Technical Report NOS CO-OPS 065

Estimating Vertical Land Motion from Long-Term Tide Gauge Records

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noaa National Oceanic and Atmospheric Administration

U.S. DEPARTMENT OF COMMERCE
National Ocean Service
Center for Operational Oceanographic Products and Services

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National Ocean Service
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Table of Contents

List of Figures

Executive Summary

This report documents a methodology that can be used to estimate the vertical land motion (VLM) at NOAA tide stations by performing an oceanographic analysis of the long-term data sets. In the near future, VLM measurements will be the primary adjustment needed to locally calibrate scenario projections of global sea level rise such as those being generated by the National Climatic Assessment (NCA) for the US Global Climate Research Program (USGCRP).

The methodology presented here involves the decomposition of the observed relative mean sea level data and their computed trends. It is recognized that the long-term sea level time series observed at tide stations contains a component due to oceanography and a component due to VLM. The oceanographic signal is not completely described by a simple global sea level trend estimate.

The purpose of the methodology is to provide a more accurate estimation of local VLM at tide stations with 30-60 years of data rather than just simply subtracting the estimated global sea level trend of 1.7mm/yr from the observed relative mean sea level trend. Relative sea level trends calculated from shorter data periods are more likely to be affected by anomalously high or low oceanographic levels at the beginning or end of their series. By removing the regional oceanographic variability as calculated based on longer-period stations, both more accurate and more precise estimates of land motion are possible at shorter-period stations.

1.0 Background

Long-term tide gauge records provide information on relative sea-level variations. This is because they measure sea level relative to local land elevations through repeat leveling surveys from the tide gauge reference points to local terrestrial bench mark networks. Over time sea level variations are thus tracked relative to a fixed station datum maintained by the bench mark network.

The sea level variations contained in the long-term tide gauge records contain components that vary in frequency (e.g., from storm surge to decadal scale) and that vary spatially. Some common influences include tidal variations, local hydrodynamic variability, dynamical changes in regional and coastal oceanographic processes, climate-related global sea level variations and local and regional VLM (NOAA, 2010). The sea level trends that NOAA derives from these data sets are relative sea level trends (Zervas, 2009).

In performing research into global sea-level rise, long-term tide gauge records have been a primary source of information for estimating 20th century sea-level trends (i.e., Church and White, 2011). To do this, researchers carefully select only the longest high quality tide gauge records. In addition, only tide gauges located in open coastal areas with relatively “stable” land motion are chosen. These records are then adjusted for vertical global glacial isostatic adjustment (GIA) using GIA models (Douglas et al, 2001). Using these techniques, the research community consensus rate for global sea level rise for the last century is 1.7mm/yr (IPCC, 2007).

GIA models, however, provide only the broadest scale resolution of VLM and do not have resolution to provide information at local scales. Local processes associated with tectonics, volcanism, sediment compaction, and subsurface mineral and water extraction are often of significance and generally not accounted for in the GIA models. For purposes of engineering design and planning for sea level rise in a practical sense, estimates of VLM have been estimated by simply subtracting the best estimate global rates of sea level rise from the local trend observed at a tide gauge and looking at their difference (NRC, 1987).

In the past, NOAA has investigated local vertical crustal movements using a combination of precise geodetic re-leveling and long-term observations from tide stations (Holdahl and Morrison, 1973), and data from Continuously Operating Reference Systems (CORS) as well as using re-leveling, and observations from tide stations (Shinkle and Dokka, 2004). Routine precise re-leveling of large networks of coastal benchmarks is no longer logistically feasible and nation-wide traditional network geodetic precise re-leveling is not planned by NOAA.

Emerging methods to directly measure VLM utilize the expanding network of CORS stations. CORS data have been used to estimate GIA and evaluate GIA models (Sella et al, 2007). At locations where these high accuracy GPS receivers can be co-located with tide gauges, VLM can be more precisely determined and taken into account for estimating global sea level change (Snay, et al 2007; JPL, 2012; Woppelmann, 2007). However, these CORS networks are a recent phenomenon and long –term records are only starting to be accumulated. Co-location at tide gauges is proceeding very slowly. In the absence of direct measurement, it is possible to de-compose the tide gauge records to provide an estimate of local VLM. Other methodologies for estimating VLM include comparisons of satellite altimeter data with simultaneous tide gauge data (Nerem and Mitchum, 2002) as well as using repeat static GPS bench mark surveys at tide stations over time.

2.0 Analysis

Larsen *et al.* (2003) used an analysis of monthly means for removing sea level variations due to atmospheric and oceanographic effects and using a set of stations to construct a common mode oceanographic signal or an "oceanographic correction" in order to reveal nonlinear vertical land motion in Alaska. Savage and Plafker (1991) performed a similar analysis using annual mean sea levels to estimate rates of land uplift in southeast Alaska. Here, a similar, but not identical, approach is used.

The linear trends in relative mean sea level (NOAA sea level trends) were computed from the observations using the procedures found in Zervas (2009). These are the published NOAA trends also shown at http://tidesandcurrents.noaa.gov/sltrends. Figure 1 is an example output of the standard NOAA sea level trend analysis for Boston, MA in which the station's average seasonal cycle for mean sea level is removed as part of the process.

At a few stations, there are apparent datum shifts and earthquake effects resulting in different trends before and after the earthquake. These effects were modeled in the derivation of these station's linear trends. The residual after the trend(s) and seasonal cycle are removed was called the "interannual variation" in Zervas (2009). These interannual variations will, in this report, be assumed to be caused completely by oceanographic effects. The inverted barometer effect, the ocean's response to atmospheric pressure variation, is considered here to be an oceanographic effect, as is the ocean's response to wind stress.

