Derivation of contemporary vertical deformation associated with the Cascadia Subduction Zone from historical leveling surveys

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Keywords: Fault Dynamics, Leveling

Award Period: January 1, 2004 through December 31, 2005

Final Project Report Cover Sheet

DERIVATION OF CONTEMPORARY VERTICAL DEFORMATION ASSOCIATED WITH THE CASCADIA SUBDUCTION ZONE FROM HISTORICAL LEVELING SURVEYS

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2. Abstract

I analyze data from 29 tide gauges and 113 pairs of 1st and 2nd order leveling lines to determine the pattern of vertical deformation in the Pacific Northwest of the United States. The data span nearly 100 years and represent the interseismic elastic deformation related to the great earthquake cycle. Uplift rates calculated from leveling surveys are adjusted to a model surface in the tidal reference frame using a robust, weighted, linear, least square technique. Rapid uplift occurs in two distinct broad regions along the coast separated by a narrow zone of slow subsidence. Vertical deformation rates range from >4mm/yr of uplift on southern Vancouver Island to >2 mm/yr of subsidence in northern coastal Oregon. The deformation pattern is consistent with the results of previous studies and subduction models.

3. Final Report

Introduction

I use data from tide gauges and repeated leveling surveys to determine the pattern of vertical deformation in the Pacific Northwest of the United States. Because the data used in this study span less than 100 years, I believe the current crustal motion represents regional interseismic deformation associated with a great mega-trust earthquake on the Cascadia Subduction Zone. A better understanding of the vertical deformation pattern in the PNW should provide essential information for assessing the great earthquake hazard throughout the region.

Tide Gauge Data and Analysis

I analyze data from 29 tide gauges operating digital data spanning at least 15 years (Table 1). The gauges are located in the United States and Canada and were obtained from two sources, the US National Ocean Service (NOS) and the Marine Environmental Data System (MEDS) operated by Fisheries and Oceans Canada. In order to determine the rate of crustal motion, I calculate the average motion of the gauge relative to the reference surface and then correct for eustatic sea level rise of 2.0 mm/yr. I calculated the least square linear trend to the entire record of monthly mean sea level values at each station after removing the mean annual cycle for each station. The results for each station are shown in Appendix A.

Table 1. Crustal Deformation Rates from Tide Gauge Data

Tide Gauge	This Study				Holdahl et al. [1989]		Mitchell et al. [1994]		Weldon [pers. comm.]	
	Rate	Error	Months	Source	Rate	Error	Rate	Error	Rate	Error
Alert Bay	3.8	0.4	367	F&O	2.8	1.3				
Astoria	2.3	0.1	925	F&O	1.7	1.0	2.0	0.2	2.9	0.2
Bamfield	1.7	0.4	415	F&O						
Bella Bella	2.7	0.3	516	F&O						
Campbell River	4.8	0.4	406	F&O	2.3	1.1				
Charleston	0.9	0.4	414	NOS			2.4	0.7	1.0	0.7
Cherry Point	1.4	0.4	386	NOS					1.4	0.8
Cresent City	2.7	0.1	799	F&O			2.9	0.2	2.9	0.2
Friday Harbor	0.9	0.1	679	F&O	0.4	0.8			1.1	0.3
Fulford Harbour	1.9	0.6	283	F&O	0.8	0.9				
Neah Bay	4.0	0.1	532	F&O	2.5	0.8	3.6	0.2	3.8	0.2
New Westminster	5.7	0.8	415	F&O						
North Spit	-2.5	0.5	324	NOS					-3.3	1.0
Patricia Bay	2.4	0.5	331	F&O						
Point Arena	2.0	0.5	228	NOS					1.7	1.5
Point Atkinson	1.2	0.1	779	F&O	-0.2	0.8				
Port Alberni	2.1	0.6	319	F&O						
Port Angeles	2.0	0.5	354	NOS	0.4	0.9			1.6	0.9
Port Hardy	3.2	0.3	484	F&O	3.3	1.1				
Port Orford	2.1	0.7	262	NOS			7.0	1.1	1.8	1.3
Port Townsend	0.1	0.4	397	NOS					-0.2	0.7
Seattle	-0.1	0.1	1261	NOS	-1.4	0.8			-0.1	0.1
South Beach	-0.6	0.3	457	NOS			-0.2	0.4	-0.7	1.0
Steveston	-0.1	0.5	338	F&O						
Tofino	3.6	0.1	821	F&O	1.9	0.8				
Toke Point	0.5	0.5	371	NOS	-1.0	0.9	-0.1	0.3	-0.2	0.7
Vancouver	1.7	0.1	933	F&O	0.7	0.8				
Victoria	1.2	0.1	1077	F&O	0.2	0.8				
Winter Harbour	2.6	1.3	193	F&O						

NOS – United States National Ocean Service – Tides Online
F&O – Fisheries and Oceans Canada – Marine Environmental Data Services

Repeated Leveling Data and Analysis

I obtained all the available digital leveling data from the US National Geodetic Survey (NGS) archives for Washington, Oregon, and northern California. The NGS data had the following corrections applied directly by the NGS, orthometric, rod, level, temperature, refraction, magnetic, astronomical. In a rapidly deforming environment such as Cascadia measurable deformation can be detected within a decade if precise leveling techniques are used. In this study, I limited the data to 1st and 2nd order surveys [Bossler, 1984] and searched for leveling lines that were repeated after at least five years. I also constrained the selection process to pairs of lines with at least 10 common benchmarks over at least 25 km.

Crustal deformation calculations from repeated leveling surveys are notorious for having many anomalous results. The anomalies are the results of a variety of causes including surveying blunders, benchmark instability, and localized deformation. In order to assess the quality of the results each uplift rate profile (calculated from a pair of leveling lines) was reviewed. I calculated and plotted a least squares B-spline for each profile. Figure 1 shows four representative examples of uplift rate profiles along with the best-fit B-spline. I removed the mean from each profile for graphing purposes. Figure 1A shows one of the better quality profiles. There were several other profiles that were similar in quality to that shown in Figure 1A. The profile shown in Figure 1B shows results with relatively large estimated error. There were several profiles similar to that shown in Figure 1B, however, the majority of the profiles had a quality similar to Figure 1C. The Figure 1C profile has relatively low estimated error but the results appear noisy in the sense that the points do not all fall directly along a smooth curve. Figure 1C shows a profile where the misfit is much larger than the estimated error. As shown in Figure 1, the uplift rates calculated from the repeated leveling are of varying quality. I believe the overall quality of the results is more than sufficient to provide a reliable pattern of crustal deformation at the scale presented in this study.

