Crustal uplift and sea level rise in northern Cascadia from GPS, absolute gravity, and tide gauge data

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[1] We combine data from nine GPS, absolute gravity, and tide gauge stations to estimate the relation between sea-level rise, vertical motion, and solid Earth processes in the Pacific Northwest. GPS vertical velocities (in ITRF2000) and absolute gravity rates are well correlated, with a gradient of 0.2 ± 0.1 μGal mm^{-1}, but show a significant offset of 0.53 $\pm$ 0.30 μGal yr^{-1} (2.2 $\pm$ 1.3 mm yr^{-1}) (95% confidence). Tide gauge and GPS data indicate a northeast Pacific regional sea-level rise of 1.7 $\pm$ 0.5 mm yr^{-1}, aligned to ITRF2000, or an unlikely regional sea-level fall of $-0.5 \pm$ 0.5 mm yr^{-1}, aligned to absolute gravity. Although we cannot rule out a bias in the GPS reference-frame alignment, our results suggest a possible absolute gravity bias by a long-period mass increase from an unknown near-surface or deep-seated source. The impact of such a mass increase on gravity, vertical motion, and sea level remains to be defined.
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1. Introduction

[2] Present-day crustal uplift in northern Cascadia is controlled by two main solid Earth processes: interseismic loading of the Cascadia subduction fault and postglacial rebound from the last Ice Age (Figure 1). Because of the very low regional mantle viscosity, postglacial rebound was mostly complete by the mid Holocene. Current rebound velocities are negligible along most of the margin, about 0.1–0.3 mm yr^{-1} based on regional models [*Clague and James*, 2002] and Holocene sea-level data in the northern Strait of Georgia [*James et al.*, 2002]. In contrast, strain accumulation along the locked subduction fault is expected to produce a significant landward tilt of the forearc, with the west coast rising at 1–4 mm yr^{-1} relative to the inland region [*Flück et al.*, 1997]. The pattern and amplitude of crustal uplift are very sensitive to the Earth rheology and seismic-cycle parameters used in the subduction models and thus provide important constraints to seismic hazard assessments. Crustal uplift is also a critical component of relative sea-level rise estimates along the Pacific Northwest margin. Vertical motions can vary by several mm yr^{-1} along the coastline and can significantly alleviate or aggravate the impact of eustatic sea-level rise.

[3] We use three independent geodetic techniques to estimate the regional pattern of crustal uplift and sea-level rise in the north-western Washington, south-western British Columbia region (Figure 1). We combine Global Positioning System (GPS), absolute gravity (AG), and tide gauge (TG) data at nine collocated or nearly collocated sites to take advantage of the strengths of each technique. Continuous GPS data acquired over the last decade provide an excellent means of measuring the relative motion between the sites, whereas AG data can provide a measure of height change and mass redistribution independently of satellite-based reference frames.

2. GPS Vertical Velocities

[4] GPS vertical velocities are estimated based on continuous time series spanning 1996 to 2006. Pre-1996 data are characterized by higher noise due to poorer satellite orbit and reference frame definitions [e.g., *Williams et al.*, 2004] and are not used here. The GPS data are processed with the BERNESE 4.2 software [*Hugentobler et al.*, 2001] using a double-difference phase solution, with the inland station DRAO constrained to a fixed a priori position (cf. details in *Mazzotti et al.* [2003]). Site velocities are aligned a posteriori to a given reference frame by propagating the appropriate DRAO velocity to the network.

[5] As one of the oldest global stations, DRAO has been continuously used in the definition of the International Terrestrial Reference Frame (ITRF). Its vertical velocity is 1.2 ± 0.5 mm yr^{-1} in the ITRF2000 realization [*Altamimi et al.*, 2002]. More recent realizations suggest different rates varying between 1.7 $\pm$ 0.7 mm yr^{-1} (IGb00) and 0.8 $\pm$ 0.2 mm yr^{-1} (ITRF2005). Although all these solutions are compatible at the 95% confidence level, their range directly translates into a shift in the velocities of the other GPS sites, thus leading to a systematic (reference frame) uncertainty of about $\pm$0.5 mm yr^{-1}. A recent study of the Earth center of mass motion suggests that the ITRF2005 translation rate may be significantly biased [*Argus*, 2007]. Thus, we decided to align our solution to the ITRF2000 – "average" of the various recent realizations – with an extra uncertainty to account for the reference frame inconsistency.

