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

A. Bellas-Manley[1], K. Kang[2], T. W. Becker[2,3,4], and R. S. Nerem[1,5]

[1]Colorado Center for Astrodynamics Research, Department of Aerospace Engineering Sciences, University of Colorado Boulder, Boulder, CO, USA, [2]Institute for Geophysics, Jackson School of Geosciences, The University of Texas at Austin, Austin, TX, USA, [3]Department of Earth and Planetary Sciences, Jackson School of Geosciences, The University of Texas at Austin, Austin, TX, USA, [4]Oden Institute for Computational Engineering & Sciences, The University of Texas at Austin, Austin, TX, USA, [5]Cooperative Institute for Research in Environmental Sciences, University of Colorado Boulder, Boulder, CO, USA

Key Points:

- Considering 3D-viscosity in models of glacial isostatic adjustment (GIA) reconciles a persistent discrepancy in mantle viscosity inferred from GIA and mantle convection
- Models of GIA with 3D-viscosity can accommodate an upper/lower mantle viscosity contrast consistent with mantle convection models ($\Delta\eta \sim 30$)
- A GIA model with 3D-viscosity and $\Delta\eta \sim 30$ significantly improves the fit to a range of observational constraints compared to previous models

Supporting Information:

Supporting Information may be found in the online version of this article.

Correspondence to:

A. Bellas-Manley,
ashley.bellas@colorado.edu

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Author Contributions:

Conceptualization: A. Bellas-Manley
Data curation: K. Kang
Formal analysis: A. Bellas-Manley
Funding acquisition: T. W. Becker, R. S. Nerem
Investigation: A. Bellas-Manley
Methodology: A. Bellas-Manley
Project administration: R. S. Nerem
Resources: T. W. Becker, R. S. Nerem
Software: A. Bellas-Manley, K. Kang, T. W. Becker
Supervision: T. W. Becker, R. S. Nerem
Validation: K. Kang
Visualization: A. Bellas-Manley

Abstract A widely accepted global model of glacial isostatic adjustment (GIA) is based on ICE-6G ice loading and 1D-viscosity model VM5a, a viscosity profile which remains at odds with mantle convection constraints such as from geoid modeling. We explore 3D-viscosity variations in models of GIA and show that a model with lateral viscosity variations (LVVs) scaled from seismic tomography and lower mantle viscosity compatible with mantle convection constraints (~30 times upper mantle viscosity) significantly reduces the misfit to relative sea level (~40%), $\dot{J}_2$ (60%), and polar motion (75%) while incurring only a small misfit penalty (~5%) for GNSS-uplift compared to VM5a, which has lower mantle viscosity ~6 times upper mantle viscosity. Regional results exhibit additional tradeoffs but indicate that comparable solutions might be found with additional model refinement. The origin of a longstanding disagreement on lower mantle viscosity may thus be resolved by accounting for LVVs in models of GIA.

Plain Language Summary Glacial isostatic adjustment (GIA) is the solid Earth response to the melting of ice sheets since the end of the last ice age, and models of this process are primarily constrained by observations of relative sea level (RSL) and uplift rates from satellite geodesy (GNSS). To fit these observations, GIA studies often assume that the viscosity of the mantle varies with depth only and find that the lower mantle is less than 10 times stronger than the upper mantle. This modest increase is inconsistent with mantle convection constraints which imply that the lower mantle must be stronger (30–100 times more viscous than the upper mantle) to fit observations including the geoid and slab sinking rates. We show that this disagreement can be reconciled if models of GIA are formulated with 3D-viscosity where lateral variations are scaled from seismic tomography. Our preferred new model has a strong lower mantle (30 times upper mantle viscosity), significant lateral viscosity variations, and improves the fit to RSL records (40%), changes in the Earth's oblateness (60%), polar motion rates (75%), and incurs only a small penalty in the misfit to measured crustal uplift rates from GNSS (5%).

1. Introduction

Glacial isostatic adjustment (GIA) is an important global process that interacts with ice sheet dynamics (Gomez et al., 2024; Houriez et al., 2025; Weertman, 1964), glacial cycles (Berends et al., 2021; H. K. Han et al., 2021), lithospheric plate motions (Yuan & Zhong, 2025), and provides important constraints on absolute mantle viscosity (Cathles, 1975; Haskell, 1935; Mitrovica, 1996). A commonly accepted model of GIA is based on the ice loading history ICE-6G and the 1D-radial mantle viscosity profile VM5a (Argus et al., 2014; Peltier et al., 2015). The ICE-6G/VM5a GIA model is widely used to correct data including satellite altimeter measurements of sea surface height (Beckley et al., 2017), uplift from GNSS (N. Lau et al., 2020), time-variable gravity from GRACE and GRACE-FO (Landerer et al., 2020), and changes in Earth oblateness from satellite laser ranging (Nerem & Wahr, 2011). GIA models thus have a significant impact on studies of hydrology, ice mass loss, sea level, and global change.

The viscosity of the lower mantle matters for such models. Early GIA calculations were interpreted to preclude a highly viscous lower mantle based on crustal uplift rates which require lower mantle viscosity ~10^{21}–10^{22} Pa s,

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Writing – review & editing: A. Bellas-Manley, K. Kang, T. W. Becker, R. S. Nerem

equivalent to a viscosity contrast $\Delta\eta < 10$ times that of the upper mantle (Cathles, 1975; Peltier & Andrews, 1976). However, the observed static geoid can be reproduced by mantle convection models with density inferred from seismic tomography only if $\Delta\eta = 30$–100 (Hager, 1984; Hager & Richards, 1989), an inference confirmed by subsequent inversions (e.g., King, 1995; Panasyuk & Hager, 2000). Models of mantle convection likewise indicate a preference for slab slowdown and accumulated slab material below reconstructed convergent margins consistent with a similar increase in lower mantle viscosity (e.g., Lithgow-Bertelloni & Richards, 1998; Ricard et al., 1993; Steinberger et al., 2010). Such strong lower mantle viscosity also reproduces a range of other dynamical constraints including supercontinent-cycles, and true polar wander (e.g., Bunge et al., 1996; Z. X. Li & Zhong, 2009; Mao & Zhong, 2021; Rolf et al., 2018; Steinberger & O'Connell, 2002).