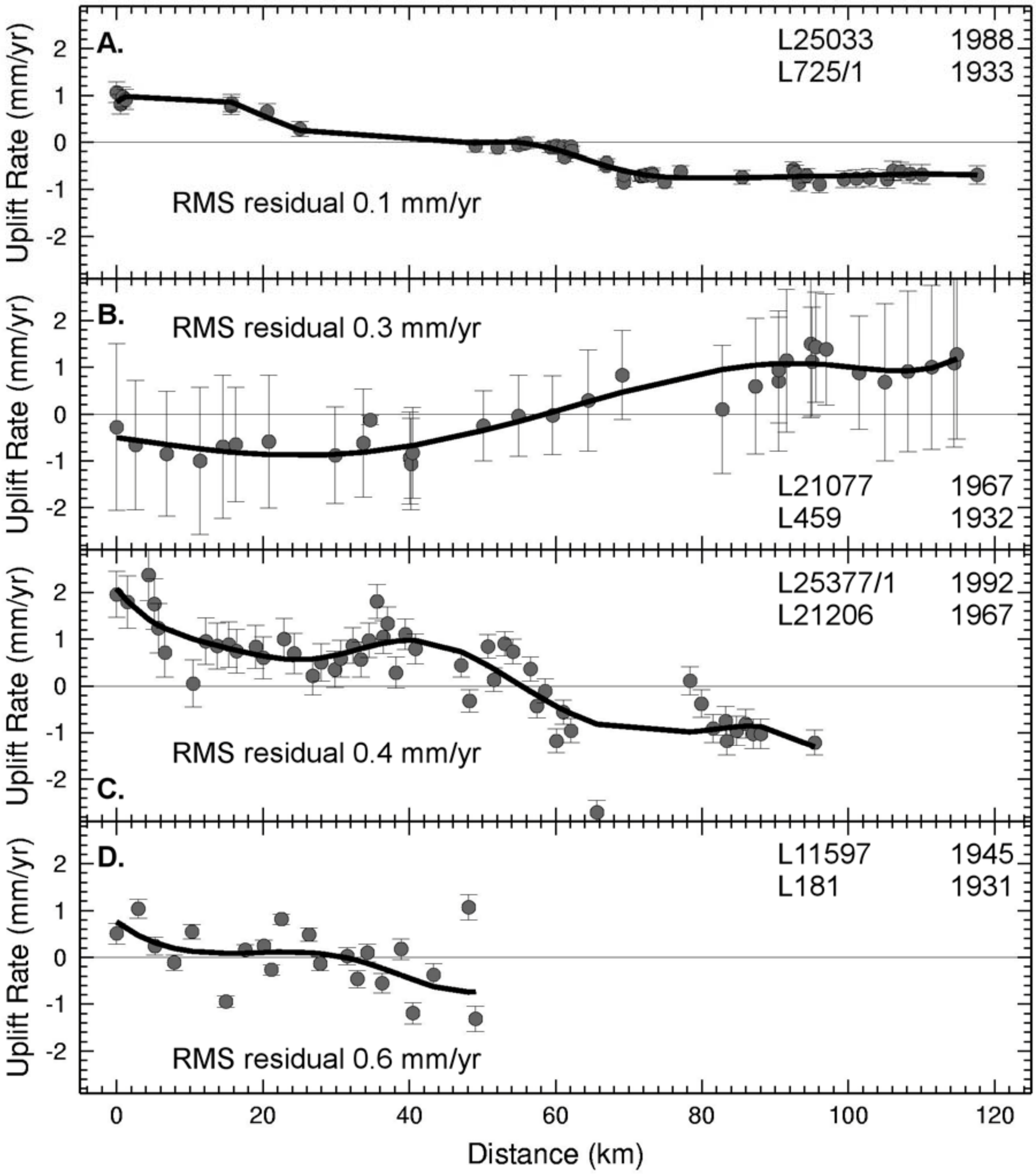


Figure 1. Four representative examples of uplift rate profiles calculated from repeated leveling surveys. Each graph shows the calculated uplift rate (gray circles) and the associated estimated error from the two leveling lines listed on the graph. The year of each survey is also show. The heavy line is a B-spline fit to the calculated uplift rates using a least square method.

Regional Deformation Analysis

Because many of the profiles in this study do not form closed circuits or contain common benchmarks, a different method must be utilized. The uplift rate results from tidal data must also be included. I chose to adjust all the leveling results to a model surface. The basic procedure is to use a linear least square method to determine the coefficients for a model surface. The constant term is allowed to be different for each uplift rate profile except for the tide gauge results which are fixed at zero. Therefore the constant for each of the other profiles represents a vertical offset relative to the tidal results. The constant for each profile is then subtracted from the profile, effectively adjusting the results to the tidal reference frame.

The best fitting results were obtained using a bivariate cosine series polynomial. To provide robustness, I used an iterative inverse approach. The weights were modified after each iteration based on a median absolute deviation technique. The process was stopped after no significant improvement was made to the model (Chi-squared test). The results are imaged in Figure 2. In the image, the uplift rates are illuminated by the relative data weights so that results from poor or little data are not interpreted. The relative data weight was determined by calculating the total weight for 20km square cells (sum of all the weights in the cell). The total weight for each cell was then scaled from 0 (minimum) to 1 (maximum). Highly illuminated areas, pale colors to white, should not be interpreted because they have either poor or insufficient data.

Conclusions

Although some of the leveling lines are noisy and some have low precision, it does produce and accurate pattern of uplift when combined with results from tide gauge analysis. Until the vertical resolution of GPS we must rely on this data. The simple analysis method used in this study produced results consistent with the methods used by other researchers in the past. The results of the deformation analysis suggest that crustal uplift along the Pacific Northwest coast is divided into two broad regions of rapid uplift separated by a narrow region of slow subsidence (Figure 2). The most rapid uplift is occurring in northwest Washington and on Vancouver Island and locally exceeds 4mm/yr. The overall pattern of uplift is also consistent with models of shallow coupling on the plate interface.

