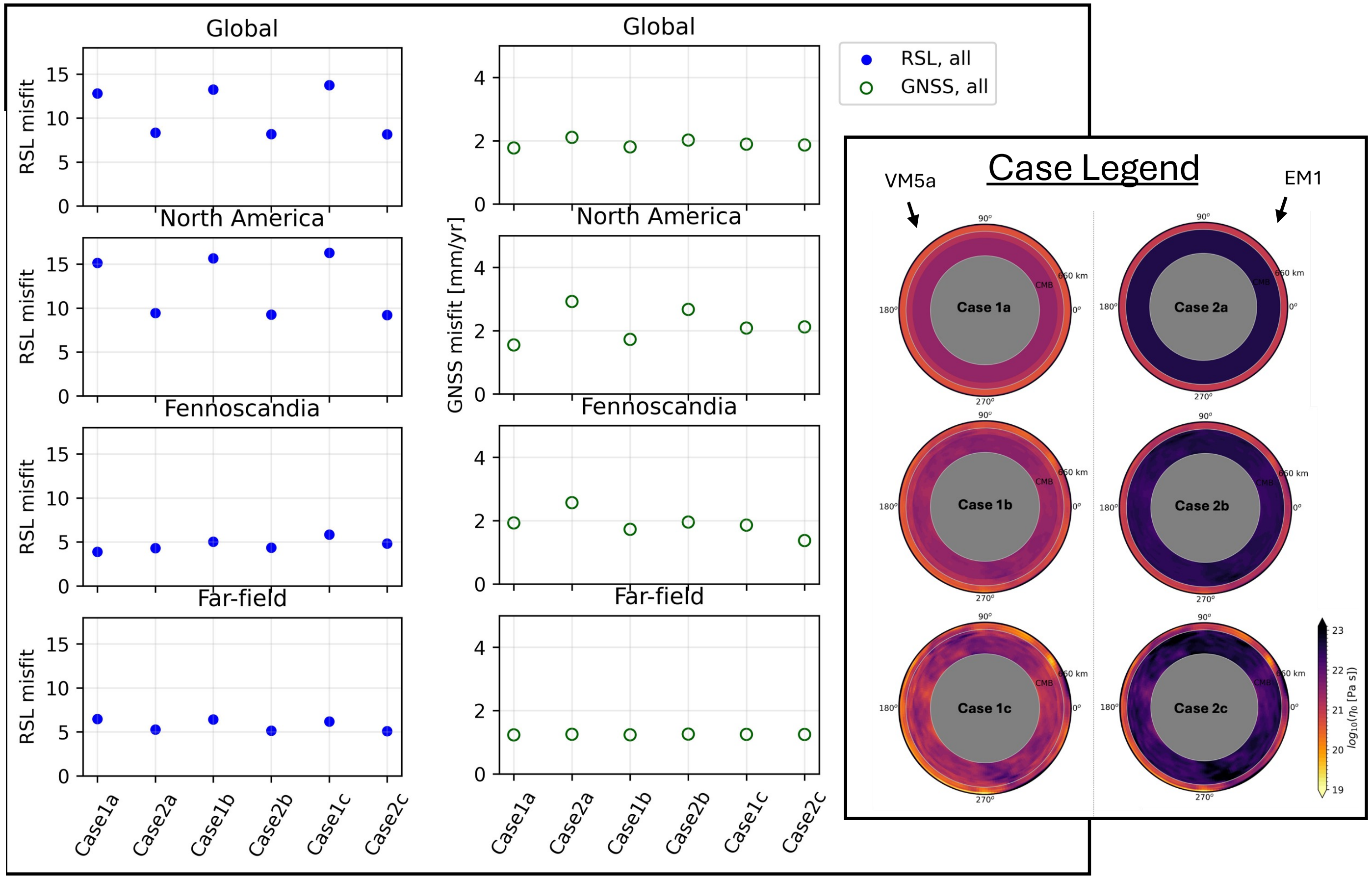
Results

1. The misfit to global RSL records is reduced by ~40% for models with a strong lower mantle vs. those with a weak lower mantle like VM5a
2. If LVVs are neglected or moderate, then a strong lower mantle significantly degrades the fit to GNSS uplift rates (especially in North America)
3. However, the GNSS-uplift rate misfit becomes ~insensitive to lower mantle viscosity if LVVs are strong

→This means the misfit to RSL records is significantly reduced while the misfit to GNSS is ~unchanged for a strong versus weak lower mantle, when LVVs are strong



