Vertical Land Motion in Western Washington:
Separating Cascadia Locking from Other Sources

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ABSTRACT

To help forecast local relative sea level rise in coastal Washington, we have compiled a new vertical land motion (VLM) dataset for Western Washington that combines GPS, tide gauges, and differential leveling data. We find two dominant signals in the data that are most-evident in north-central Washington, an east-west gradient consistent with locking along the Cascadia subduction zone (CSZ), and a smaller magnitude north-south gradient that is apparent east of the region affected by subduction zone locking. The two gradients are superimposed in the coastal region, although VLM data are routinely used to inform subduction zone models that assume the data are absent of independent sources of motion. To assess the contribution of each component, we generate simple elastic dislocation models for CSZ locking with and without the north-south gradient by subtracting the observed gradient east of the Puget Sound from all of Washington, including the CSZ locking-dominated gradient in coastal Washington, west of the Cascades. We compare the predicted horizontal strain from each model to the observed horizontal strain, measured from horizontal GPS motion. Preliminary results show that the observed vertical and horizontal strain best fit our model with the north-south regional uplift gradient removed. Therefore we hypothesize that this gradient is superimposed on the coastal region, and likely unrelated to the CSZ. We suggest that the observed north-south gradient is GIA, however other possible mechanisms are possible, including a 3D viscoelastic response to past CSZ rupture, and local subsidence associated with the broader Puget Sound forearc basin region.

MOTIVATION

Moving from absolute sea level rise estimates to regional sea level rise estimates.

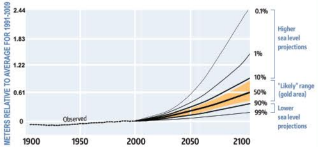

Figure 1. Modified from Miller et al. (2018). Absolute sea level rise projections through 2100, for a high greenhouse gas scenario (RCP 8.5), for Washington State. Projections based on Kopp et al. (2014) and observed variations in absolute sea level are shown for 1907-2007. Results are shown relative to the average for 2001-2009. The probability values are probabilities of exceedance, i.e., the current best assessment of the likelihood that absolute sea level will rise by at least a given change in elevation.

PROJECTED RELATIVE SEA LEVEL CHANGE FOR 2100
(cm , averaged over a 19-year time period)

Location	Vertical Land Movement Estimate	Greenhouse Gas Scenario	Central Estimate (50%)	Likely Range (83-17%)	Higher magnitude, but lower likelihood possibilities		
					10% probability of exceedance	1% probability of exceedance	0.1% probability of exceedance
Tacoma (47.3N, 122.4W)	-15.24±6.1	Low	64.0	45.7-82.3	91.4	140.2	240.8
		High	76.2	57.9-100.6	109.7	161.5	268.2
Neah Bay (48.4N, 124.6W)	33.5±9.1	Low	15.2	-3.0-36.6	45.7	94.5	192.0
		High	30.5	9.1-51.8	60.9	115.8	225.6
Taholah (47.4N, 124.3W)	9.1±15.24	Low	39.6	18.3-64.0	73.2	118.9	216.4
		High	51.8	30.5-79.2	88.4	140.2	246.9

Table 1. Modified from Miller et al. (2018). Absolute sea level rise projections, in cm, for Washington State. Projections are expressed in terms of the probability of exceedance for three different time periods (2050, 2100, and 2150) and two different greenhouse gas scenarios (RCP 4.5 ["Low"] and RCP 8.5 ["High"]; van Vuuren et al., 2011). Projected changes are assessed relative to contemporary sea level, which we define as the average sea level over the 19-year period 1991-2009. Projections for 2050 and 2100 for RCP 8.5 (highlighted below) are also shown in Figure 2. Examples of location-specific relative sea level rise projections are available in Table 2.

DATA

To estimate regional sea level rise, we must constrain VLM with data.