That $\Delta\eta$ inferred from GIA is significantly lower than $\Delta\eta$ inferred from mantle convection has long been recognized (e.g., S. Han et al., 2024; Yuen et al., 1986). Yet, modern GIA-models continue to favor $\Delta\eta < 10$ (e.g., Peltier, 2004; Peltier et al., 2015) with some important exceptions (e.g., $\Delta\eta \sim 100$, Mitrovica & Forte, 2004; $\Delta\eta \sim 10$–100, H. C. P. Lau et al., 2016; $\Delta\eta \sim 25$, Lambeck et al., 2017; and $\Delta\eta \sim 40$, Caron et al., 2018) and while North American uplift rates have been interpreted to require a weak lower mantle (Argus et al., 2021), such constraints are dependent on ice loading history and the assumption of radial viscosity structure. Indeed, all of the above models rely on spherical symmetry and neglect the effects of lateral variations in mantle viscosity.

Approximating the Earth's viscosity structure as a 1D-profile was necessary to make the GIA problem tractable (e.g., Cathles, 1975; Peltier, 1974). However, mantle viscosity is expected to vary in 3D from laboratory-derived olivine creep laws (e.g., Hirth & Kohlstedt, 2003), tectonic plate motions (Becker, 2006; van Summeren et al., 2012; Zhong, 2001), thermal boundary layer instabilities (van Hunen et al., 2005), and lithospheric thickness variations (Bellas & Zhong, 2021; Burov & Diament, 1995). The importance of lateral viscosity variations (LVVs) to GIA has long been recognized (e.g., A et al., 2013; Kaufmann & Wu, 1998; Latychev et al., 2005; Paulson et al., 2005; Sasgen et al., 2017) and recent studies explored a range of observational constraints and viscosity fields (e.g., Bagge et al., 2021; T. Li et al., 2018, 2020). For example, relative sea level (RSL) records in Fennoscandia are best fit by $\Delta\eta \sim 10$, while those in North America are best fit by $\Delta\eta \sim 30$ (Kang et al., 2025; Kuchar et al., 2019; Parang et al., 2024). Meanwhile, geodetically inferred uplift rates in North America are best-fit by $\Delta\eta \sim 10$ in 1D-viscosity models of GIA with ICE-6G (Argus et al., 2021). Furthermore, different GIA observables are associated with different sensitivity to both viscosity and ice loading history (H. C. P. Lau et al., 2018). Deformation induced by the shorter lengthscale Fennoscandian loading is sensitive to shallower mantle viscosity than North American loading (Mitrovica, 1996). The rate of change in Earth oblateness, $\dot{J}_2$, constrains viscosity at the largest depths but may still be regionally biased (Kim et al., 2022). Thus, differences in viscosity inferred from different methods may stem from an incomplete sampling of the mantle by GIA observations.

We aim to reconcile the persistent discrepancies in bulk mantle viscosity by exploring the effects of 3D viscosity variations in models of GIA, using a range of constraints including RSL records, GNSS-observed crustal uplift, $\dot{J}_2$, and polar motion rates. We show that accounting for 3D-viscosity allows GIA models to accommodate a strong lower mantle ($\Delta\eta \sim 30$), reconciles the discrepancy between lower mantle viscosity inferred from GIA ($\Delta\eta \sim 10$), and mantle convection ($\Delta\eta \sim 30$), as well as that between North American GNSS uplift ($\Delta\eta \sim 10$) and RSL ($\Delta\eta \sim 30$), and improves the fit to global RSL records, $\dot{J}_2$, and polar motion in exchange for a small penalty to the GNSS-uplift misfit compared to VM5a.

2. Observations

We consider four types of observations: RSL records, GNSS-uplift rates, $\dot{J}_2$, and polar motion rates. For RSL, the records span North America, Fennoscandia, and the far-field (i.e., far from the ice sheets of the last glacial maximum) at 192 sites, where a timeseries of RSL at each site is derived from observations spanning thousands of years (Engelhart & Horton, 2012; Engelhart et al., 2015; Lambeck et al., 2017; Peltier et al., 2015; Vacchi et al., 2018) (Figure S1 in Supporting Information S1).

For GNSS-based vertical land motion rates, we use the analyses of (a) Hammond et al. (2016) where uplift rates are interpolated onto a grid that spans all land, (b) Schumacher et al. (2018) where non-GIA sources of vertical motion are removed, and (c) Argus et al. (2021) which includes 146 campaign sites across North America.

We use $\dot{J}_2$ as estimated from satellite laser ranging data (Loomis et al., 2025) and simultaneously fit annual, semi-annual, and linear terms to estimate a total mean $\dot{J}_2$ ($1976 \leq t \leq 1991$) $= -3.1 \pm 0.2 \times 10^{-11}$ yr^{-1}. However, for the GIA-driven component, we estimate an adjusted $\dot{J}_2 = -4.5 \pm 0.5 \times 10^{-11}$ yr^{-1} by calculating the glacier mass loss contribution $\dot{J}_2 = 1.4 \times 10^{-11}$ yr^{-1} between 1980 and 1992 (Rounce et al., 2023) with composite error based on climate variability and tides (0.3×10^{-11} yr^{-1}, Cheng et al., 2013), glaciers (0.4×10^{-11} yr^{-1}, H. C. P. Lau et al., 2016), and formal error (0.2×10^{-11} yr^{-1}, Loomis et al., 2025).

Long term polar motion rates are based on the IERS C01 EOP timeseries from 1900 to 2000 (Vondrak et al., 2010), where $x_p = 0.55$ milliarcseconds/year and $y_p = -2.61$ milliarcseconds/year.

3. Methods

We employ the finite element model CitcomSVE-3.0 (Yuan et al., 2025; Zhong et al., 2022) to compute the viscoelastic response of a self-gravitating, compressible, Maxwellian, 3D-spherical continuum including the effects of sea level change, polar- and center-of-mass-motion (for details, see Supporting Information S1) to ICE-6G (122 ka to present).