[6] The final standard errors of the vertical velocities are estimated based on a frequency-dependent noise model for the GPS time series [*Mao et al.*, 1999] scaled by the root-mean-square of the residual daily positions [*Mazzotti et al.*, 2003]. This leads to standard errors of 0.7–1.2 mm yr^{-1}, to which we add geometrically 0.5 mm yr^{-1} to account for the reference frame alignment uncertainty (Figure 1 and Table 1).

3. Absolute Gravity

[7] Absolute gravity measurements, consisting of measurements of the acceleration of a test mass falling in

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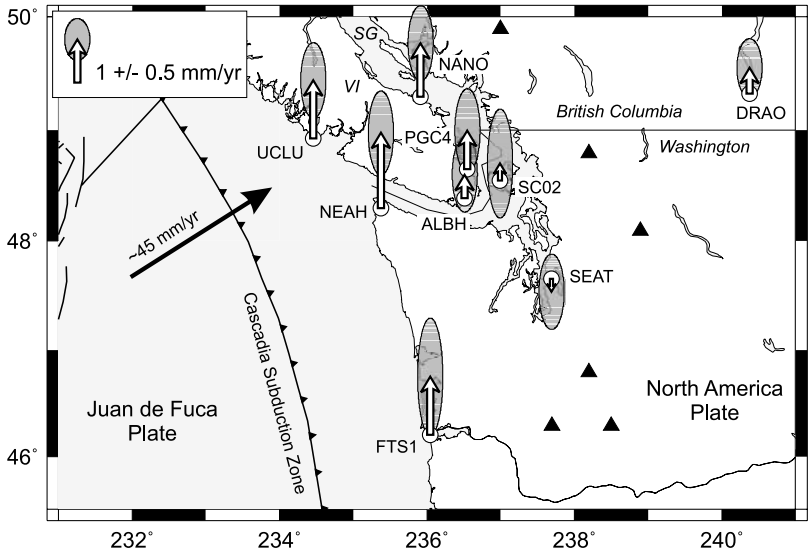

Figure 1. Northern Cascadia vertical GPS velocities. White arrows show vertical GPS velocities aligned to ITRF2000. Grey shade ellipses are 95% confidence regions (example not to scale). Collocated AG sites are UCLU, NANO, PGCV (PGC4), ALBH and DRAO. Black triangles are Cascade volcanoes. SG, Strait of Georgia; VI, Vancouver Island.

a vacuum, have been carried out repeatedly at five sites in south-western British Columbia (Figure 1) since the mid 1990s using an FG5 instrument [*Niebauer et al.*, 1995]. Typical AG time series consist of several measurements per year, each data point being an average over at least one 24-hour period (Figure 2). AG data are corrected for solid Earth tides, ocean tide loading, atmospheric effects, and polar motion, as well as for soil moisture [*Lambert et al.*, 2006].

[8] An inter-annual signal of unknown origin common to all five sites is identified by combining the data after removing linear trends (Figure 2, bottom plot). We estimate an empirical inter-annual correction by smoothing the combined residuals (Savitzky-Golay smoothing with 2 year cut-off). Correcting the AG data for this inter-annual signal has the effect of reducing the errors on the estimated linear trends, while shifting the trend values by less than 0.1 μGal yr^{-1} (1 μGal = 10 nm s^{-2}). We note that the correlation with the GPS vertical velocities is much higher for the inter-annual-corrected AG rates than for the non-corrected ones. Thus, we use the inter-annual corrected rates at all sites (Table 1).