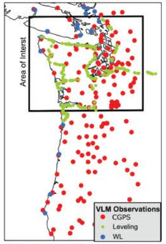

Figure 2. Modified from Miller et al. (2018). Vertical land movement observations compiled and analyzed for this study. Vertical rate estimates were derived for specific locations associated with three separate methods, continuous GPS analysis ("CGPS" in the legend), water-level differencing (based on tide gauges; "WL" in the legend), and survey marker leveling ("Leveling" in the legend). Estimates for each of the sites shown are included on the WCRP project website; combined estimates of coastal vertical rates were calculated only for the area of interest.

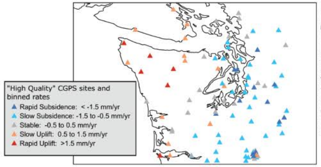

Figure 3. Modified from Miller et al. (2018). Vertical land movement best estimate rates derived from CGPS data from multiple data providers (UNR, JPL, SOPAC, PANGA, NMIMT).

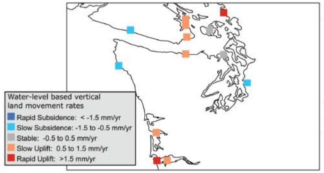

Figure 4. Modified from Miller et al. (2018). Vertical land movement best estimate rates from water-level differencing approaches, binned into vertical rate categories.

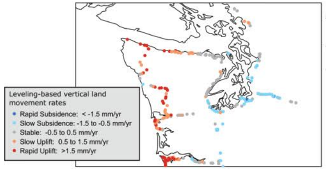

Figure 5. Modified from Miller et al. (2018). Binned vertical land movement best estimate rates (in mm/yr) derived from leveling.

ESTIMATING VERTICAL VELOCITY

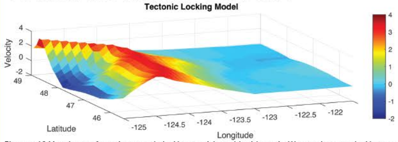

Figure 6. VLM estimates from the tectonic locking model used in this study. We use the same locking model presented in Burgette et al. (2009).

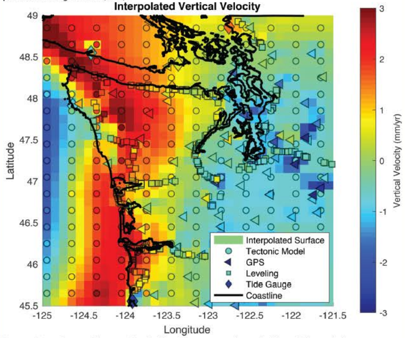

Figure 7. Best estimate of the rate of vertical land movement as determined by a 3D interpolation.

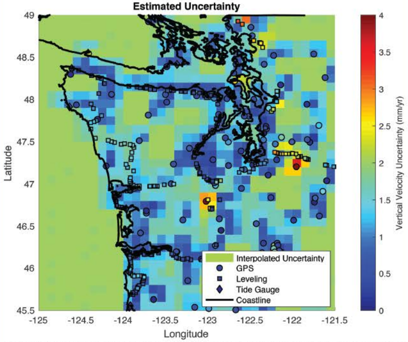

Figure 8. Uncertainty estimates for vertical land movement observations included in our analysis, as determined by bootstrap resampling of 1000000 iterations.

RELATIVE SEA LEVEL RISE RESULTS

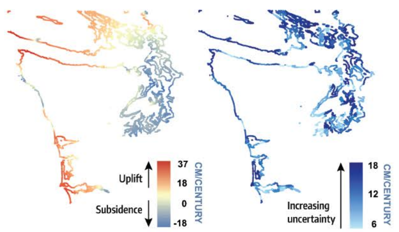

Figure 9. Modified from Miller et al. (2018). Vertical land movement best estimate rates (left) expressed in rates of feet/century, and their uncertainties (1 standard deviation, right) as estimated for Washington's coastline.