3.1. Viscosity

We construct 3D-viscosity fields by scaling the seismic tomographic model S40RTS (Ritsema et al., 2011) to dimensionless temperature following

$$T'(\boldsymbol{r}) = 1 - dT'(\boldsymbol{r}) \tag{1}$$

$$\mathrm{d}T'(\boldsymbol{r}) = \frac{0.035\rho_{\mathrm{PREM}}(r)}{\rho_0}\mathrm{d}v_S(\boldsymbol{r}) \tag{2}$$

where $T'(\boldsymbol{r})$ is dimensionless temperature ($T'(\boldsymbol{r}) = (T(\boldsymbol{r}) - T_0)/(T_1 - T_0)$, $T_0 = 273$ K, $T_1 = 1{,}573$ K), $\mathrm{d}T'(\boldsymbol{r})$ is the dimensionless temperature perturbation, $\boldsymbol{r}$ is position in 3D-spherical geometry, 0.035 is a scaling factor (e.g., Becker, 2006; Panasyuk & Hager, 2000), $\rho_{\mathrm{PREM}}(r)$ is the density profile based on PREM (Dziewonski & Anderson, 1981), $\rho_0 = 3{,}300$ kg/m^3 is the reference mantle density, and $\mathrm{d}v_S(\boldsymbol{r})$ is the seismic velocity perturbation. Viscosity, $\eta(\mathbf{r})$, is estimated following

$$\eta(\boldsymbol{r}) = \eta_0(r)\exp\left(\frac{E'}{T'(\boldsymbol{r}) + T_0{}'} - \frac{E'}{1 + T_0{}'}\right), \tag{3}$$

where $\eta_0(r)$ is the reference viscosity profile, $E' = E/R(T_1 - T_0)$ is the nondimensional activation energy which controls the amplitude of lateral variations in viscosity, R is the universal gas constant, and $T_0{}' = T_0/(T_1 - T_0)$ is the nondimensional surface temperature. We ignore effects from compositional or volatile differences and use Newtonian viscosity for simplicity.

We explore the effects of 1D-radial viscosity ($E = 0$) compared to moderately ($E = 120$ kJ/mol) and strongly temperature-dependent viscosity ($E = 360$ kJ/mol), where the latter values appear appropriate for diffusion and dislocation creep rheology in olivine (e.g., Becker, 2006; Hirth & Kohlstedt, 2003; van Hunen et al., 2005). The reference viscosity profile VM5a has a weak lower mantle ($\Delta\eta = 6.4$) compared to EM1 ($\Delta\eta = 31.5$), where EM1 is consistent with mantle convection studies and produces a good fit to North American RSL (Kang et al., 2025). We explore six cases, setting $\eta_0(r)$ equal to VM5a or EM1 and E equal to zero (*WeakLM_NoLVVs* and *StrongLM_NoLVVs*, respectively), 120 kJ/mol (*WeakLM_ModerateLVVs* and *StrongLM_ModerateLVVs*), or 360 kJ/mol (*WeakLM_StrongLVVs* and *StrongLM_StrongLVVs*) (Figure 1). Note the Haskell constraint degenerates from radial to volumetric for 3D viscosity.

3.2. Misfits

We compute the root of the mean squared error (RMSE) to the RSL record at each site, i, as

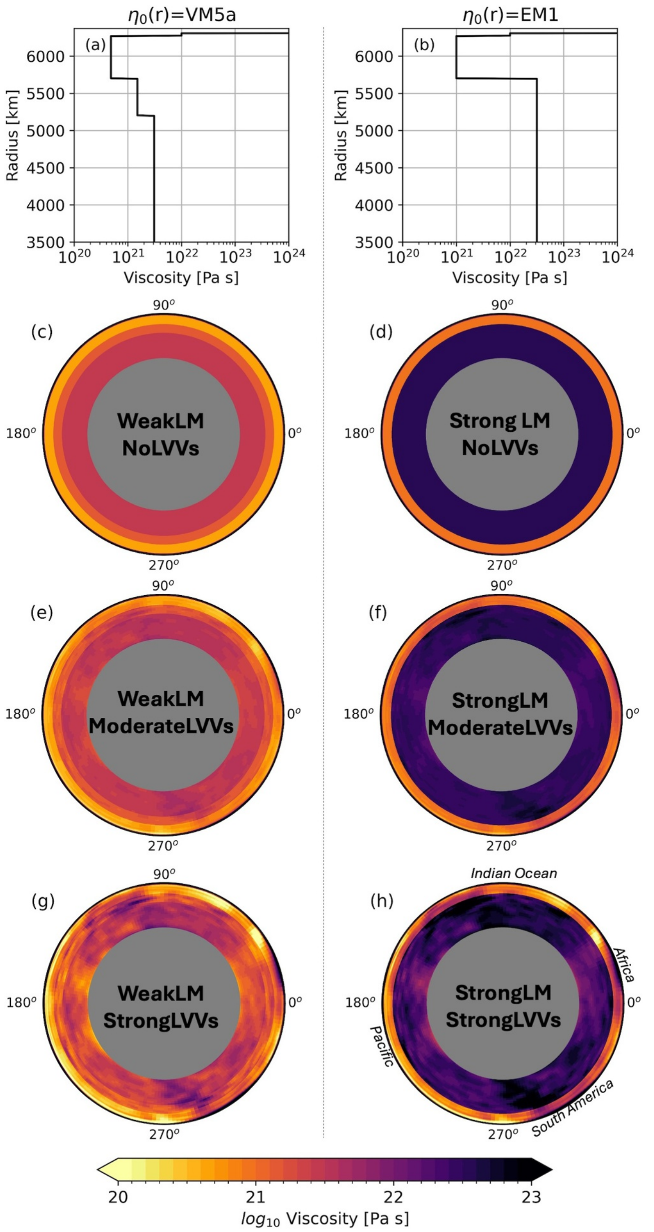

Figure 1. (a, b) The reference viscosity profiles, and equatorial slices of the 3D-viscosity fields based thereupon for increasing activation energy, E, which controls the amplitude of lateral viscosity variations scaled from seismic tomography: (c, d) $E = 0$ kJ/mol, (e, f) $E = 120$ kJ/mol, and (g, h) $E = 360$ kJ/mol.