[9] The error estimates on the AG rates assume that, at periods longer than 1 day, the gravity noise spectrum can be modeled as a first-order Gauss Markov process with a spectrum index of −2, except at very long periods where it becomes 0 (white) [*Van Camp et al.*, 2005]. As pointed out by these authors, the applicability of the Gauss Markov model to gravity can only be confirmed with much longer gravity time series. By removing the seasonal soil moisture gravity signal and a common inter-annual signal with power in the period range 4–6 years, we attempt to remove the frequency-dependent part of the noise spectrum, rendering the residual spectrum white. This procedure also produces normally distributed gravity residuals with respect to the linear trends (Figure 2). The variance of the normalized gravity residuals divided by the number of degrees of freedom reduces from an average of 1.43 to 0.97 at our sites. The one-sigma error of a 24-hour gravity value is taken to be 1.6 μGal, which is the geometric sum of the known systematic instrumental biases. This is the "instrument setup" error estimated by *Van Camp et al.* [2005].

4. Gravity/Uplift Ratio

[10] The AG/GPS rate comparison is shown in Figure 3a. The gravity/uplift ratio is related directly to the solid Earth processes sampled by the AG and GPS measurements. For

Table 1. Crustal Uplift, Absolute Gravity, and Relative Sea-Level Rise Rates[a]

		GPS, mm yr^{-1}			AG, μGal yr^{-1}			TG, mm yr^{-1}		
GPS/AG site	TG Location	V	σ	T	V	σ	T	V	σ	T
ALBH	Victoria	1.1	0.9	10.7	0.27	0.11	10.5	0.6	0.3	88
PGC4	Patricia Bay	1.8	1.0	7.0	0.06	0.06	9.0	0.1	1.3	26
NANO	Nanoose	2.5	0.9	10.7	−0.11	0.12	10.5	–	–	–
UCLU	Tofino	2.7	0.9	10.7	−0.09	0.07	10.5	−1.7	0.6	44
DRAO	Penticton	1.2	0.7	*	−0.22	0.24	7.0	–	–	–
SC02	Friday Harbor	0.8	1.3	4.9	–	–	–	0.9	0.3	62
SEAT	Seattle	−0.6	0.9	10.7	–	–	–	2.2	0.2	92
NEAH	Neah Bay	3.5	1.0	10.7	–	–	–	−1.6	0.6	44
FTS1	Astoria	2.7	1.4	6.9	–	–	–	−0.4	0.3	77

[a]V, rate; σ, standard error; T, length (yr) of the time series. Asterisk indicates that DRAO velocity is taken from the ITRF2000 realization.