The oceanographic residuals are obtained from each of these station time series by de-trending them with the derived relative NOAA sea level trend and removing each station's individual seasonal cycle simultaneously. Conceptually;

$$1) \quad O_{res} = MMSL_{obs} - MSL_{seasonal} - RSLR$$

Where,
$MMSL_{obs}$ = Observed monthly mean sea level
$MSL_{seasonal}$ = average seasonal cycle in MSL
RSLR = relative sea level trend
O_{res} = oceanographic residual

The oceanographic residuals revealed groupings of stations with high similarity in their variations. The U.S. Coast was divided up into 11 distinct geographic regions after comparisons of the residuals along the nation's coastlines. These groupings are expressed as the following regions:

Gulf of Maine
Mid-Atlantic Bight
South Atlantic Bight
Eastern Gulf of Mexico
Western Gulf of Mexico
Puerto Rico and Virgin Islands

Hawaii
Southern and Central California
Northern California, Oregon, and Washington
Southeastern Alaska
Southern Alaska and Aleutian Islands

An average oceanographic residual time series was constructed for each region by averaging the residuals from the set of tide stations in each region. Figure 2 is an example of the average regional oceanographic residual constructed from tide stations in the Gulf of Maine. These eleven residual series which extend up to 2009, begin as early as 1900 for the Mid-Atlantic and as late as 1944 for the Western Gulf of Mexico and 1962 for Puerto Rico and the Virgin Islands. Any decadal variation in the regional rate of absolute sea level rise over these years will also be incorporated into the average regional oceanographic residuals.

In the next step, the 20th century global sea level trend of 1.7mm/yr (Church and White, 2011) was added back into each of the average regional oceanographic residuals. The resulting time series represents an estimate of the regional sea level response to a full spectrum of oceanographic forcings within the data series as well as global sea level rise. Appendix 1 contains each of the regional oceanographic signals with the 1.7 mm/yr trend added in. Conceptually;

$$2)\quad O_{response} = O_{reg\ ave} + GSLR$$

where,

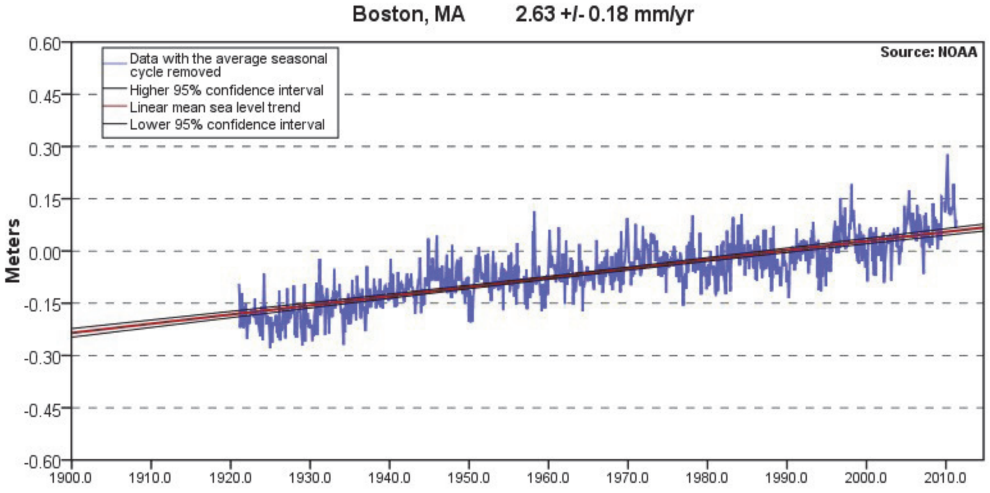
$O_{response}$ = total regional sea level response
$O_{reg\ ave}$ = average regional oceanographic residuals
GSLR = rate of global sea level rise for last century (1.7 mm/yr).

As the last step, this regional oceanographic sea level response time series was subtracted out from each observed monthly mean sea level time series originally used to compute each individual NOAA sea level trend (with the average seasonal cycle also removed). A linear trend was fit to the resultant data, as shown in Figure 3 for Boston, to provide the VLM estimate. Conceptually;

$$3)\quad VLM_{series} = (MMSL_{obs} - MSL_{seasonal}) - O_{response}$$

The premise of this methodology is that the linear trend of this final time series will approximate the VLM taking place at the station, assuming that this process detected and removed the oceanographic signal appropriately. The underlying assumption of a linear trend in the global sea level of 1.7 mm/yr over the last century and that the linear trends in VLM are constant in time are implicit in the methodology used. For purposes of this analysis, individual tide station trends are derived from varying lengths of record but are assumed to have remained constant over the last century, except for stations affected by great earthquakes which are assumed to have different trends before and after the seismic event. An assumption is made of no appreciable acceleration in the rate of sea-level rise over the last century and actual non-linear variability will add to the uncertainty of the results.

8443970 Boston, Massachusetts



The mean sea level trend is 2.63 millimeters/year with a 95% confidence Intervals of +/-0.18mm/yr based on monthly mean sea level data from 1921 to 2006 which is equivalent to a change of 0.86 feet in 100 years

Figure 1. The monthly mean sea level time series at Boston with the average seasonal cycle removed and showing the computed trend.

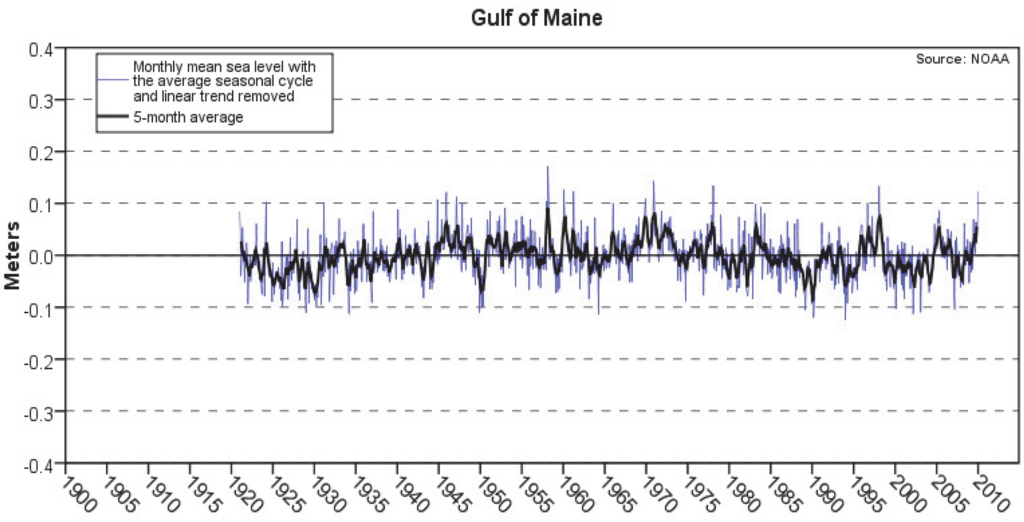


Figure 2. The regional oceanographic residual using an average of the data from Eastport. ME to Boston, MA