$$\mathrm{RMSE}_i^{(\mathrm{RSL})} = \sqrt{\frac{1}{N_t^{(i)}}\sum_{j=1}^{N_t^{(i)}}\left(\frac{\mathrm{RSL}_i^{(\mathrm{obs})}(t_j) - \mathrm{RSL}_i^{(\mathrm{pred})}(t_j)}{\sigma_i^{(\mathrm{obs})}(t_j)}\right)^2} \quad (4)$$

and the misfit to the set of RSL records

$$\mathrm{RMSE}^{(\mathrm{RSL})} = \frac{1}{N_{\mathrm{sites}}}\sum_{i=1}^{N_{\mathrm{sites}}}\mathrm{RMSE}_i^{(\mathrm{RSL})} \quad (5)$$

where $N_t^{(i)}$ is the number of data points in the RSL timeseries at each site i, $\mathrm{RSL}_i^{(\mathrm{obs})}(t_j)$ is the observed RSL at site i and time j, $\mathrm{RSL}_i^{(\mathrm{pred})}(t_j)$ is the predicted RSL at site i and time j, and $\sigma_i^{(\mathrm{obs})}(t_j)$ is the error in $\mathrm{RSL}_i^{(\mathrm{obs})}(t_j)$.

We compute the misfit to GNSS-uplift rates as RMSE based on a regular grid to avoid overweighting densely sampled regions. Observations are interpolated onto a grid where any grid point with distance >100 km from a GNSS-site is masked (i.e., assigned NaN). Then,

$$\mathrm{RMSE}^{(\mathrm{VLM})} = \sqrt{\frac{1}{A}\int\left(v_z^{(\mathrm{obs})}(\theta,\phi) - v_z^{(\mathrm{pred})}(\theta,\phi)\right)^2 dA} \quad (6)$$

where A is the total area of the unmasked grid region, θ is latitude, and ϕ is longitude, and dA is the area increment.

4. Results

4.1. Global Misfits

The misfit to RSL records is reduced by ~40% when the reference viscosity is changed from VM5a (weak lower mantle) to EM1 (strong lower mantle), regardless of the strength of LVVs (Figure 2 and Table S1 in Supporting Information S1). If LVVs are zero or moderate, the GNSS-misfit is increased by 10%–20% for a strong versus weak lower mantle (Figure 2, Tables S2 and S3 in Supporting Information S1). However, if LVVs are strong, changing the reference viscosity from VM5a to EM1 has no effect on the misfit to GNSS-uplift (compare *WeakLM_StrongLVVs* to *StrongLM_StrongLVVs*). Therefore, increasing lower mantle viscosity and implementing strong LVVs (*StrongLM_StrongLVVs*) reduces the $\mathrm{RMSE}^{(\mathrm{RSL})}$ by ~40%, while the misfit to GNSS-uplift is unchanged compared to *WeakLM_StrongLVVs*, or slightly increased (~5%) compared to *WeakLM_NoLVVs* (i.e., VM5a). The reduction in the misfit to RSL records is ~50% if we do not normalize by error in Equation 4 (Table S1 in Supporting Information S1).

This is significant because GIA models that neglect LVVs predict uplift rates that are much larger than observed when a strong lower mantle is implemented, especially in North America (e.g., 2 times larger, Argus et al., 2021) and have long been interpreted to preclude a strong lower mantle (e.g., Cathles, 1975). However, we show here that *StrongLM_StrongLVVs* reproduces global GNSS-uplift nearly equally well with just a 5% penalty compared to models with a weak lower mantle. In the regional results presented below, we show that lateral variations in viscosity have a strong influence on the predicted uplift rates, especially in North America.

4.2. North America

In North America, the relationship between $\eta_0(r)$ and the misfit to RSL records is the same as the global average: the misfit to RSL records is reduced by ~40% for $\eta_0(r)$ = EM1 (strong lower mantle) compared to VM5a (weak