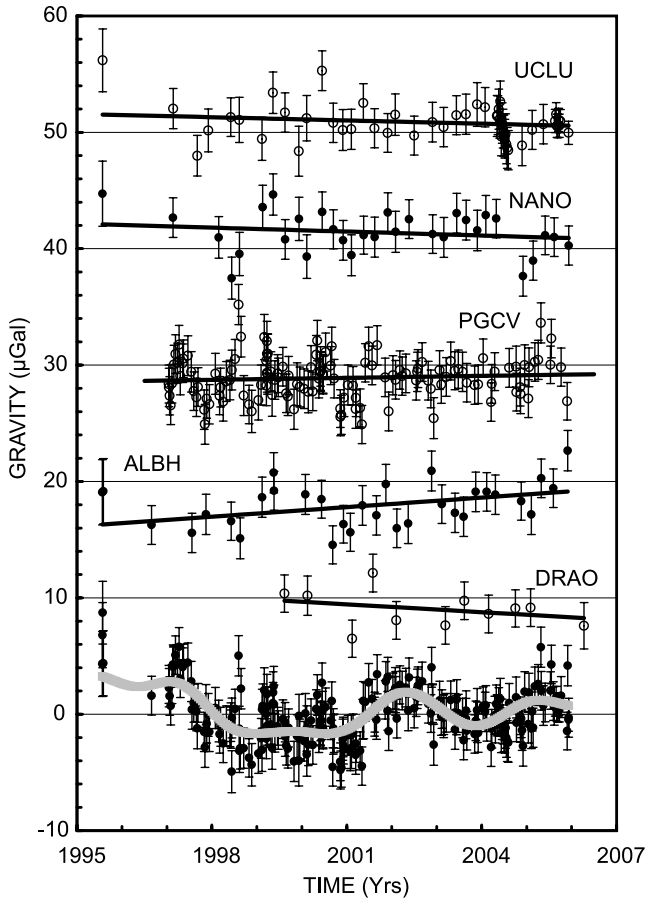

Figure 2. Absolute gravity time series. Top five plots show gravity data at individual sites (shifted for clarity). Circles and error bars represent 24-hour data points with their standard errors. Black lines are best-fit linear models. Bottom plot shows combined gravity residual and interannual best-fit model (cf. text).

interseismic deformation in the Cascadia subduction zone, assuming a Poisson's ratio of 0.25 and a crustal density of 2800 kg m^{-3}, the gravity/uplift ratio is expected to be about -0.19 μGal mm^{-1} [*Rundle*, 1978]. The AG and GPS data for DRAO, which is not in the subduction zone, does not align with that of the other four sites. Thus, we estimate the AG/GPS relationship for the four sites on Vancouver Island by solving for a linear model with uncertainties on both axes (so-called Model II or geometric mean regression, cf. *York* [1966]). The best-fit gravity/uplift ratio is -0.24 ± 0.13 μGal mm^{-1} (95% confidence limit), close to the expected subduction value. However, both vertical GPS and gravity rates at site NANO are higher than expected from general 2-D subduction-loading model predictions [e.g., *Flück et al.*, 1997], suggesting a more complex dynamics of the northern Cascadia forearc.

[11] The most significant result of this comparison is the offset of 0.53 ± 0.30 μGal yr^{-1} (gravity) or 2.2 ± 1.3 mm yr^{-1} (GPS) of the AG/GPS fit from the origin (Figure 3a), where the errors are 95% confidence limits. The choice of reference frame for the GPS velocity only affects the estimated offset at a sub-mm yr^{-1} level. In fact, our "slowest" vertical velocity solution is the one aligned to the ITRF2005 realization, leading to an AG/GPS offset equivalent to 1.8 ± 1.3 mm yr^{-1}, slightly lower than the ITRF2000-aligned value, but still significantly larger than zero at the 95% confidence level.

5. Tide Gauge and Regional Sea-Level Rise

[12] Tide gauge data are selected for seven northern Cascadia sites based on the record length, quality, and the proximity of a permanent GPS station. The selected sites have at least 40 years of continuous recording, except for the Patricia Bay (PGC) site with only 26 years (Figure 4). Relative sea-level (RSL) analysis is based on monthly means obtained from the Canadian Hydrographic Service and the U.S. National Oceanographic and Atmospheric Administration.

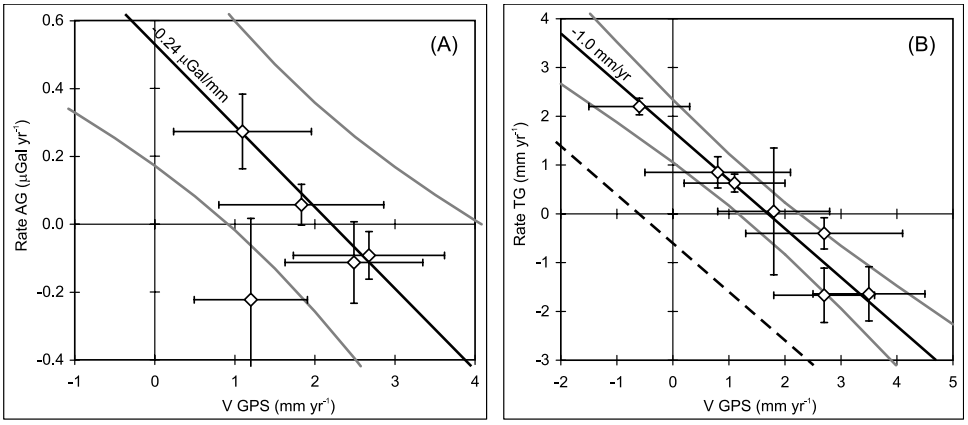

Figure 3. Uplift-gravity-sea level combination. (a) Absolute gravity rates versus vertical GPS velocities (in ITRF2000). Error bars are standard errors. Black and grey lines show best-fit geometric mean model and 95% confidence region (excluding DRAO outlier). (b) Relative sea-level rise rates versus GPS vertical velocities (in ITRF2000). Error bars are standard errors. Black and grey lines show best-fit geometric mean model and 95% confidence region. Black dashed line shows best-fit model for GPS velocities aligned to absolute gravity rates.