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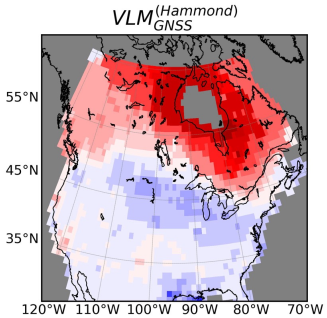
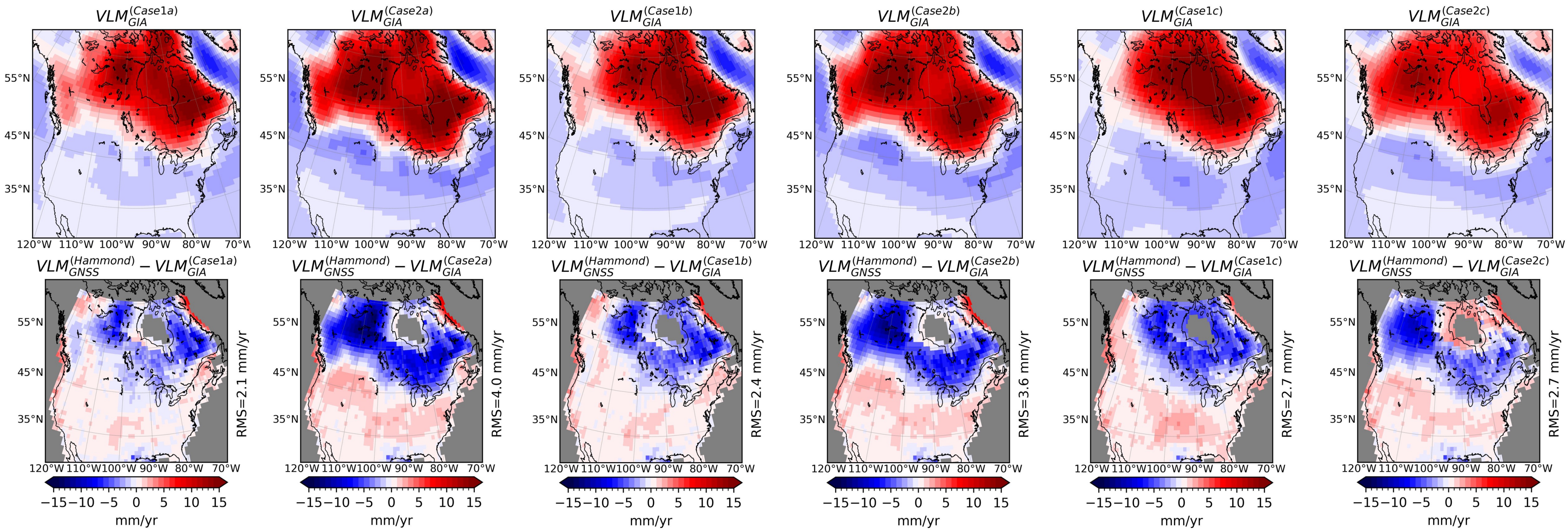


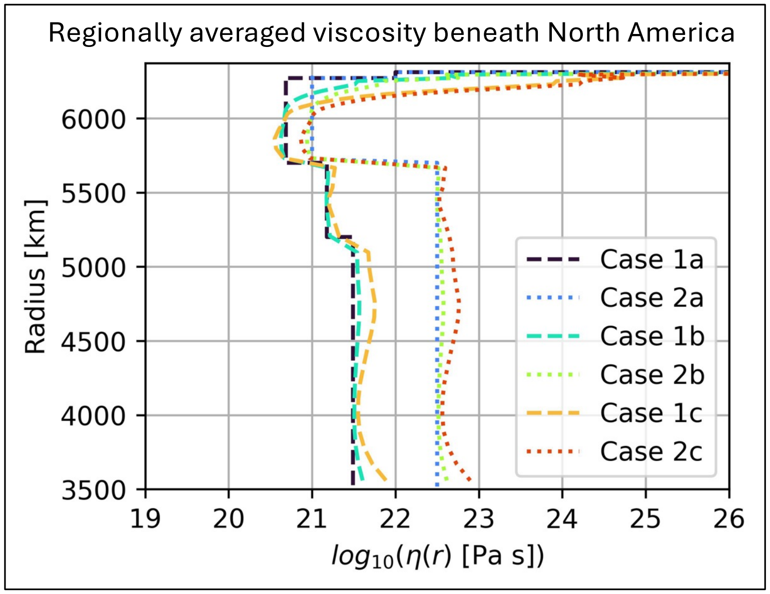
Regional trade-off in the North American uplift rate misfit