PROJECTED RELATIVE SEA LEVEL CHANGE FOR 2100
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Table 2. Modified from Miller et al. (2018). Relative sea level projections, in cm, for three of the 171 locations along Washington's coastline. Example locations in Washington include the Taholah, Neah Bay, and Long Beach. Projections are expressed in terms of the probability of exceedance for 2100 (2090-2109) under two different greenhouse gas scenarios (RCP 4.5 ["Low"] and RCP 8.5 ["High"]; van Vuuren et al., 2011). Projected changes are assessed relative to contemporary sea level, which we define as the average sea level over the 19-year period 1991-2009. Data for all 171 locations are available at www.wacoastalnetwork.com/wcrp-documents.html.

INVESTIGATING A NORTH-SOUTH UPLIFT GRADIENT

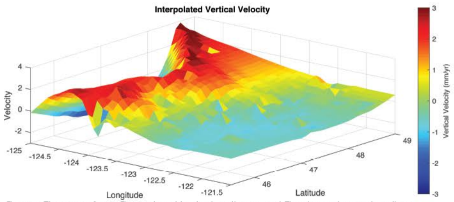

Figure 10. The same surface as Figure 7, but with volcanic outliers removed. There is a north to south gradient east of the subduction-driven uplift profile. We estimate this gradient and correct our tectonic locking model for it. The results are shown in subsequent figures.

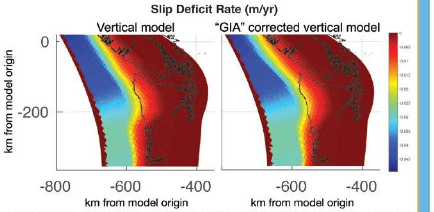

Figure 11. Correcting for the north to south "GIA" gradient in our model extends the extent of locking farther downdip and reduces the RMS error by 2%.

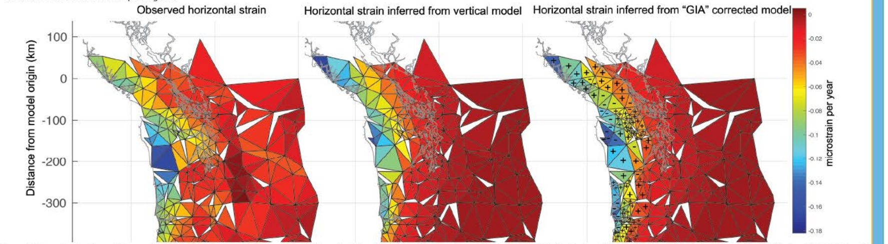

Figure 12. Correcting for the north to south "GIA" gradient in our model reduces the RMS error by 2% and better predicts the observed horizontal strain in Washington. Observed horizontal strain is shown on the left. Horizontal strain inferred from vertical uplift data used in the relative sea level rise analysis is shown in the center. Horizontal strain inferred from correcting the dataset for the observed "GIA" gradient is shown on the right. + indicates a better fit to observed horizontal strain than the model without "GIA" correction, for the labeled bin. - indicates a worse fit to observed horizontal strain than the model without "GIA" correction, for the labeled bin.

ACKNOWLEDGMENTS & REFERENCES

Thanks to David Schmidt for his work on the tectonic locking model. Thanks to the coauthors of our sea level rise assessment: Miller, I.M., Morgan, H., Mauger, G., Welch, M., and Grossman, E.

-Burgette, R. J., Weldon, R. J., & Schmidt, D. A. (2009). Interseismic uplift rates for western Oregon and along-strike variation in locking on the Cascadia subduction zone. Journal of Geophysical Research: Solid Earth, 114(B1). https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2008JB005679
-Miller, I.M., Morgan, H., Mauger, G., Newton, T., Weldon, R., Schmidt, D., Welch, M., Grossman, E. 2018. Projected Sea Level Rise for Washington State – A 2018 Assessment. A collaboration of Washington Sea Grant, University of Washington Climate Impacts Group, Oregon State University, University of Washington, and US Geological Survey. Prepared for the Washington Coastal Resilience Project.
-Kopp et al 2014
-Van Vuuren, D. P., Edmonds, J., Kainuma, M., Riahi, K., Thomson, A., Hibbard, K., ... & Masui, T. (2011). The representative concentration pathways: an overview. Climatic change, 109(1-2), 5. https://doi.org/10.1007/s10584-011-0148-z