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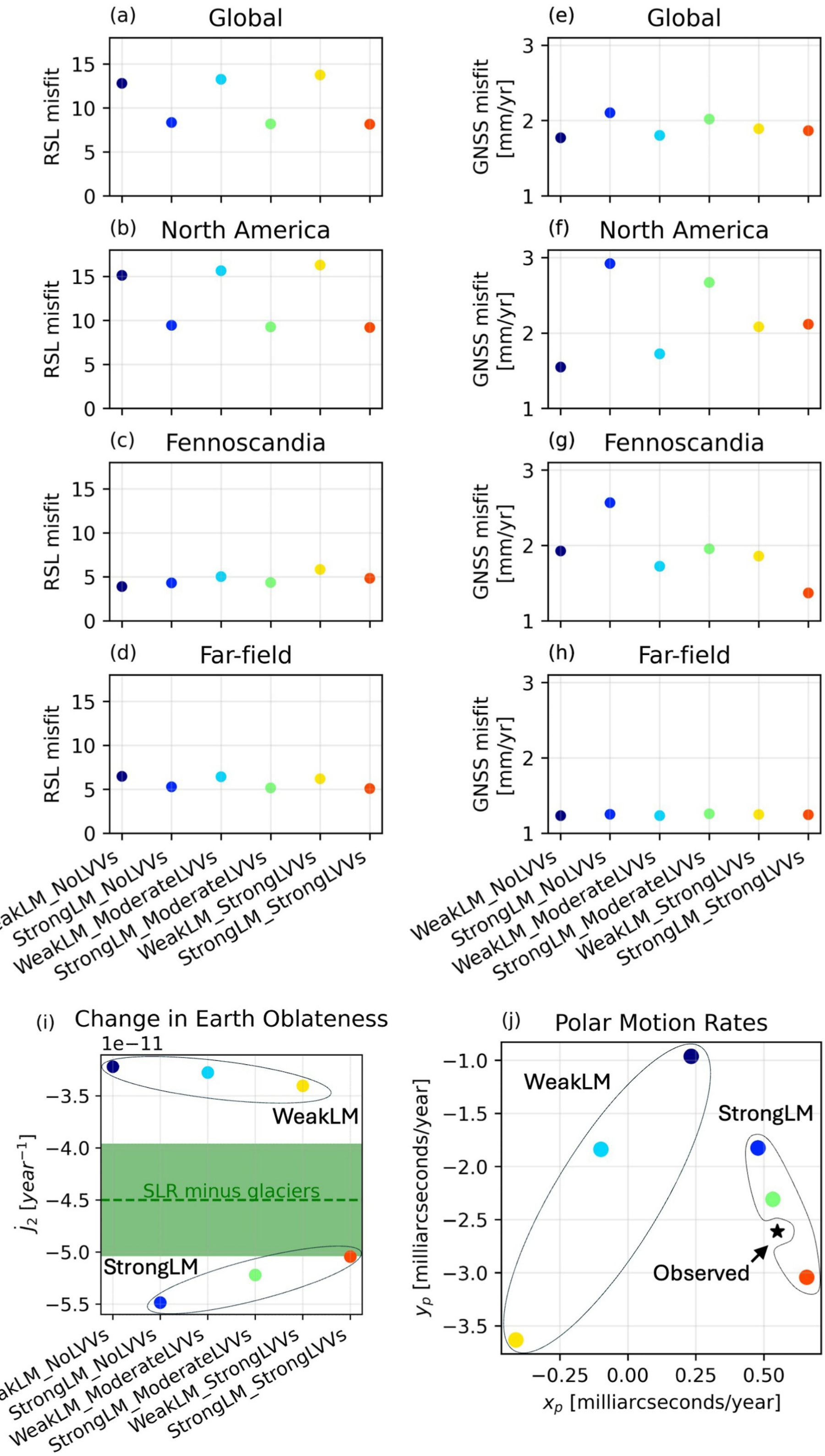

Figure 2. (a–d) Misfits to relative sea level records, (e–h) GNSS-uplift, (i) $\dot{J}_2$, and (j) polar motion rates. Our new preferred 3D-viscosity model of glacial isostatic adjustment is *StrongLM_StrongLVVs* (red dot).

lower mantle), regardless of the strength of LVVs (Figure 2, Figures S2–S6 and Table S4 in Supporting Information S1). The relationship between the GNSS misfit and lower mantle viscosity is similar to the global average, in that strong LVVs make the GNSS misfit insensitive to lower mantle viscosity, but penalties associated with accounting for LVVs arise. Considering cases with a weak lower mantle only ($\eta_0(r)$ = VM5a), accounting for LVVs in North America results in a 10%–30% increase in the GNSS misfit, compared to 5% in the global average. This may be a consequence of the coupled solution for ICE-6G with VM5a. If LVVs are strong and $\eta_0(r)$ = EM1 (the preferred case globally, *StrongLM_StrongLVVs*), then the GNSS misfit is (a) equal to that of *WeakLM_StrongLVVs*, (b) increases by 20% compared to *WeakLM_ModerateLVVs*, and (c) increases by 35% compared to *WeakLM_NoLVVs*. Maps of the North American uplift pattern from GNSS and predictions from *WeakLM_NoLVVs*, *WeakLM_StrongLVVs*, *StrongLM_StrongLVVs* are presented in Figure 3.

Compared to the global average, the penalty to the GNSS misfit for increasing lower mantle viscosity is greater in North America. Nonetheless, the penalty for a strong lower mantle is significantly reduced by accounting for LVVs (*StrongLM_StrongLVVs* vs. *WeakLM_StrongLVVs*, Figure 3) compared to 1D-viscosity (*StrongLM_NoLVVs* vs. *WeakLM_NoLVVs*, Figure 2f). Furthermore, it is not clear that the 35% increase in GNSS misfit of *StrongLM_StrongLVVs* compared to *WeakLM_NoLVVs* is the most representative comparison, since that latter neglects LVVs. Rather, comparing *StrongLM_StrongLVVs* with *WeakLM_ModerateLVVs* and *WeakLM_StrongLVVs* yields a 0%–20% increase in the misfit. In combination with the 40% reduction in the RSL misfit, this leads us to conclude that *StrongLM_StrongLVVs* is the preferred model on a regional basis in North America despite larger tradeoff with GNSS-uplift than the global average.

The misfit to North American uplift is highly sensitive to lower mantle viscosity when the lithosphere is thinner (e.g., *WeakLM_NoLVVs*, *WeakLM_ModerateLVVs*, *StrongLM_NoLVVs*, and *StrongLM_ModerateLVVs*) but becomes insensitive to lower mantle viscosity when the lithosphere is thicker (e.g., *WeakLM_StrongLVVs* and *StrongLM_StrongLVVs*). To understand this result, we present horizontal averages and vertical transects of 3D-viscosity which show that for *WeakLM_StrongLVVs* and *StrongLM_StrongLVVs*, the average viscosity is ∼equal to the reference viscosity profiles (cf. *WeakLM_NoLVVs* and *StrongLM_NoLVVs*) at depths larger than ∼200 km, but converge at shallow depths <200 km to a much stronger viscosity profile (Figure 4). This indicates that lithospheric thickness has a significant impact on uplift and reduces sensitivity of the misfit to lower mantle viscosity (Figure 4 and Figure S7 in Supporting Information S1, cf. H. C. P. Lau et al., 2018). However, differences in lower mantle viscosity produce differences in the pattern of uplift (Figure 3) and mantle strain rate (Figure 4) even when the lithosphere is thick. For example, *WeakLM_StrongLVVs* exhibits a single maximum center of uplift around the Hudson Bay (Figure 3e), while *StrongLM_StrongLVVs* exhibits two maximum uplift centers in Quebec and Northwestern Canada (Figure 3f). The maximum uplift center in Northwestern Canada produces most of the misfit in *StrongLM_StrongLVVs* (Figure 3o) and is sparsely sampled by GNSS observations (Figure 3a), highlighting the need for additional permanent stations in this region.