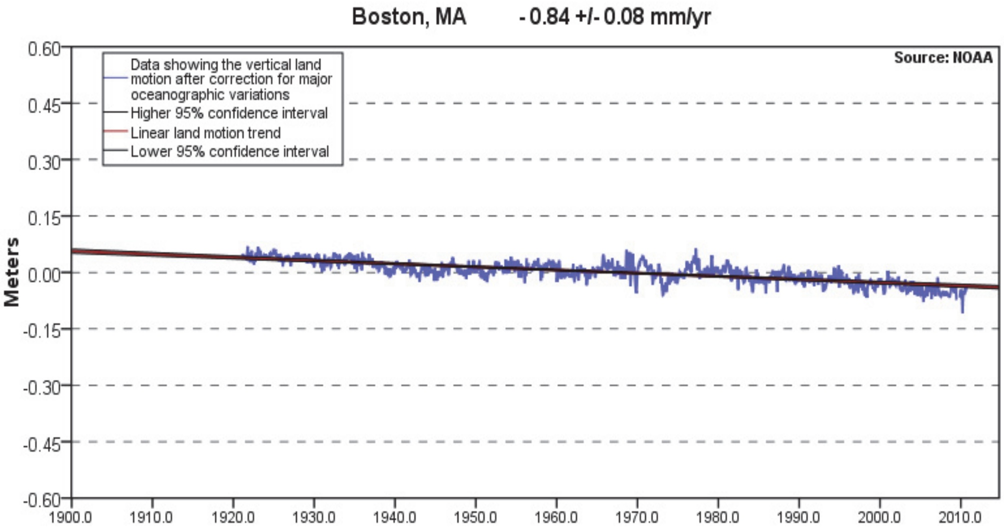


Figure 3. The estimated vertical land motion at Boston, MA

3.0 Results

Table 1 lists the published relative NOAA sea level trend for each station (along with the 95% Confidence Interval of the trend) and the estimated rate of VLM (along with the 95% Confidence Interval) using the methodology described above (see equation 3). 95% Confidence Intervals are 1.96 times the standard error obtained from the linear trend computation process (Zervas, 2009) and are inversely correlated with record length. Positive trends in sea level indicate sea level is rising relative to the land, negative trends in mean sea level indicate sea level is falling relative to the land. Positive trends in VLM indicate that the land is rising and negative trends in VLM indicate that the land is subsiding.

At the stations with the longest periods of record, the VLM rates obtained by this method are very close to the values that would be obtained by simply subtracting 1.7 mm/yr from the relative sea level trend. This method of obtaining VLM rates is more useful at some of the stations with shorter record lengths, where the relative sea level trend may be biased by anomalously high or low sea levels near the beginning or end of the series. For example at Lewisetta, the relative sea level trend is 4.97 +/- 1.04 mm/yr derived from 33 years of data. Subtracting the global rate of 1.7 mm/yr implies a subsidence rate of 3.27 mm/yr. However, in this report, we obtained a subsidence rate of 2.42 +/- 0.37 mm/yr, identical to the rate at nearby Gloucester Point derived from 54 years of data. In theory, this method of estimating VLM rates can be extended to other stations with periods of record shorter than 30 years, where a precise and accurate relative sea level trend cannot be obtained with much confidence.

Table 1. NOAA Tide Station Relative Sea Level Trends and Estimated Rates of Vertical Land Movement

Station Number	Station Name	First Year	Last Year	Series Length	MSL trend (mm/yr)	95% C.I.	Est. Vertical Land Movement (mm/yr)	95% C.I.
1611400	Nawiliwili	1955	2006	52	1.53	0.59	0.20	0.25
1612340	Honolulu	1905	2006	102	1.50	0.25	0.18	0.08
1612480	Mokuoloe	1957	2006	50	1.31	0.72	0.03	0.15
1615680	Kahului	1947	2006	60	2.32	0.53	-0.51	0.12
1617760	Hilo	1927	2006	80	3.27	0.35	-1.47	0.17
8410140	Eastport	1929	2006	78	2.00	0.21	-0.35	0.11
8413320	Bar Harbor	1947	2006	60	2.04	0.26	-0.75	0.19
8418150	Portland	1912	2006	95	1.82	0.17	-0.16	0.11
8419870	Seavey Island	1926	2001	76	1.76	0.30	0.21	0.15
8443970	Boston	1921	2006	86	2.63	0.18	-0.84	0.08
8447930	Woods Hole	1932	2006	75	2.61	0.20	-0.97	0.12
8449130	Nantucket Island	1965	2006	42	2.95	0.46	-1.16	0.33
8452660	Newport	1930	2006	77	2.58	0.19	-0.88	0.09
8454000	Providence	1938	2006	69	1.95	0.28	-0.30	0.14
8461490	New London	1938	2006	69	2.25	0.25	-0.67	0.10
8467150	Bridgeport	1964	2006	43	2.56	0.58	-0.76	0.15