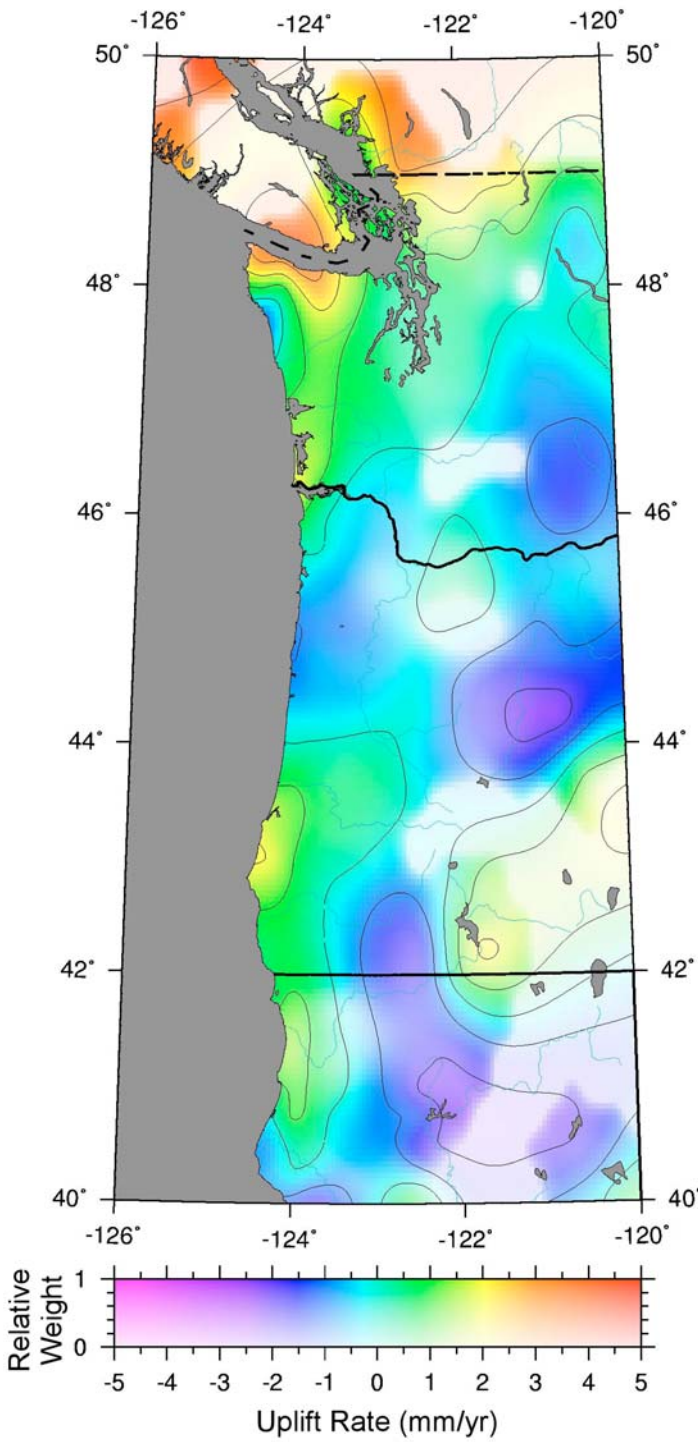
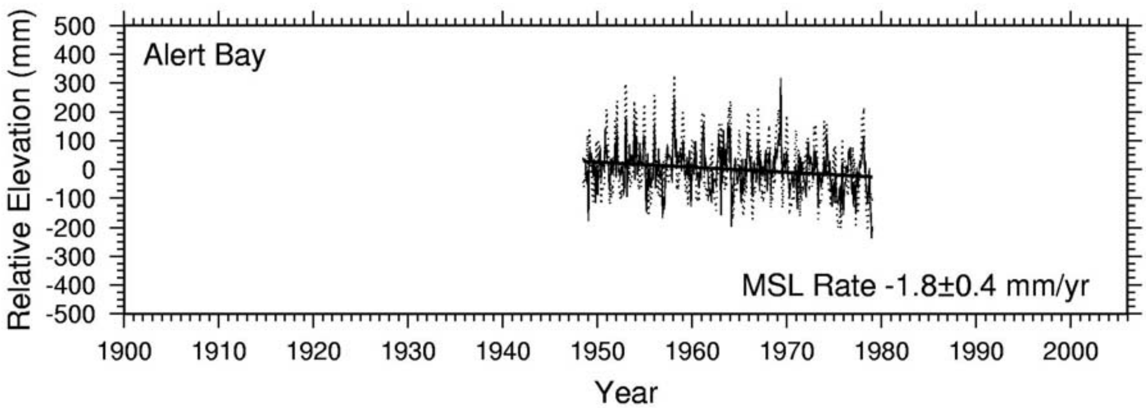
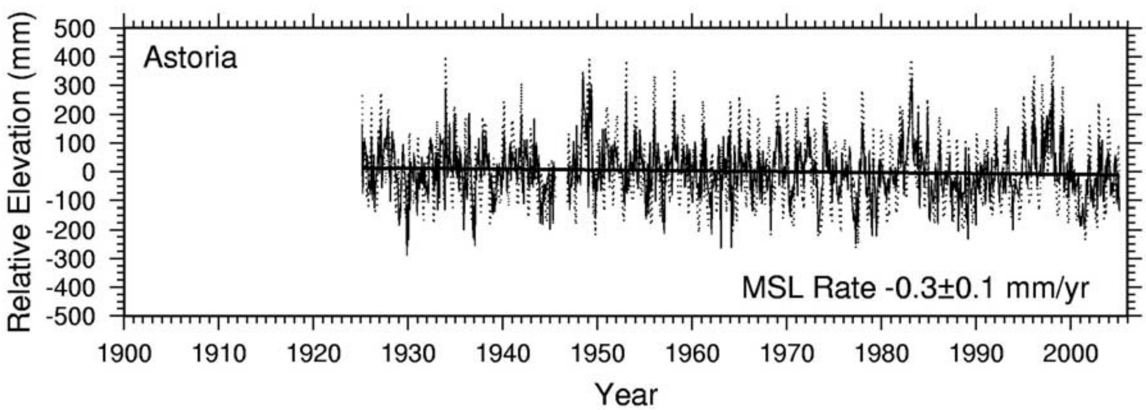


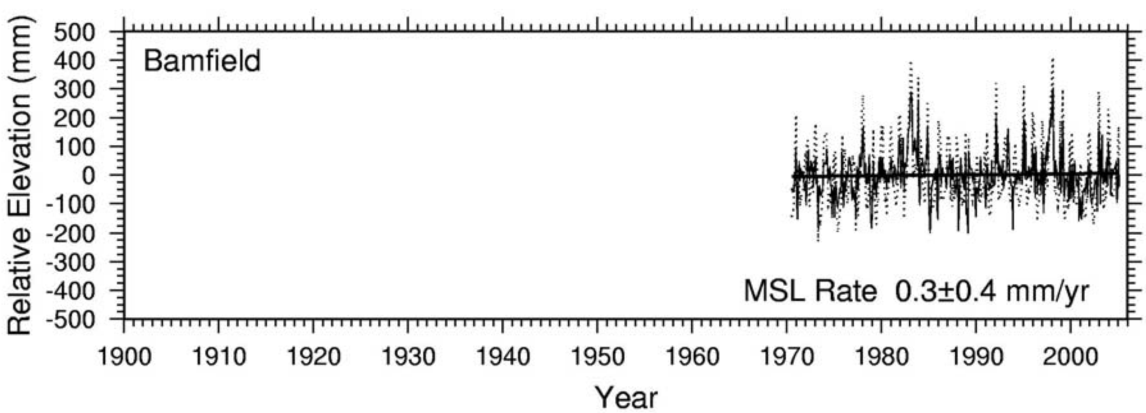
Figure 2. Regional uplift analysis results illuminated by the relative weighted data density with 0 and 1 representing minimum and maximum weighted data density, respectively. The bright colors represent region with high data quality and quantity. The pale areas show regions with low data quality and quantity.