Our results imply that the disagreement on lower mantle viscosity from mantle convection and GIA may be resolved by considering 3D-viscosity in models of GIA. Predictions from GIA models that neglect LVVs suggest the lower mantle cannot be strong because North American uplift rates preclude it (Argus et al., 2021). However, our results show that accounting for 3D-viscosity (in particular, lithospheric thickness variations) makes a strong lower mantle viable in terms of reproducing the observed uplift rates in North America, while contributing a greater reduction to the RSL misfit.

Previous efforts to reconcile mantle viscosity from studies of mantle convection and GIA performed joint inversions for 1D-viscosity (Mitrovica & Forte, 2004) and we find this profile produces a smaller reduction in the misfit to RSL records (∼15%) and a greater increase in the misfit to GNSS-uplift (∼45%) compared to our preferred 3D model *StrongLM_StrongLVVs*. The 1D-viscosity profile from H. C. P. Lau et al. (2016) reproduces RSL records and GNSS-uplift similarly to *WeakLM_NoLVVs*, and that from Caron et al. (2018) performs similarly to *StrongLM_NoLVVs*. Within the confines of ice loading from ICE-6G, this substantiates the importance of 3D-viscosity, particularly lithospheric thickness variations, in reconciling viscosity inferred from GIA and mantle convection studies. Misfits are similar to *StrongLM_NoLVVs* if the viscosity contrast is increased to $\Delta\eta = 50$, with some degradation if $\Delta\eta = 100$ particularly in $\dot{J}_2$ and polar motion, although the latter improves mantle convection model fits to the geoid (Mao & Zhong, 2021, Figure S8 in Supporting Information S1).

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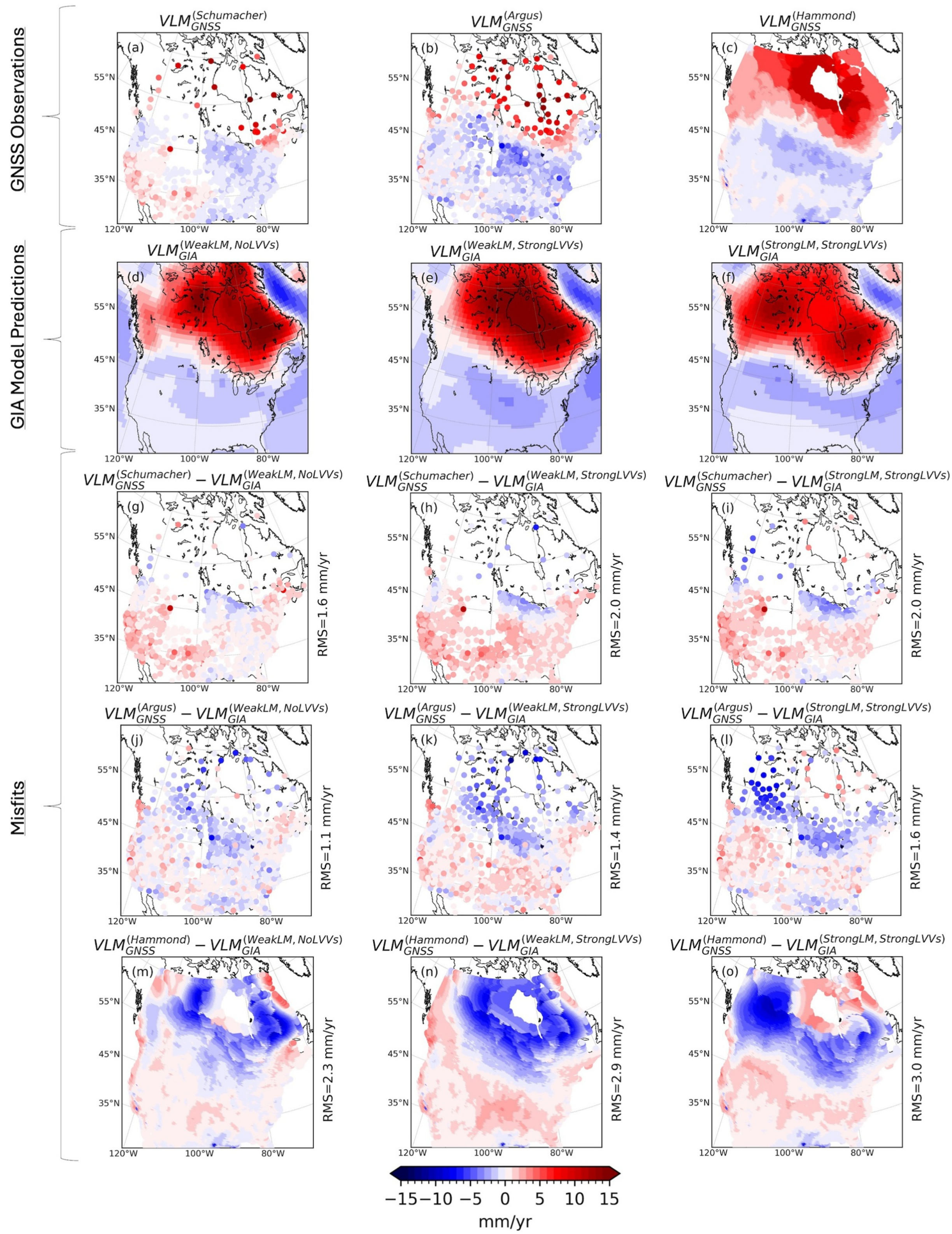

Figure 3. North American uplift rates from (a–c) three GNSS data sets, (d–f) models *WeakLM_NoLVVs, WeakLM_StrongLVVs, StrongLM_StrongLVVs*, and (g–o) the corresponding misfits computed on a point-by-point basis.