Station Number	Station Name	First Year	Last Year	Series Length	MSL trend (mm/yr)	95% C.I.	Est. Vertical Land Movement (mm/yr)	95% C.I.
8510560	Montauk	1947	2006	60	2.78	0.32	-1.23	0.15
8516945	Kings Point / Willets Point	1931	2006	76	2.35	0.24	-0.67	0.07
8518750	The Battery	1856	2006	151	2.77	0.09	-1.22	0.06
8531680	Sandy Hook	1932	2006	75	3.90	0.25	-2.27	0.07
8534720	Atlantic City	1911	2006	96	3.99	0.18	-2.17	0.11
8536110	Cape May	1965	2006	42	4.06	0.74	-2.10	0.25
8545240	Philadelphia	1900	2006	107	2.79	0.21	-1.06	0.11
8551910	Reedy Point	1956	2006	51	3.46	0.66	-1.71	0.30
8557380	Lewes	1919	2006	88	3.20	0.28	-1.66	0.11
8570283	Ocean City	1975	2006	32	5.48	1.67	-2.73	1.19
8571892	Cambridge	1943	2006	64	3.48	0.39	-1.90	0.08
8573927	Chesapeake City	1972	2006	35	3.78	1.56	-1.33	0.34
8574680	Baltimore	1902	2006	105	3.08	0.15	-1.33	0.05
8575512	Annapolis	1928	2006	79	3.44	0.23	-1.62	0.07
8577330	Solomons Island	1937	2006	70	3.41	0.29	-1.83	0.08
8594900	Washington	1924	2006	83	3.16	0.35	-1.34	0.17
8632200	Kiptopeke	1951	2006	56	3.48	0.42	-1.90	0.14
8635150	Colonial Beach	1972	2003	32	4.78	1.21	-3.07	0.31
8635750	Lewisetta	1974	2006	33	4.97	1.04	-2.42	0.37
8637624	Gloucester Point	1950	2003	54	3.81	0.47	-2.42	0.14
8638610	Sewells Point	1927	2006	80	4.44	0.27	-2.61	0.11
8638863	Chesapeake Bay Br. Tunnel	1975	2006	32	6.05	1.14	-3.34	0.36
8652587	Oregon Inlet Marina	1977	2006	30	2.82	1.76	-0.64	0.84
8656483	Beaufort	1953	2006	54	2.57	0.44	-0.79	0.20
8658120	Wilmington	1935	2006	72	2.07	0.40	-0.43	0.22
8659084	Southport	1933	2006	74	2.08	0.46	-0.52	0.16
8661070	Springmaid Pier	1957	2006	50	4.09	0.76	-2.34	0.63
8665530	Charleston	1921	2006	86	3.15	0.25	-1.24	0.07
8670870	Fort Pulaski	1935	2006	72	2.98	0.33	-1.36	0.10
8720030	Fernandina Beach	1897	2006	110	2.02	0.20	-0.60	0.11
8720218	Mayport	1928	2006	79	2.40	0.31	-0.59	0.12
8723970	Vaca Key	1971	2006	36	2.78	0.60	-1.20	0.45
8724580	Key West	1913	2006	94	2.24	0.16	-0.50	0.10
8725110	Naples	1965	2006	42	2.02	0.60	-0.27	0.43
8725520	Fort Myers	1965	2006	42	2.40	0.65	-0.62	0.41
8726520	St. Petersburg	1947	2006	60	2.36	0.29	-0.92	0.14
8726724	Clearwater Beach	1973	2006	34	2.43	0.80	-0.86	0.51

Station Number	Station Name	First Year	Last Year	Series Length	MSL trend (mm/yr)	95% C.I.	Est. Vertical Land Movement (mm/yr)	95% C.I.
8727520	Cedar Key	1914	2006	93	1.80	0.19	-0.11	0.08
8728690	Apalachicola	1967	2006	40	1.38	0.87	0.24	0.44
8729108	Panama City	1973	2006	34	0.75	0.83	0.60	0.30
8729840	Pensacola	1923	2006	84	2.10	0.26	-0.33	0.10
8735180	Dauphin Island	1966	2006	41	2.98	0.87	-1.22	0.36
8761724	Grand Isle	1947	2006	60	9.24	0.59	-7.60	0.22
8770570	Sabine Pass	1958	2006	49	5.66	1.07	-3.85	0.52
8771450	Galveston Pier 21	1908	2006	99	6.39	0.28	-4.72	0.15
8771510	Galveston Pleasure Pier	1957	2006	50	6.84	0.81	-4.94	0.45
8772440	Freeport	1954	2006	53	4.35	1.12	-3.65	0.41
8774770	Rockport	1948	2006	59	5.16	0.67	-3.65	0.39
8779770	Port Isabel	1944	2006	63	3.64	0.44	-2.16	0.20
9410170	San Diego	1906	2006	101	2.06	0.20	-0.37	0.07
9410230	La Jolla	1924	2006	83	2.07	0.29	-0.37	0.13
9410660	Los Angeles	1923	2006	84	0.83	0.27	0.91	0.11
9410840	Santa Monica	1933	2006	74	1.46	0.40	0.28	0.18
9411340	Santa Barbara	1973	2006	34	1.25	1.82	2.02	0.64
9412110	Port San Luis	1945	2006	62	0.79	0.48	0.93	0.22
9413450	Monterey	1973	2006	34	1.34	1.35	0.33	0.25
9414290	San Francisco	1854	1897	44	2.05	0.85		
9414290	San Francisco	1897	2006	110	2.01	0.21	-0.36	0.08
9414523	Redwood City	1974	2006	33	2.06	3.12	0.10	0.86
9414750	Alameda	1939	2006	68	0.82	0.51	0.78	0.20
9415020	Point Reyes	1975	2006	32	2.10	1.52	-0.51	0.29
9415144	Port Chicago	1976	2006	31	2.08	2.74	-1.09	1.42
9418767	North Spit	1977	2006	30	4.73	1.58	-3.43	0.54
9419750	Crescent City	1933	2006	74	-0.65	0.36	2.38	0.16
9431647	Port Orford	1977	2006	30	0.18	2.18	1.40	0.70
9432780	Charleston	1970	2006	37	1.29	1.15	0.57	0.24
9435380	South Beach	1967	2006	40	2.72	1.03	-1.12	0.22
9437540	Garibaldi	1970	2006	37	1.98	1.82	0.01	0.97
9439040	Astoria	1925	2006	82	-0.31	0.40	2.10	0.23
9440910	Toke Point	1973	2006	34	1.60	1.38	0.22	0.44
9443090	Neah Bay	1934	2006	73	-1.63	0.36	3.34	0.10
9444090	Port Angeles	1975	2006	32	0.19	1.39	1.57	0.24
9444900	Port Townsend	1972	2006	35	1.98	1.15	-0.24	0.16
9447130	Seattle	1898	2006	109	2.06	0.17	-0.54	0.08
9449424	Cherry Point	1973	2006	34	0.82	1.20	1.17	0.23