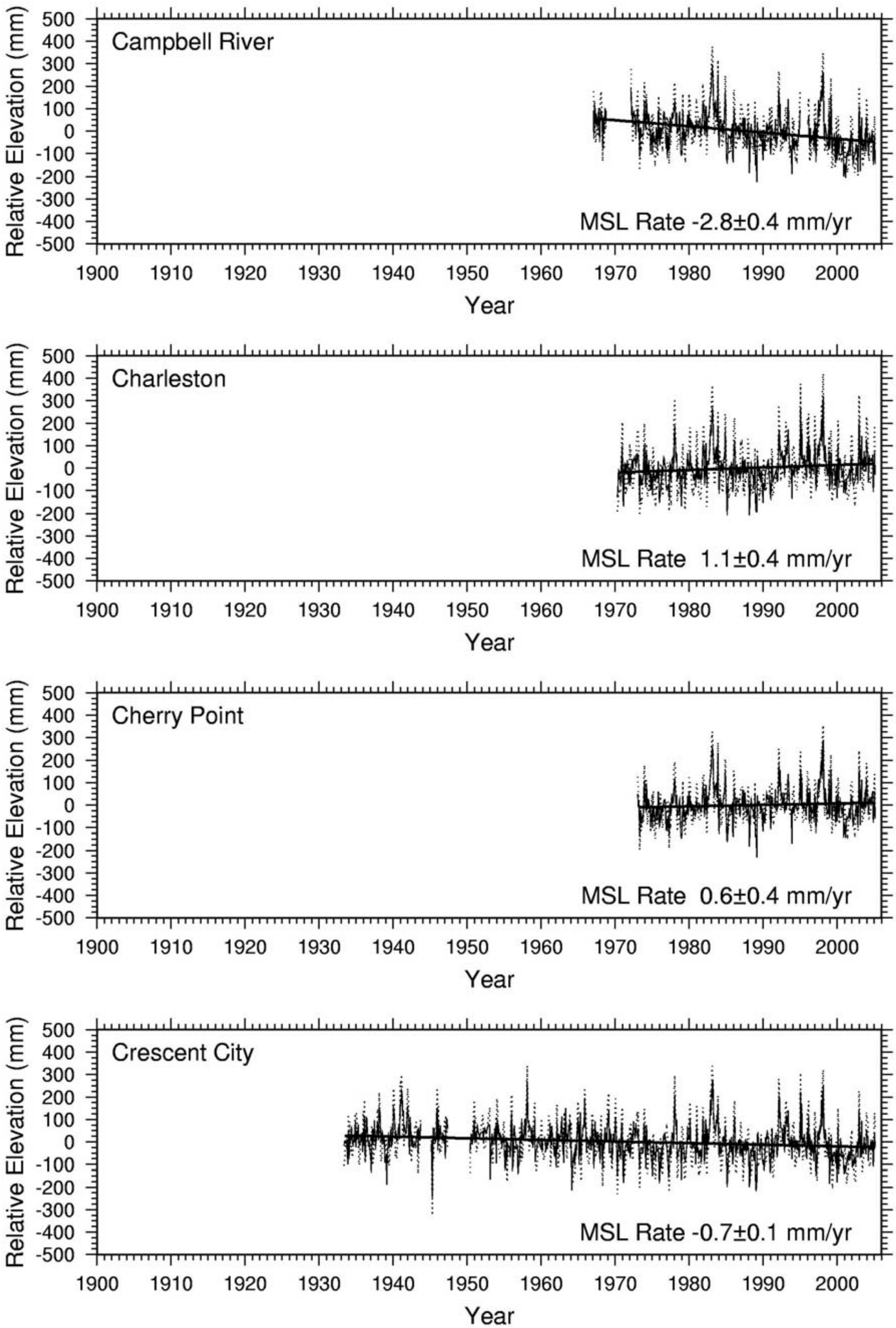
Appendix A. Average Monthly Sea Level Graphs

The graphs presented in this appendix show the monthly average mean sea level at each of the tide gauges used in this study. The dotted line in each graph represents the average mean sea level as reported by the agency listed in table 1. The solid line represents the data after removal of the annual cycle at each station. The heavy line shows the long term, local, change in mean sea level. I calculated the rate after the annual cycle was removed from the original data. The local change in sea level is a combination of global sea level change and local crustal deformation. To determine the crustal deformation rates listed in table 1, I added 2.0mm/yr global sea level rise to the inverse of the local rate of sea level change.