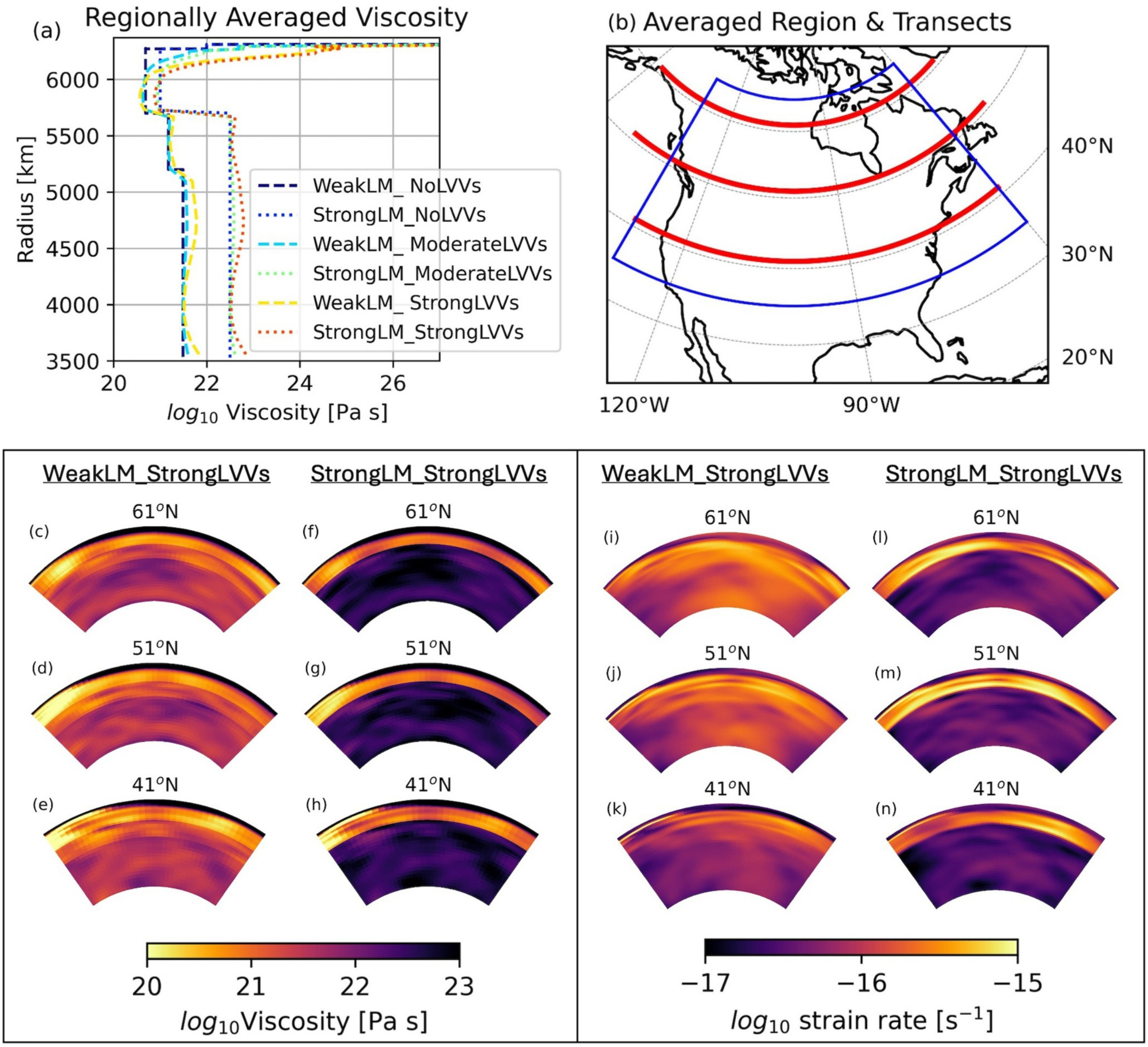

Figure 4. (a) Laterally averaged viscosity in the region outlined in blue in panel (b), as well as three cross-sections of (c–h) mantle viscosity and (i–n) strain rate shown by red curves in panel (b). *WeakLM_StrongLVVs* and *StrongLM_StrongLVVs* reproduce North American GNSS-uplift equally well despite different lower mantle viscosities.

4.3. Fennoscandia

In Fennoscandia, the RSL misfit based on 12 sites is not particularly sensitive to changes in lower mantle viscosity, which is not unexpected given the short lengthscale of this region. The RSL misfit decreases by 10%–20% for a strong lower mantle ($\eta_0(r)$ = EM1) compared to a weak lower mantle ($\eta_0(r)$ = VM5a) when LVVs are moderate or strong (Figure 2). While the minimum RSL misfit is produced by *WeakLM_NoLVVs* (e.g., ~25% smaller than *StrongLM_StrongLVVs*), the misfit values in Fennoscandia are substantially smaller than global and North American results, indicating that the RSL records are quite well-fit by all viscosity structures considered herein (Figure 2 and Figure S9 in Supporting Information S1). The GNSS misfit is minimized by *StrongLM_StrongLVVs* which produces a 30% reduction compared to *WeakLM_NoLVVs*, and a ~25% decrease compared to *WeakLM_StrongLVVs*, suggesting increased T_e increases sensitivity to lower mantle viscosity (Figure S7 in Supporting Information S1, cf. H. C. P. Lau et al., 2018).

4.4. Far-Field

In the far-field, the RSL misfit based on 36 sites decreases by ∼20% for a strong versus weak lower mantle, with *StrongLM_StrongLVVs* producing the best-fit (Figure S10 in Supporting Information S1). The GNSS residuals do not change appreciably across the cases considered, where the misfit of *StrongLM_StrongLVVs* is approximately equal (<10% difference) to that of *WeakLM_NoLVVs* (Figure 2).