Station Number	Station Name	First Year	Last Year	Series Length	MSL trend (mm/yr)	95% C.I.	Est. Vertical Land Movement (mm/yr)	95% C.I.
9449880	Friday Harbor	1934	2006	73	1.13	0.33	0.58	0.10
9450460	Ketchikan	1919	2006	88	-0.19	0.27	1.88	0.15
9451600	Sitka	1924	2006	83	-2.05	0.32	3.71	0.11
9452210	Juneau	1936	2006	71	-12.92	0.43	14.62	0.15
9452400	Skagway	1944	2006	63	-17.12	0.65	18.96	0.31
9453220	Yakutat	1940	2006	67	-6.44	0.47		
9453220	Yakutat (Pre EQ)	1940	1979	40	-4.81	0.89	12.31	0.51
9453220	Yakutat (Post EQ)	1979	2006	28	-11.53	1.46		
9454050	Cordova (Pre EQ)	1949	1961	13	5.01	10.92	-3.45	0.44
9454050	Cordova (Post EQ)	1964	2006	43	5.76	0.87		
9454240	Valdez	1973	2006	34	-2.52	1.36	3.88	0.71
9455090	Seward (Pre EQ)	1925	1964	40	-0.11	1.08	3.82	0.35
9455090	Seward (Post EQ)	1964	2006	43	-1.74	0.91		
9455500	Seldovia	1964	2006	43	-9.45	1.10	11.42	0.61
9455760	Nikiski	1973	2006	34	-9.80	1.50	11.83	0.99
9455920	Anchorage	1972	2006	35	0.88	1.54	1.40	0.80
9457292	Kodiak Island (Pre EQ)	1949	1964	16	1.19	3.70	11.59	0.65
9457292	Kodiak Island (Post EQ)	1975	2006	32	-10.42	1.33		
9459450	Sand Point	1972	2006	35	0.92	1.32	0.58	0.56
9461380	Adak Island (Pre EQ)	1943	1957	15	2.45	3.61	4.33	0.37
9461380	Adak Island (Post EQ)	1957	2006	50	-2.75	0.54		
9462620	Unalaska (Pre EQ)	1934	1957	24	-0.57	2.16	7.25	0.28
9462620	Unalaska (Post EQ)	1957	2006	50	-5.72	0.67		
9751401	Lime Tree Bay	1977	2006	30	1.74	1.20	-0.15	0.44
9751639	Charlotte Amalie	1975	2006	32	1.20	0.96	0.52	0.25
9755371	San Juan	1962	2006	45	1.65	0.52	0.02	0.11
9759110	Magueyes Island	1955	2006	52	1.35	0.37	0.49	0.10

For reference, comparison of estimated rates of vertical land motion from three independent methodologies is presented in Table 2. The NOAA values are taken from Table 1 as derived from the procedure described in this report. The Woppelmann *et al* (2007) data are derived from selected long-term continuous GPS measurements located near tide gauges. The Nerem and Mitchum (2002) values are derived from simultaneous comparison of satellite altimeter and tide gauge time series.The relative “co-location” of the data and their spatial representation becomes an issue when comparing these data as well as the series lengths being used. In general, table 2 shows better comparison between the NOAA estimated rates and the GPS-derived rates.

Table 2. Comparison of Estimated Rates of Vertical Land Motion (three independent sources)

Station	NOAA	Woppelmann et al	Nerem and Mitchum
Honolulu, HI	0.18 +/- 0.08 mm/yr	0.46 +/- 0.17 mm/yr	-2.26 +/- 0.71 mm/yr
Neah Bay, WA	3.34 +/- 0.10 mm/yr	4.21 +/- 0.13 mm/yr	-0.07 +/- 1.55 mm/yr
Charleston, SC	-1.24 +/- 0.07 mm/yr	-1.80 +/- 0.23 mm/yr	-3.19 +/- 1.38 mm/yr
Fernandina Bch. FL	-0.60 +/- 0.11 mm/yr	-4.28 +/- 0.13 mm/yr	3.54 +/- 3.23 mm/yr
Key West, FL	-0.50 +/- 0.10 mm/yr	-0.50 +/- 0.16 mm/yr	1.94 +/- 1.05 mm/yr
Newport, RI	-0.88 +/- 0.09 mm/yr	-0.18 +/- 0.12 mm/yr	-0.69 +/- 1.59 mm/yr

Sources: NOAA trends using >60 years tide gauge data ; Woppelmann et al GPS trends from GPS data series averaging 5.9 years, Nerem and Mitchum trends averaging 7.5 years simultaneous tide gauge/altimeter data. The uncertainties expressed in the table should not directly be compared as they are derived using different methodologies.

Table 3 is a comparison of the NOAA derived trends with a selected set of GPS-derived time series from JPL (2013). The GPS stations were selected based on closeness of co-location with the tide gauge location, series length, and data completeness and datum continuity. These recent data analyses represent more GPS information with longer data series than previous studies (Snay et al, 2007 and Woppelmann et al, 2007). The largest difference is found at Skagway, AK where the assumption of linearity in VLM may not hold and for Monterey, CA where the reason for the large difference is not obvious as the tide gauge and GPS are fairly close. The NOAA analysis and error estimates are derived from tide gauge record lengths provided in Table 1. GPS record lengths are provided in Table 3.