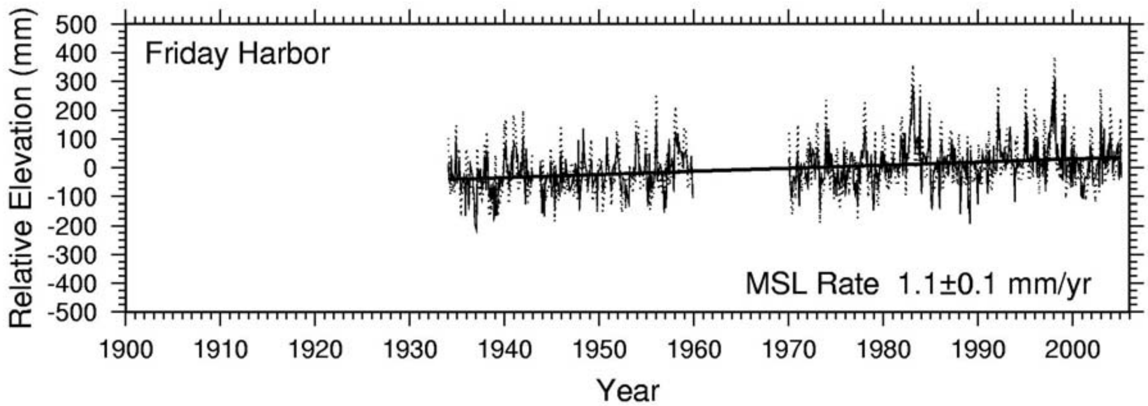


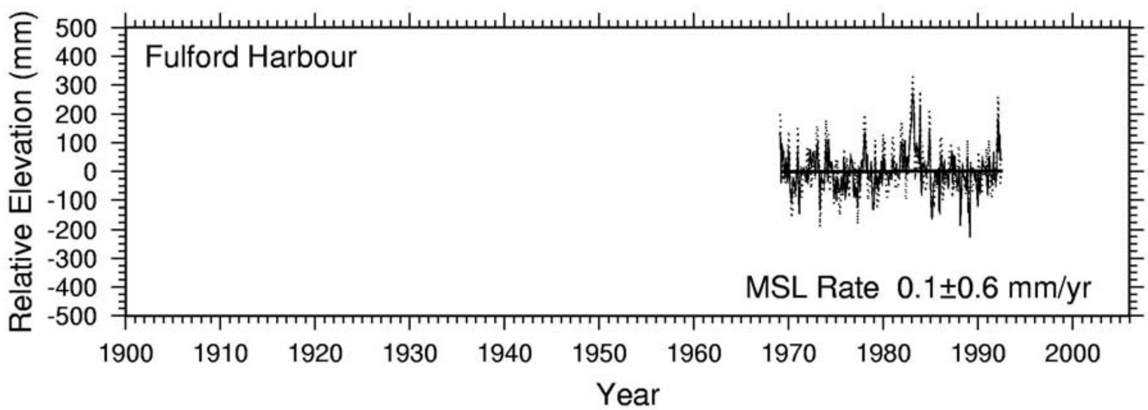


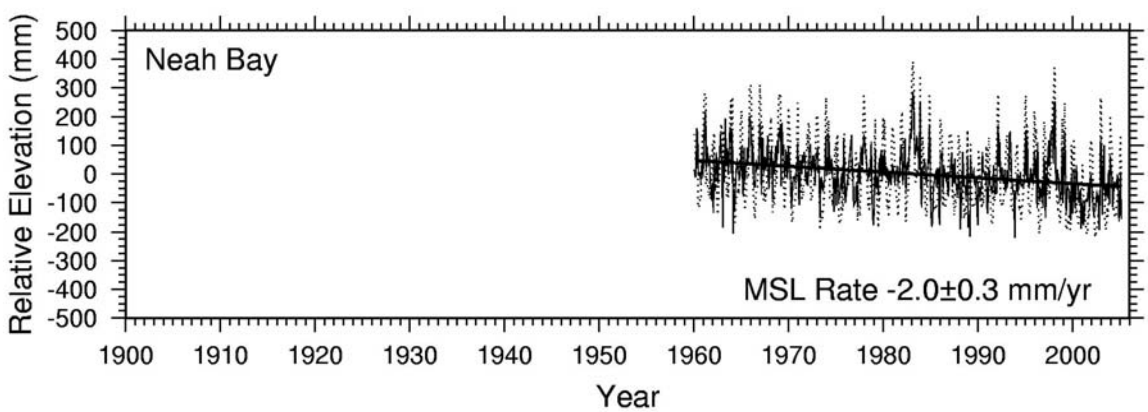


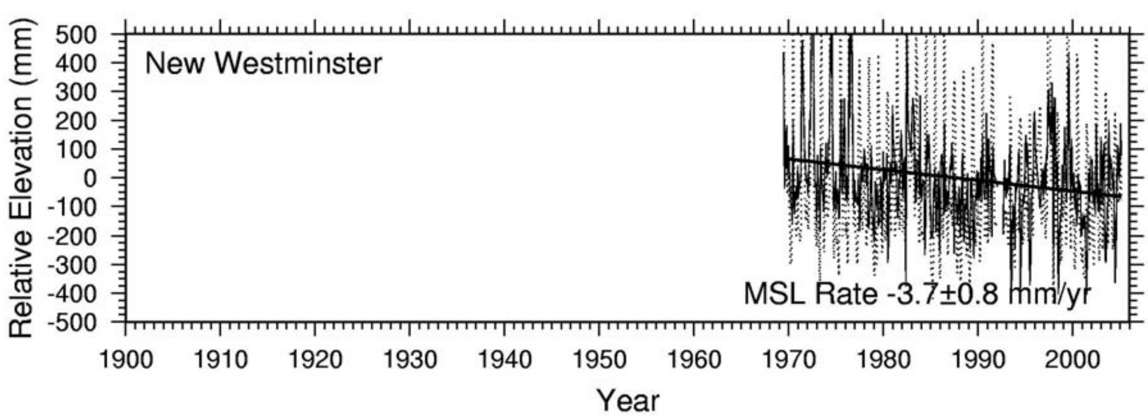


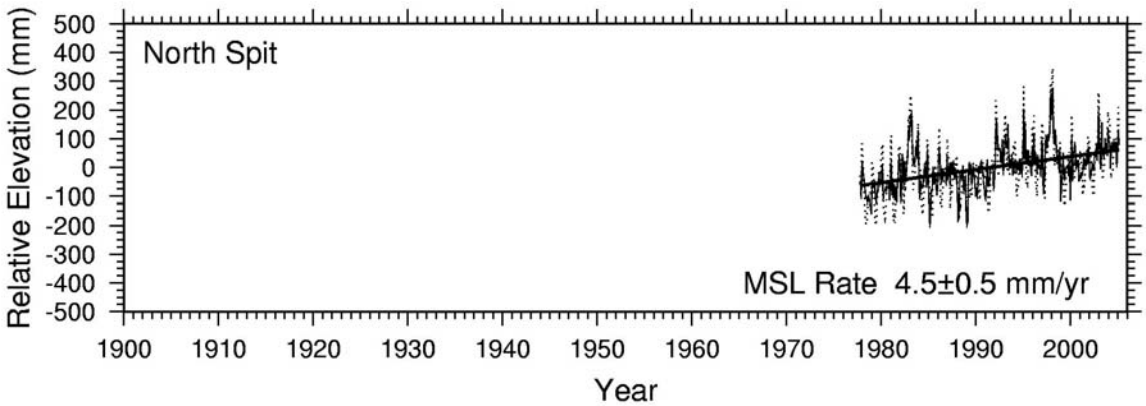
Campbell River
MSL Rate -2.8±0.4 mm/yr
Charleston
MSL Rate 1.1±0.4 mm/yr
Cherry Point
MSL Rate 0.6±0.4 mm/yr
Crescent City
MSL Rate -0.7±0.1 mm/yr
Relative Elevation (mm)
Year

