Glacial Isostatic Adjustment in Central Cascadia: Insights from 3-D Earth Modeling

Relative Sea Level records from the Central Sector of the Cascadia Subduction Zone

The sea-level data set we adopt (Figure 2) is comprised of index points from salt and freshwater wetland environments or estuarine sediments that closely constrain former sea level and limiting points that provide maximum or minimum constraints on former sea level (Engelhardt et al., 2015). Several index and limiting points are also based on stratigraphy from coastal archaeological sites (e.g., midden deposits) that indicate occupation of most sites within the last 2 kyr.

The RSL history for the northern Washington coast (site 1) is based on 14 index points and three limiting points and is restricted to the last ~2.5 kyr. The RSL history for the southern Washington coast (site 2) is based on 128 index points and 4 limiting points that span the Holocene. The RSL history of the northern Oregon coast (site 3) includes 110 index points and 11 limiting points that extend to ~9.3 ka. The Holocene RSL history of the central Oregon coast (site 4) is constrained by 110 index points and 17 limiting points extending to ~11.5 ka. We note that the misfit analysis described in the main text focuses on the RSL data plotted in Fig. 2 only; prior to this time window, gravitational and elastic deformation effects play an important role in the predicted adjustment, and these are also particularly sensitive to errors in the ice-loading history.

Post-Glacial Decay Times

It is well established that sea level histories at sites near the center of previously glaciated regions, such as Hudson Bay and the Gulf of Bothnia, may be modeled with reasonable accuracy using the following simple exponential form (Walcott, 1972):

$$RSL_i(t) = A_i \left[ \exp \left( \frac{t}{\lambda_i} \right) - 1 \right]$$  \hspace{1cm} (1)

where $t$ is time, and $A_i$ and $\lambda_i$ are the amplitude and decay time of the best-fit form (1) through the post-glacial relative sea level history at the $i^{th}$ site, i.e., $RSL_i(t)$. The second term in the square brackets is included so that a model RSL history is identically zero at present day ($t=0$). Whereas the amplitudes, $A_i$, are a strong function of the history of regional ice cover, the $\lambda_i$ are less sensitive to this history than the raw RSL curves, and thus decay times have been important in GIA studies of Earth structure (e.g., Mitrovica and Forte, 2004).

Sensitivity Test: Alternative Earth Models and Ice Histories

In the main text we considered results for the ICE-6G/VM5a GIA model. The
question arises as to whether we can reduce the upper mantle viscosity of the VM5a model \((5 \times 10^{20} \text{ Pa s})\) to produce a 1-D model that produces the same reconciliation. The decay time-versus-\(\varepsilon\) results in Figure 4C suggest that this is not possible since any reduction in the viscosity would also reduce the decay time computed for Richmond Gulf below the lower bound of the observational constraint (4 kyr). This is confirmed on the same figure, where the blue symbols at \(\varepsilon=0\) are results for the 1-D case where the upper mantle viscosity is reduced to \(2 \times 10^{20} \text{ Pa s}\). This reduction significantly improves the fit to the RSL histories in Cascadia (Figure 4A), but lowers the predicted post-glacial decay time at Richmond Gulf to \(~3\) kyr, well below the estimate from observations.

We also performed calculations based on an earlier iteration of the model – the ICE-5G ice history and the VM2 viscoelastic structure (Peltier, 2004). VM2 and VM5a are comparable Earth models, but the ICE-5G ice history is significantly different from ICE-6G in area covered by the Cordilleran and western Laurentide Ice Sheets. Finally, we also considered a GIA model in which an ice history developed at the Australian National University is paired with the 1-D viscoelastic profile that provided a best-fit to a global data base of GIA observables they adopted (Lambeck et al., 2014). The model has an elastic lithosphere of 50 km, an upper mantle viscosity of \(0.15 \times 10^{21} \text{ Pa s}\) and a lower mantle viscosity of \(50 \times 10^{21} \text{ Pa s}\).

In both cases, we introduced lateral variations in viscosity for a range of \(\varepsilon\) values and computed RSL histories for each. The ICE-5G/VM2 calculations predict significantly greater Late Holocene sea level rise at the sites in Washington and Oregon, and a higher value of \(\varepsilon\) (> 0.02) was required to reduce the RMS misfit to levels ~1.0; however, introducing this level of lateral variability led to predictions of decay times at both Richmond Gulf and James Bay that exceeded the observational constraints. In the case of the ANU model, the optimal value of \(\varepsilon\), in terms of the ability to fit both the RSL data in Cascadia and post-glacial decay times in Hudson Bay was 0.0075. This is lower than the optimal value of \(\varepsilon\) in the ICE-6G/VM5a case (i.e., 0.01) because the upper mantle viscosity of the 1-D model adopted in the ANU case is significantly lower than the value which characterizes VM5a \((1.5 \times 10^{20} \text{ Pa s} \text{ versus } 5 \times 10^{20} \text{ Pa s}, \text{ respectively})\). This provides an example of another ice history/3-D Earth model pairing that fits the RSL record in both Cascadia and Hudson Bay.

**Sensitivity Test: Tectonic Uplift**

The Washington and Oregon shorelines are subject to tectonic deformation in response to subduction of the Juan de Fuca Plate. Peterson and Cruikshank (2014) used the present-day elevation of marine terraces dated to Marine Isotope Stages 5a and 7 to estimate tectonic rates in Washington and northern Oregon (sites 1-3 on Figure 1). Adjusting their estimates for GIA and eustasy following the approach of Creveling et al. (2017) suggests a relatively minor long-term tectonic uplift rate of 0.1-0.2 mm/yr.
However, the uplift rate in central Oregon is thought to be significantly higher (e.g., ~0.5-0.8 mm/yr; e.g., Muhs et al., 1990). Given this potentially large tectonic contamination of the RSL history at site 4, we repeated the RMS analysis in Figure 4A using only data from sites 1-3 (Figure 4A, dotted line), and the result shows only minor differences with the 4-site analysis. We next applied a tectonic uplift (sea level fall) correction of either 0.1 mm/yr and 0.2 mm/yr to these observations, and repeated the misfit analysis. In these cases, the minimum misfit shifted to $\varepsilon=0.0125$ and $\varepsilon=0.01$, respectively. We are assuming in this exercise that the tectonic uplift signal is compensated by a change in lateral viscosity structure alone, but the same compensation could be achieved through a small change in the underlying 1-D viscosity profile. In any case, we conclude that in the case of the ICE-6G history our best-fit level of lateral variability in viscosity, including fits to the post glacial decay times ($\varepsilon=0.01$), would be unchanged if we limited our analysis to the tectonically relatively stable sites 1-3.

**DR References**


Figure Captions

**Figure DR1.** Lateral variation in the (base 10) logarithm of mantle viscosity relative to the background 1-D profile at a depth of 150 km beneath North America for the case $\varepsilon=0.01$.

**Figure DR2.** Maps of (A) Sea-level change over the past 2 kyr (units, m) and (B) present-day rate of change of sea level (mm/yr) in the Pacific Northwest computed using the ICE-6G ice history and a 3-D viscoelastic Earth model constructed by combining the 1-D model VM5a and lateral variations in lithospheric thickness and viscosity ($\varepsilon=0.01$), as described in the text. The same ice/Earth model was used to compute the RSL histories shown by red lines in Fig. 2. The similarity between the two figures reflects the near linearity of the modeled GIA response over the last two millennia.
Figure DR2