Table 3. Comparison of Estimated Rates of Vertical Land Motion: Selected Tide Gauge and GPS time series.

Station	NOAA Analysis	JPL GPS Analysis	GPS Analysis Time Period
Honolulu, HI	0.18 +/- 0.08 mm/yr	-0.50 +/- 0.27 mm/yr	14 years
Hilo, HI	-1.47 +/- 0.17 mm/yr	-1.57 +/- 0.61 mm/yr	12 years
Newport, RI	-0.88 +/- 0.09 mm/yr	-0.43 +/- 0.74 mm/yr	9 years
Sandy Hook, NJ	-2.27 +/- 0.07 mm/yr	-2.17 +/- 1.88 mm/yr	10 years
Reedy Point, DE	-1.71 +/- 0.30 mm/yr	-2.04 +/- 0.80 mm/yr	8 years
Cambridge, MD	-1.90 +/- 0.08 mm/yr	-1.27 +/- 0.67 mm/yr	17 years
Gloucester Point, VA	-2.42 +/- 0.14 mm/yr	-2.25 +/- 0.70 mm/yr	9 years
Key West, FL	-0.50 +/- 0.10 mm/yr	-0.86 +/- 0.82 mm/yr	10 years

Station	NOAA Analysis	JPL GPS Analysis	GPS Analysis Time Period
Galveston PP, TX	-4.94 +/- 0.45 mm/yr	-5.41 +/- 1.14 mm/yr	7 years
Monterey, CA	0.33 +/- 0.25 mm/yr	-1.43 +/- 0.86 mm/yr	6 years
Point Reyes, CA	-0.51 +/- 0.29 mm/yr	-0.81 +/- 0.22 mm/yr	13 years
Crescent City, CA	2.38 +/- 0.16 mm/yr	2.51 +/- 0.43 mm/yr	11 years
Seattle, WA	-0.54 +/- 0.08 mm/yr	-1.35 +/- 0.25 mm/yr	14 years
Friday Hbr., WA	0.58 +/- 0.10 mm/yr	-0.21 +/- 0.37 mm/yr	11 years
Skagway, AK	18.96 +/- 0.31 mm/yr	16.33 +/- 1.09 mm/yr	7 years
Nikiski, AK	11.83 +/- 0.99 mm/yr	11.07 +/- 2.17 mm/yr	11 years

Source: NOAA trends using >60 years tide gauge data; GPS trends from JPL GPS Time Series Web-site found at: http://sideshow.jpl.nasa.gov/mbh/series.html - *reported formal standard errors of GPS trends were multiplied by 1.96 to estimate 95% Confidence Intervals comparable to the listed 95% Confidence Intervals for the rates derived from the tide gauges.*

4.0 SUMMARY

A more robust methodology for estimating VLM at tide stations than simple subtraction of estimated global rates of sea level rise from tide gauge time series has been presented. The results using the NOAA methodology for estimating VLM may not be very different from the more simple direct subtraction of global and local trends. They may be more accurate however, as the methodology accounts for the regional variations in the long-term oceanographic signal, which can contribute to substantial variability in relatively short records biased by decadal-scale variability. The estimated VLM trends compare reasonably well with rates derived from co-located GPS time series.

Following the NRC (1987) convention, the VLM values derived here can be used as the value of "M" in the USACE EC modified NRC equations. Use of the values in Table 1 eliminates the need for the user to calculate the value of "M" in the EC equations and these tabular values can be directly entered into the calculation.

Further comparison of these VLM rates with those derived from GPS (CORS) continues along with the planning for further co-location of CORS at tide stations world-wide. Where high quality long-term GPS measurements have not been made, rates of VLM can be estimated using the methodology described in this report. The rates must be used, however, only with full understanding of their uncertainties.

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The authors wish to thank John Boon (VIMS), Philippe Tissot (CBI) and Russell Watkins (UFL) for their technical review and many helpful comments on this document. The authors also appreciate the support of Brenda Via (CO-OPS) in preparing this document for publication.