- The **regional** misfit to GNSS uplift rates increases by 30% from Case 1a (first column) to Case 2c (last column)
- However, Case 1a completely ignores LVVs
- Compared to Case 1b (third column) and Case 1c (fifth column) with moderate and strong LVVs, respectively, the misfit increases by < 15%
- This suggests that a weak lower mantle is not necessarily preferred when LVVs are accounted for



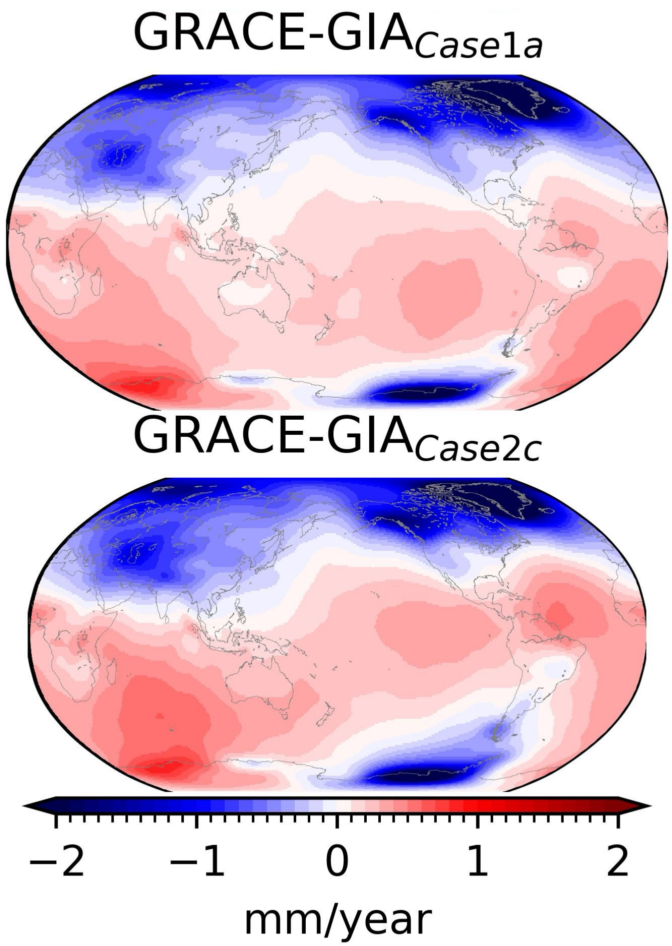
Why do strong LVVs make the misfit to GNSS insensitive to lower mantle viscosity?

- Strong LVVs produce strong variations in lithospheric thickness (T_e)
- Case 1c (dashed orange) and Case 2c (dotted red)
  - produce equivalent misfits to GNSS-uplift
  - have viscosity profiles that differ below ~185 km depth, but
  - converge to equivalent viscosity profiles at depths < 185 km (i.e., in the lithosphere)
- This suggests that accounting for lateral variations in T_e
  - has a strong influence on the predicted present-day uplift rates, and
  - makes the GNSS-misfit insensitive to lower mantle viscosity



Effect on GRACE data

- We show the effect on the geoid rate from GRACE for GIA based on the new preferred Case 2c compared to the canonical model Case 1a
- The result may have implications for resolving the **GMSL budget misclosure problem** (see my GFOSTM talk from 2023)



$\dot{J}_2$

- We recommend that the target value of $\dot{J}_2$ driven by GIA is -4.1×10^{-11} per year based on
  - The early portion (1976-1992) of the satellite laser ranging time series (Loomis et al., 2025), and
  - Glacier mass loss (Rounce et al., 2023)
- $\dot{J}_2$ from Case 1a is -3.2×10^{-11} per year
- $\dot{J}_2$ from Case 2c is -5.0×10^{-11} per year
- Both differ from the target value by ~20%

Conclusions

- The weak lower mantle inferred from GIA models can be reconciled with the strong lower mantle inferred from mantle circulation models by accounting for **3D viscosity**
- By increasing the lower mantle viscosity and including strong lateral viscosity variations, we can (compared to VM5a)
  - reduce the misfit to global RSL records by 40% without degrading the misfit to global GNSS uplift rates, and
  - fit $\dot{J}_2$ equally well
- While regional tradeoffs arise (uplift in North America), we suggest these may be mitigated with additional model refinement