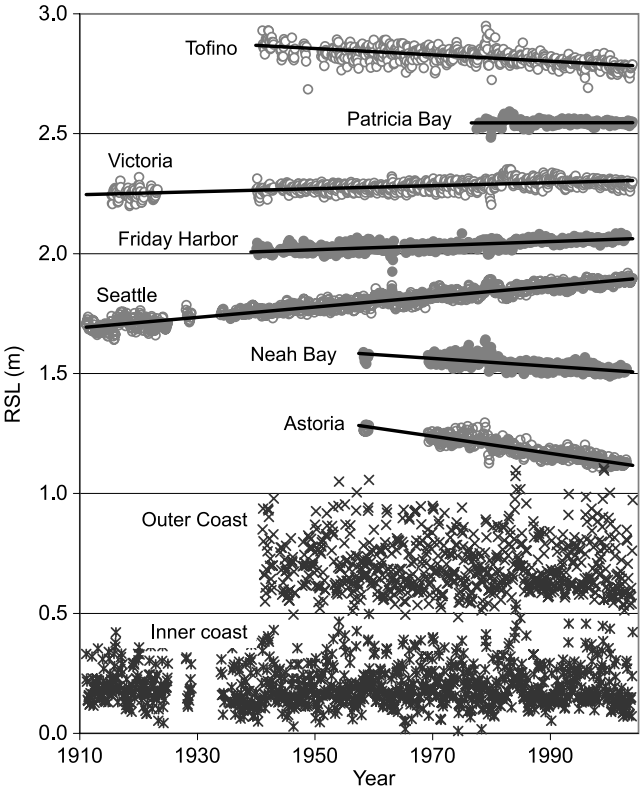

Figure 4. Tide gauge time series. Top seven plots show relative sea level data for individual tide gauge sites (shifted for clarity). Bottom two plots show outer and inner coasts common-mode oceanic and atmospheric corrections (cf. text).

[13] Most of the variance in monthly mean TG series corresponds to oceanographic and atmospheric processes on time scales of months to years. Assuming that these processes are correlated spatially, we derive two regional oceanographic correction filters by stacking the de-trended TG series for sites along the outer and inner coasts. Extra TG data sets are used to better constrain the oceanographic corrections (cf. details in *Wolynec* [2004]). Linear trends are estimated by a least squares fit to the corrected data (Table 1). The trend standard errors are estimated based on the noise model of *Zervas* [2001], scaled up 25% to account for the larger variance in western North America sea level data compared to eastern ones.

[14] Figure 3b shows the rates of RSL rise versus crustal uplift at the seven collocated or nearly collocated TG and GPS stations. The geometric mean regression indicates a correlation of 0.96 and a slope of -1.0 ± 0.3, identical to the theoretical value of -1 (assuming spatially homogeneous regional sea level changes). The offset, representing the 50-year regional sea-level rise component, is 1.7 ± 0.5 mm yr^{-1} for the GPS velocities aligned to the ITRF2000 reference frame (uncertainties at 95% confidence). This regional "oceanographic" sea-level rise is in very good agreement with estimates of 20th-Century global mean sea-level rise that range between 1.5 and 2 mm yr^{-1} [e.g., *Douglas*, 1997; *Church et al.*, 2001]. In contrast, aligning the GPS solution to the AG rates leads to a systematic vertical velocity shift of -2.2 mm yr^{-1} and a regional sea-level fall at a rate of -0.5 ± 0.5 mm yr^{-1} (Figure 3b, dashed line).