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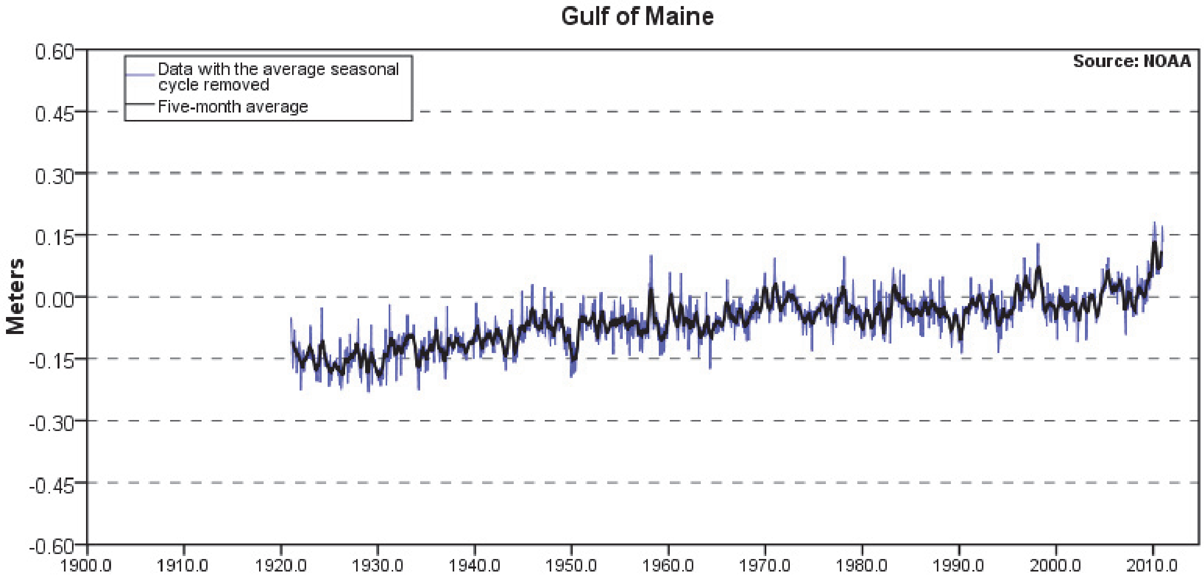
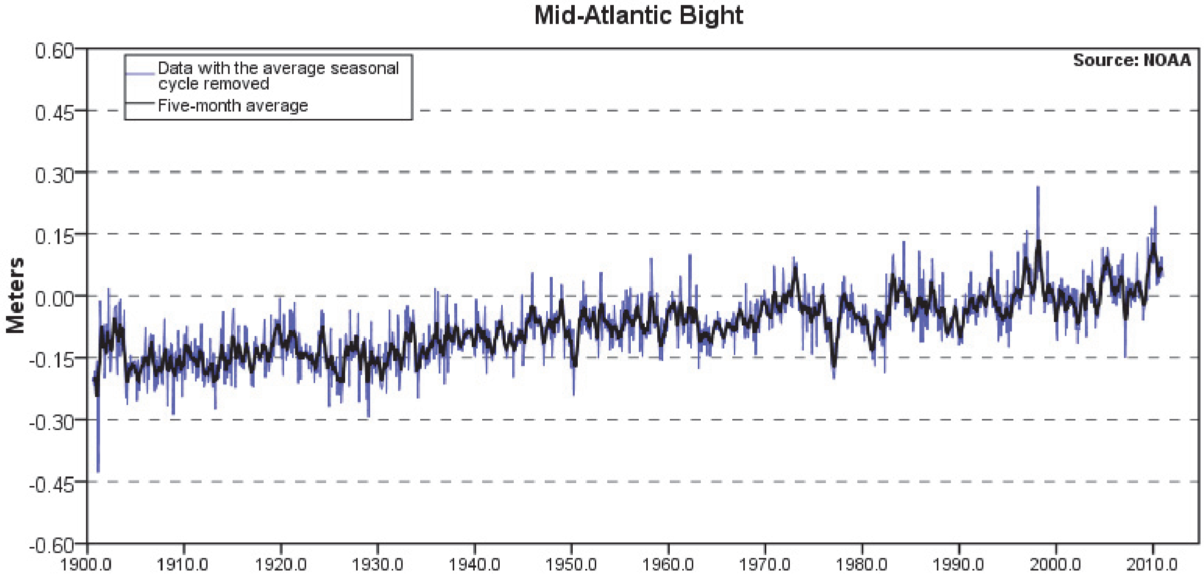
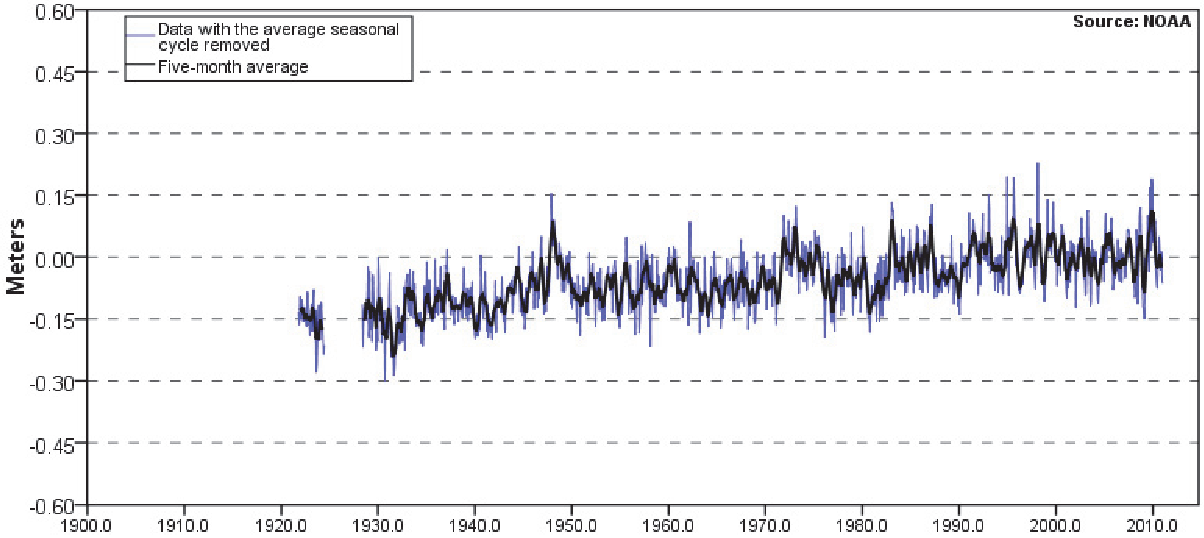
Appendix
Plots of regional oceanographic signal composites