4.5. Oblateness

In general, cases with a weak lower mantle ($\eta_0(r)$ = VM5a) produce $\dot{J}_2 \cong -3 \times 10^{-11}$ and those with a strong lower mantle ($\eta_0(r)$ = EM1) produce $\dot{J}_2 \cong -5 \times 10^{-11}$ yr^{-1} (Figure 2). Compared to the target $\dot{J}_2 = -4.5 \pm 0.2 \times 10^{-11}$ yr^{-1}, the latter group performs better and only *StrongLM_StrongLVVs* is within error of the observed estimate.

4.6. Polar Motion

Polar motion rates are best reproduced by models with a strong lower mantle. The best-fit case is *StrongLM_ModerateLVVs* while *StrongLM_StrongLVVs* is second-best with 75% reduction in the misfit compared to *WeakLM_NoLVVs* (Figure 2).

5. Discussion

The ice loading model ICE-6G combined with 1D-viscosity profile VM5a is a widely accepted global model of GIA because it fits a wealth of data, including global RSL records, GNSS-uplift, $\dot{J}_2$, and geologic constraints on the lateral extent of ice sheets through time. However, there is an equally compelling collection of observations that cannot be reconciled with the lower mantle viscosity of VM5a, including the static geoid and tectonic plate motions, which indicate a more significant increase in viscosity toward the lower mantle.

Our results show that accounting for 3D-viscosity in models of GIA can simultaneously (a) improve the fit to global RSL records in exchange for a small penalty on the GNSS-uplift residuals, and (b) reconcile the long-standing conflict with mantle convection constraints on lower mantle viscosity. In particular, the GNSS-uplift rates in North America cannot be reproduced in 1D-models of GIA with a strong lower mantle and ICE-6G, regardless of lithospheric thickness (Figure S11 in Supporting Information S1). However, we show that GNSS-uplift rates are fit equally well by a strong versus weak lower mantle when LVVs are strong.

Recent GIA studies already showed that the regional fit to RSL records in North America is improved when lower mantle viscosity is strong (e.g., $\Delta\eta \sim 30$) based on 1D- (Kang et al., 2025) and 3D-viscosity in GIA models (Kuchar et al., 2019) but GNSS-uplift was not considered. It has also been shown with 1D-viscosity models of GIA that RSL records along the Northeast coast of North America prefer a strong lower mantle while those around Hudson Bay prefer a weak lower mantle (Parang et al., 2024). While Bagge et al. (2021) considered reference viscosities consistent with geoid modeling only, T. Li et al. (2018, 2020) considered reference viscosity equal to VM5a only.

Our contribution here is thus to (a) compute the GIA response with LVVs based on seismic tomography, (b) consider the reference viscosity profiles recommended by both mantle convection and GIA studies, (c) vary the strength of LVVs, and (d) compute global misfits to RSL records, GNSS-uplift, $\dot{J}_2$, and polar motion. We show that an increased lower mantle viscosity consistent with mantle convection studies improves the fit to RSL records and fits GNSS-uplift equally well if LVVs are strong. While there is some degradation in the fit to GNSS-uplift rates in North America compared to 1D-viscosity profile VM5a, this is offset by improvement in Fennoscandia, and we suggest that additional model refinement (e.g., ice history, a weak asthenosphere) may mitigate this tradeoff. Our new preferred model is case *StrongLM_StrongLVVs* loaded by ICE-6G, which also improves the fit to $\dot{J}_2$ and polar motion.

The implications of what may be a step toward an updated global reference GIA model are broad. For example, it may have a significant impact on the global mean terrestrial water storage trend (Rodell et al., 2024), the global mean sea level budget (Barnoud et al., 2023), the pole tide correction (Wahr et al., 2015), and the hydrological component of $\dot{J}_2$ (Nerem & Wahr, 2011). We did not consider variations in the ice loading history ICE-6G. While the lateral extent of ice sheets is constrained by geological observations, the ice height within these margins is typically varied with the 1D-viscosity structure in GIA models. Advances in the ice loading history may impact the results presented herein. We also considered only one seismic tomographic model, S40RTS, but we suggest that the results will be broadly similar for others given similar long-wavelength features.

6. Conclusions

Accounting for lateral viscosity variations in GIA models reconciles two discrepancies: (a) GIA appears to require a weak lower mantle to fit global RSL records and GNSS uplift, while mantle convection constraints require a strong lower mantle to reproduce the static geoid and slab sinking rates; (b) 1D-viscosity models of GIA require a strong lower mantle to best-fit RSL records in North America, but a weak lower mantle to fit the GNSS uplift rates. Compared to the 1D reference viscosity profile VM5a ($\Delta\eta \sim 10$), the fit to RSL records, $\dot{J}_2$, and polar motion rates is substantially improved in exchange for a small penalty in the misfit to GNSS-uplift when lateral viscosity variations (LVVs) and a strong lower mantle compatible with mantle convection constraints ($\Delta\eta \sim 30$) are considered. Regionally, the misfit to GNSS-uplift is degraded in North America and improved in Fennoscandia compared to VM5a, but this is less significant compared to VM5a with moderate to strong LVVs, which may be a more representative rheological Earth structure. Our preferred model with LVVs and a strong lower mantle may be a step toward an updated global reference with broad implications for the interactions of the solid Earth, hydrosphere, and cryosphere including for the study of sea level.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Availability Statement

The gridded present-day rate maps associated with our new preferred 3D viscosity model of GIA are available for download in terms of uplift, the geoid, and RSL, along with the RSL records used to constrain the models (Bellas-Manley, 2025; Engelhart & Horton, 2012; Engelhart et al., 2015; Lambeck et al., 2017; Peltier et al., 2015; Vacchi et al., 2018; https://doi.org/10.5281/zenodo.17516836). The GNSS-uplift (Argus et al., 2021; Hammond et al., 2016; Schumacher et al., 2018), J_2 (Loomis et al., 2025) and polar motion timeseries (Vondrak et al., 2010, https://hpiers.obspm.fr/iers/eop/eopc01/) are publicly available for download from their respective references, as is the finite element model CitcomSVE-3.0 (Yuan & Zhong, 2024) and the ICE-6G ice loading history (Peltier et al., 2015, https://www.atmosp.physics.utoronto.ca/~peltier/data.php).

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