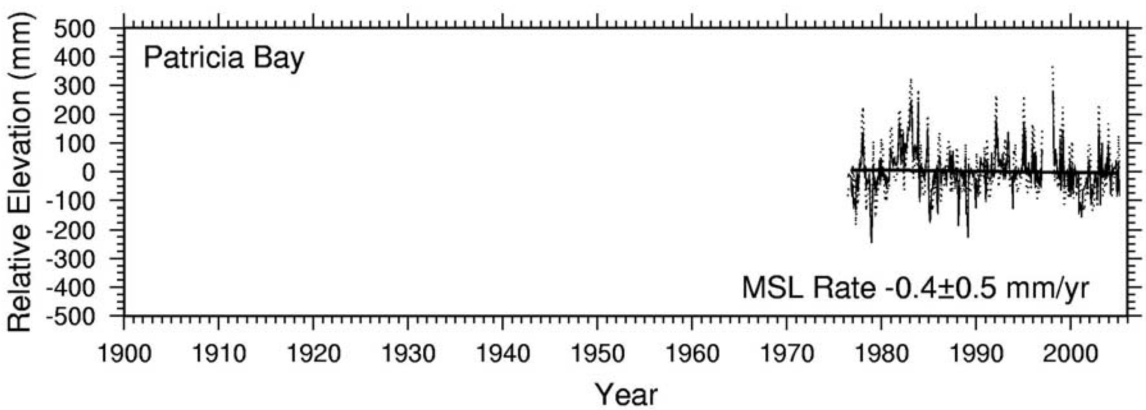

Friday Harbor
MSL Rate 1.1±0.1 mm/yr
Relative Elevation (mm)
Year

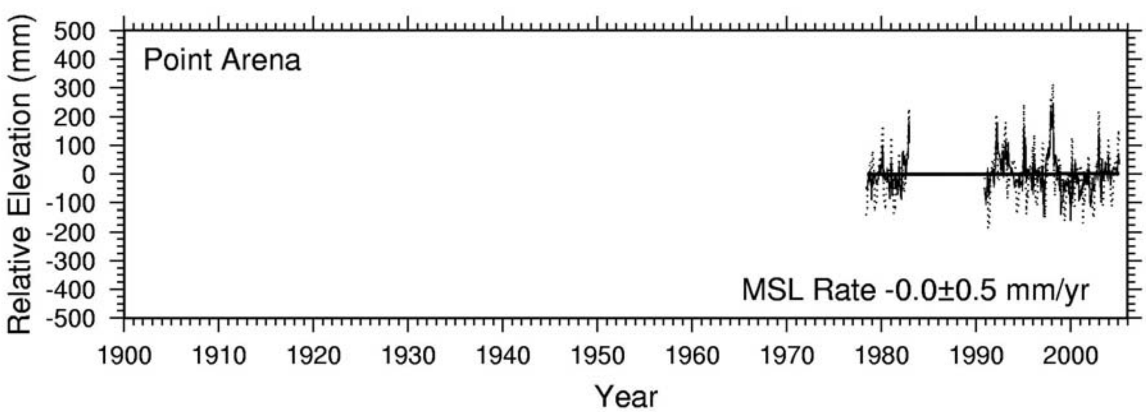

Fulford Harbour
MSL Rate 0.1±0.6 mm/yr
Relative Elevation (mm)
Year

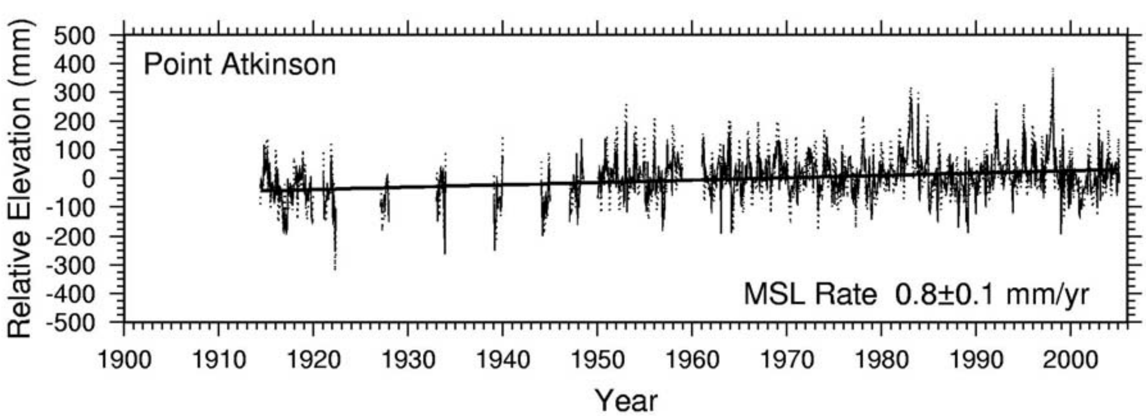

Neah Bay
MSL Rate -2.0±0.3 mm/yr
Relative Elevation (mm)
Year

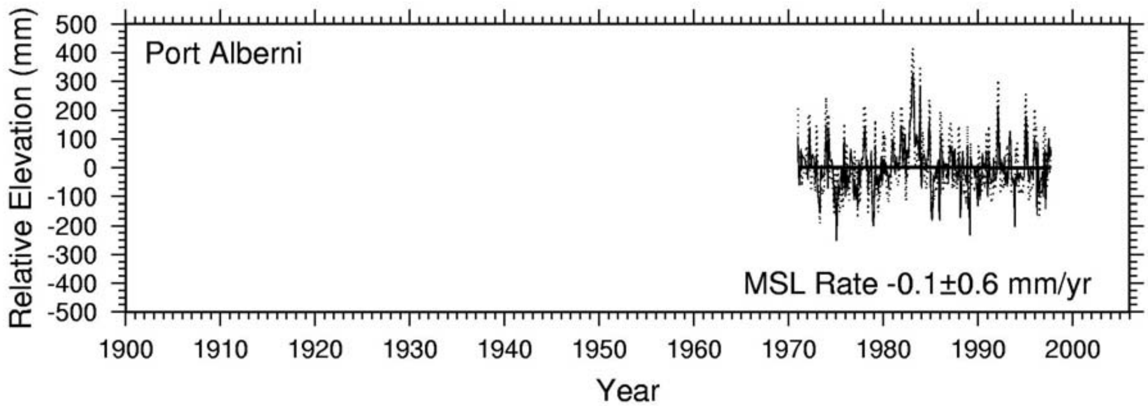

New Westminster
MSL Rate -3.7±0.8 mm/yr
Relative Elevation (mm)
Year

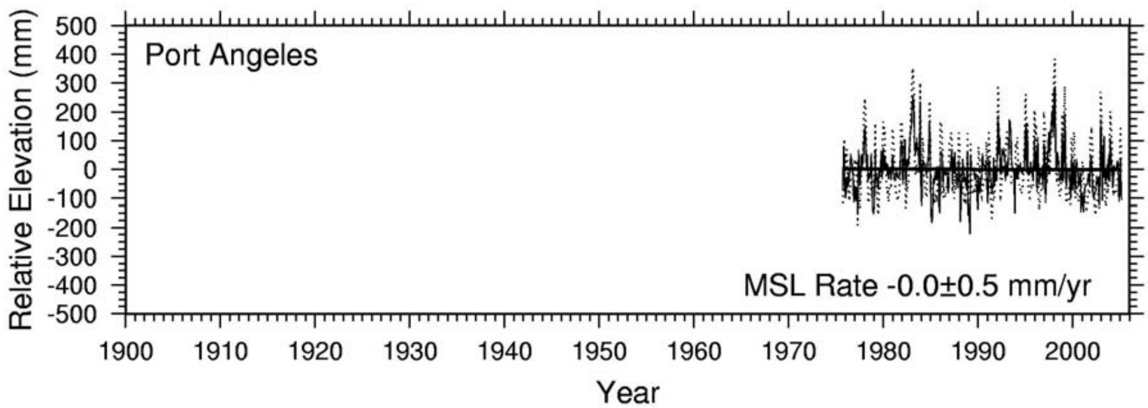

North Spit
MSL Rate 4.5±0.5 mm/yr
Relative Elevation (mm)
Year

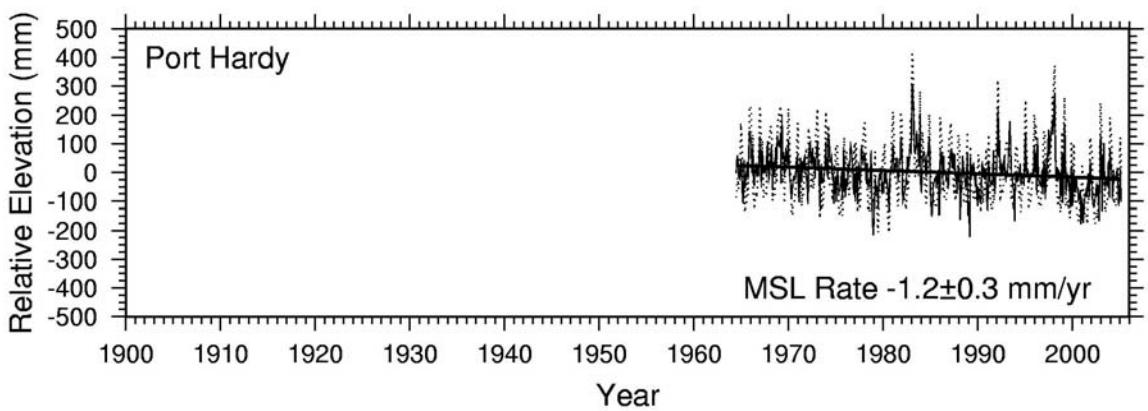

Patricia Bay
MSL Rate -0.4±0.5 mm/yr
Relative Elevation (mm)
Year

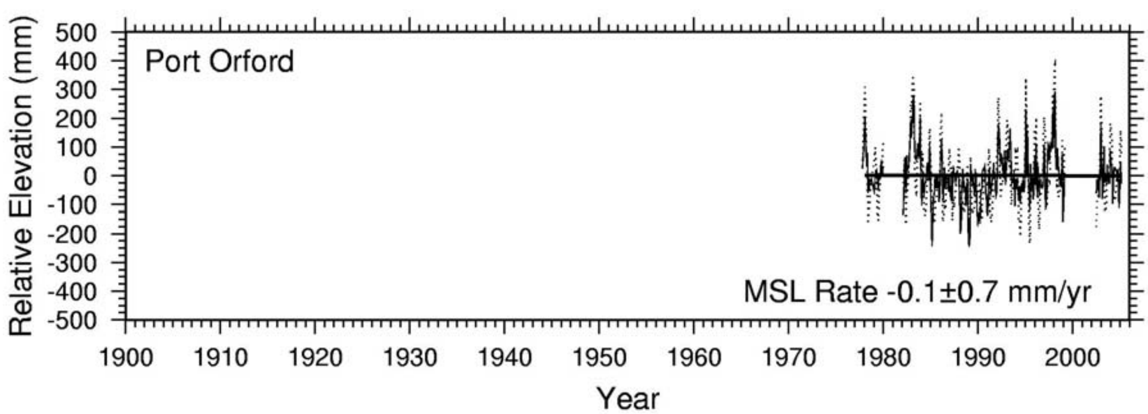

Point Arena
MSL Rate -0.0±0.5 mm/yr
Relative Elevation (mm)
Year

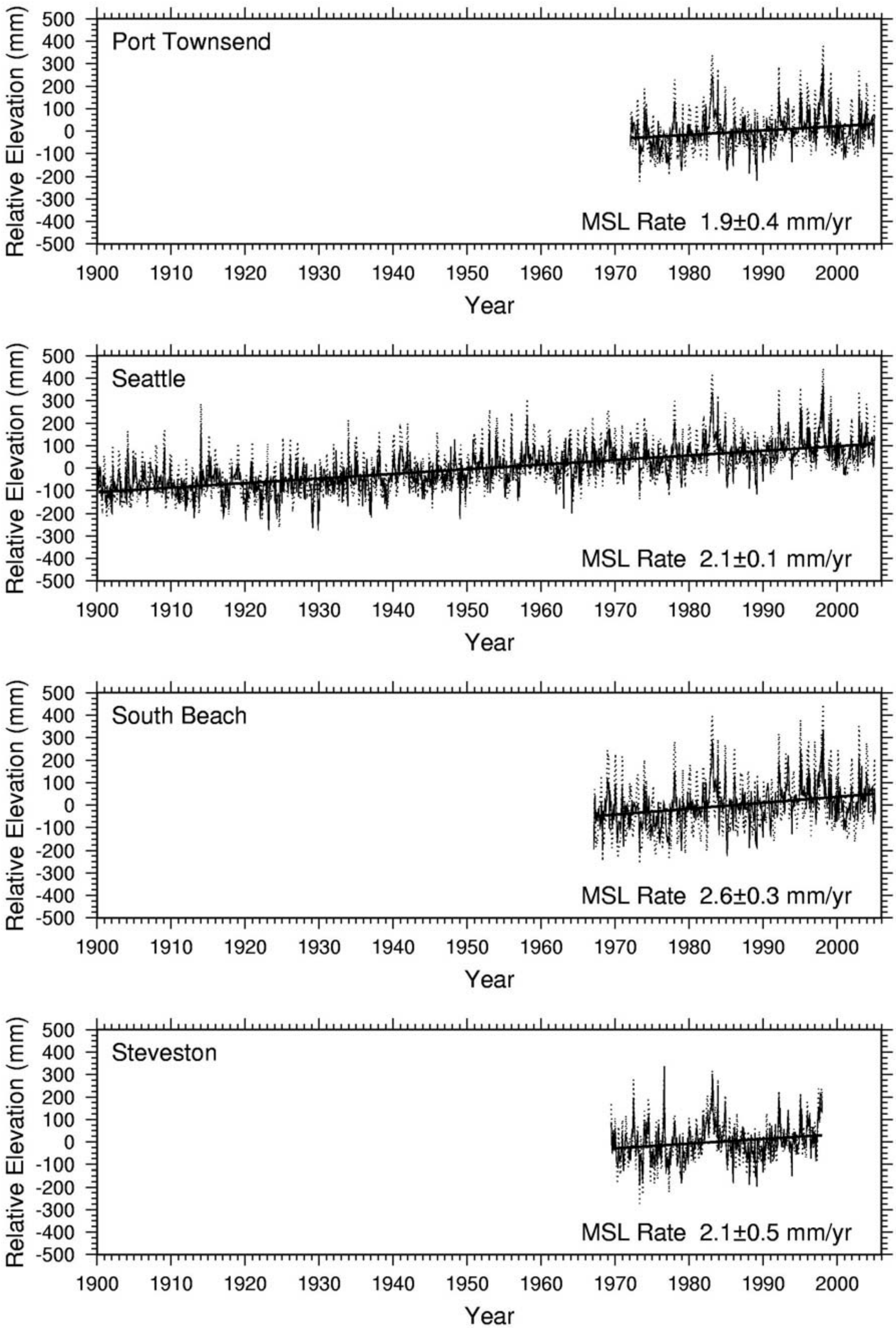

Point Atkinson
MSL Rate 0.8±0.1 mm/yr