6. Discussion

[15] The northern Cascadia GPS, absolute gravity, and tide gauge data are among the longest and most robust available worldwide. Although the uncertainties on individual vertical GPS, AG, and TG rates remain relatively large, the very good correlation between the three data sets indicates a high internal consistency and resolution within each technique. The GPS/AG offset of 0.53 μGal yr^{-1} (or 2.2 mm yr^{-1}) is significant at the 95% confidence level. Preliminary GPS/AG comparison studies in the mid-continent of North America have suggested a good agreement between the two [e.g., *Larson and van Dam*, 2000; *Lambert et al.*, 2006], but a recent comparison study from two sites in Britain finds a GPS/AG offset similar to ours, which is attributed to systematic bias in the GPS velocities [*Teferle et al.*, 2006].

[16] Vertical velocities derived from GPS data have lower resolution and higher sources of systematic errors compared to horizontal velocities. In particular, the global reference frame alignment of our solution could be systematically biased by the use of a "wrong" velocity for our fiducial station (DRAO). As discussed in Section 2, recent reference frame realizations give a vertical velocity for DRAO ranging between 0.8 and 1.7 mm yr^{-1}. An independent Very Long Baseline Interferometry analysis indicates a vertical velocity of 2.5 ± 1.7 mm yr^{-1} in ITRF2000 (A. Searle, personal communication, 2006). In contrast, a DRAO vertical velocity of about -1.0 mm yr^{-1} would be required to eliminate the full observed GPS/AG offset. Although not formally impossible, such a low rate appears at odds with all solutions so far.

[17] Another potential source of bias in the fiducial velocity used for DRAO is related to the use in the IGS products of wrong phase center values for the GPS satellite antennas. *Ge et al.* [2005] show that the use of IGS products introduces an artificial scale drift of the reference frame of $\sim 10^{-9}$ between 1997 and 2003. Thus, vertical velocities based on IGS products are potential too slow by $\sim$1 mm yr^{-1}. If confirmed, this effect would in fact increase the observed GPS/AG offset.

[18] Our study does not resolve the origin of the offset between the observed GPS and AG rates in northern Cascadia. It is tempting to relate this offset to an artificial bias, such as reference frame alignment, that may affect the GPS velocities. However, the use of AG rates as the "true" velocities with respect to the Earth center of mass leads to very low uplift rates along the western margin, which would be difficult to reconcile with most models of interseismic subduction loading [e.g., *Flück et al.*, 1997]. It also leads to a surprising sea-level fall of -0.5 mm yr^{-1} over the last 50 years. Recent studies of regional variability in sea-level over the last 50 years indicate rates of rise in the Northeastern Pacific higher than the global mean [*Church et al.*, 2004; *Cazenave et al.*, 2006]. Therefore, it seems unlikely that sea-level is falling there. Similarly, a slow near-surface increase in mass to explain the positive shift in gravity rates would have to be confined to a narrow (<100 km)

region to avoid producing an increase in the local geoid and related sea-level rise rates.

7. Conclusion

[19] The combination of vertical GPS, absolute gravity, and tide gauge data in northern Cascadia shows a very good correlation between the three data sets, pointing to a consistency and resolution within each technique equivalent to $\sim$0.5 mm yr^{-1} or better. Based on the GPS/AG comparison, we identify a significant offset between the two data sets of 0.53 ± 0.30 μGal yr^{-1} or 2.2 ± 1.3 mm yr^{-1} (95% confidence limits). This offset is reflected in the comparison with tide gauge data. We estimate a northeast Pacific regional sea-level rise of 1.7 ± 0.5 mm yr^{-1}, based on the ITRF2000-aligned GPS velocities, and a surprising sea-level fall of −0.5 ± 0.5 mm yr^{-1} using the AG-aligned GPS velocities. Although we cannot rule out a systematic bias in the GPS velocities related to reference frame issues, our results suggest that the origin of the GPS/AG offset may be associated with a near-surface or deep-seated mass increase. A detailed model that satisfies the vertical motion, gravity, and sea level rates remains to be determined.

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