Relative Elevation (mm)
Year

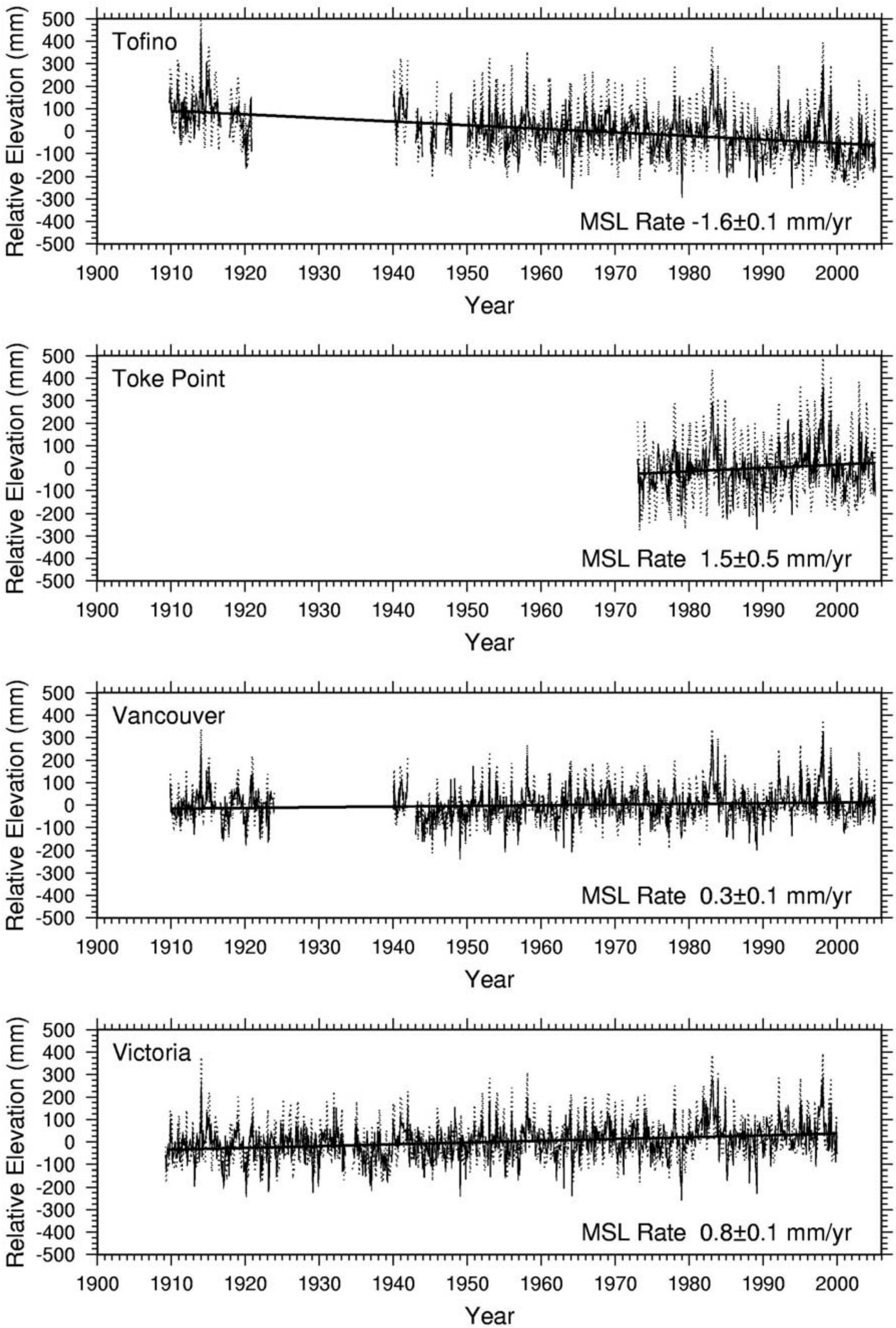

Port Alberni
Relative Elevation (mm)
MSL Rate -0.1±0.6 mm/yr
Year


Port Angeles
Relative Elevation (mm)
MSL Rate -0.0±0.5 mm/yr
Year


Port Hardy
Relative Elevation (mm)
MSL Rate -1.2±0.3 mm/yr
Year


Port Orford
Relative Elevation (mm)
MSL Rate -0.1±0.7 mm/yr
Year


Port Townsend
MSL Rate 1.9±0.4 mm/yr
Seattle
MSL Rate 2.1±0.1 mm/yr
South Beach
MSL Rate 2.6±0.3 mm/yr
Steveston
MSL Rate 2.1±0.5 mm/yr
Relative Elevation (mm)
Year
500
400
300
200
100
0
-100
-200
-300
-400
-500
1900
1910
1920
1930
1940
1950
1960
1970
1980
1990
2000


Tofino
MSL Rate -1.6±0.1 mm/yr
Toke Point
MSL Rate 1.5±0.5 mm/yr
Vancouver
MSL Rate 0.3±0.1 mm/yr
Victoria
MSL Rate 0.8±0.1 mm/yr
Relative Elevation (mm)
Year

4. Bibliography

Publications and Abstracts Related to this Project

Verdonck, D., *Contemporary vertical crustal deformation in Cascadia*, submitted to Tectonophysics.

Verdonck, D., 2005, *Vertical crustal deformation in Cascadia from historical leveling* PANGA Annual Workshop, January 2005, Vancouver, WA.

Verdonck, D., 2004, *Uplift and subsidence along the Cascadia subduction zone determined from historical repeated leveling*, Eos Trans. AGU, Fall Meet. Suppl, Abstract S43-D6.

Verdonck, D., 2004, *Vertical crustal deformation in cascadia from historical leveling*, GSA Abstracts with Programs, Paper 67-12.

Verdonck, D., 2004, *Determination of Vertical Surface Deformation From Repeated Historical Leveling in Cascadia*, Eos Trans. AGU, Spring Meet. Suppl., Abstract S421-04.

Verdonck, D., 2004, *An overview of ongoing analysis of active vertical deformation in Cascadia*, February 2004, PANGA Annual Workshop, Victoria, BC.