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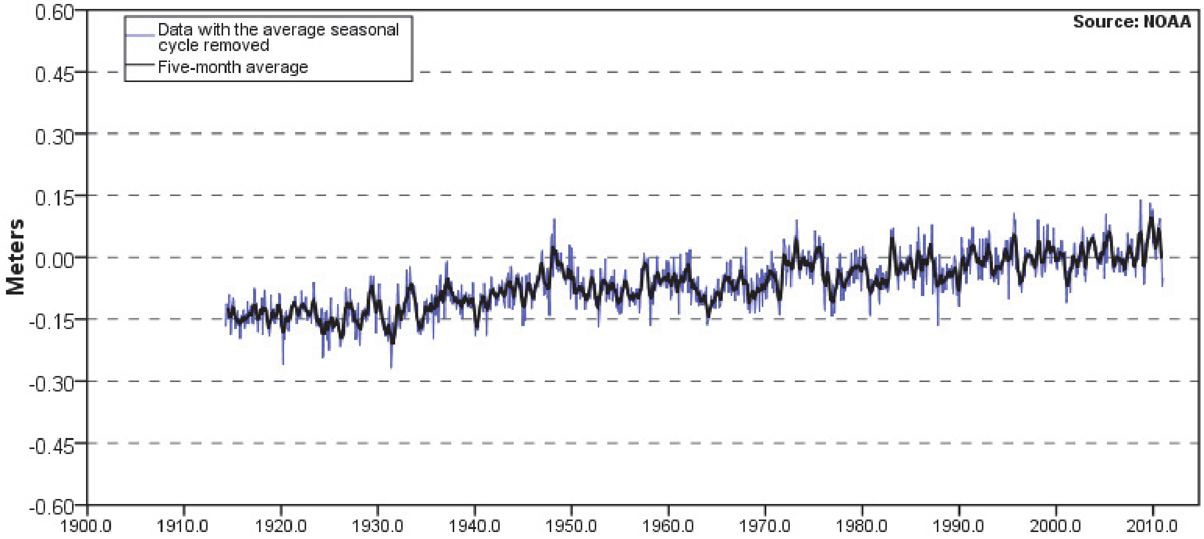
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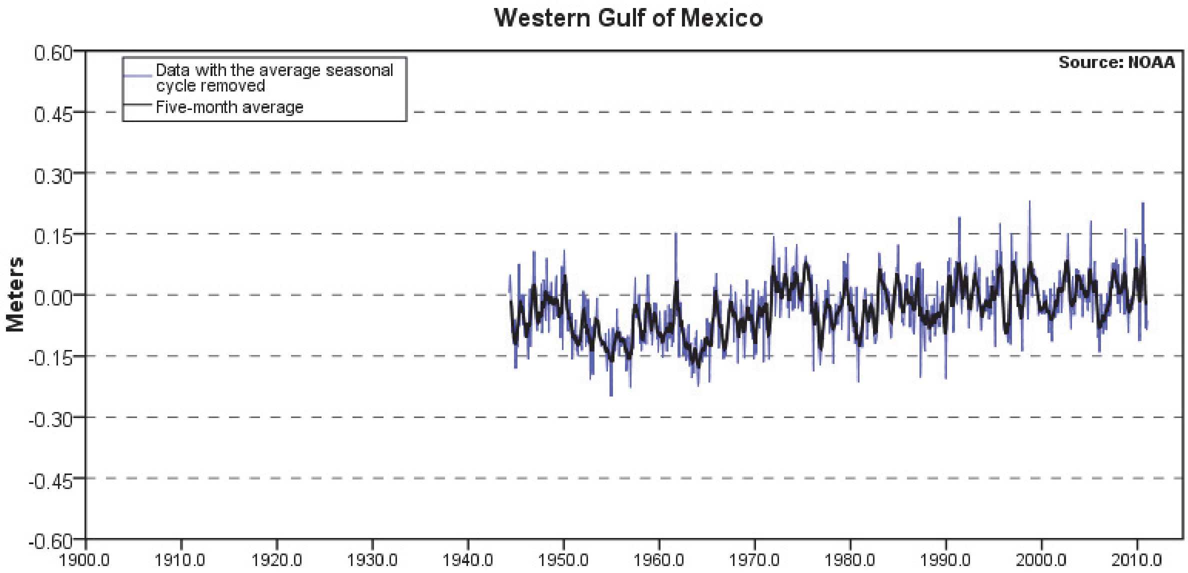
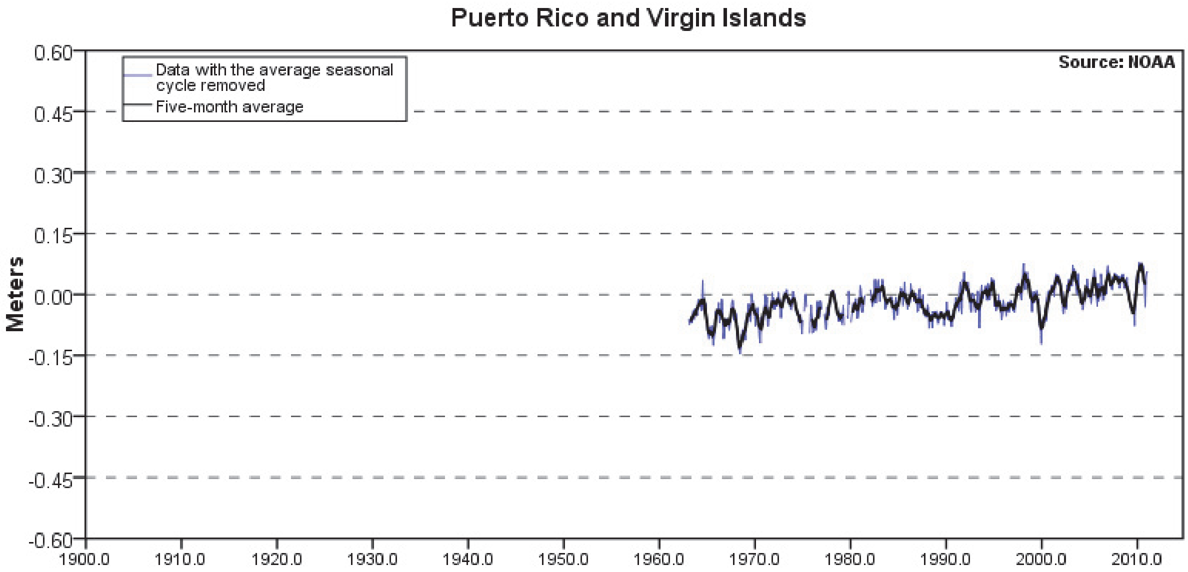

Western Gulf of Mexico
Data with the average seasonal cycle removed
Five-month average
Source: NOAA
Meters
0.60
0.45
0.30
0.15
0.00
-0.15
-0.30
-0.45
-0.60
1900.0
1910.0
1920.0
1930.0
1940.0
1950.0
1960.0
1970.0
1980.0
1990.0
2000.0
2010.0


Puerto Rico and Virgin Islands
Data with the average seasonal cycle removed
Five-month average
Source: NOAA
Meters
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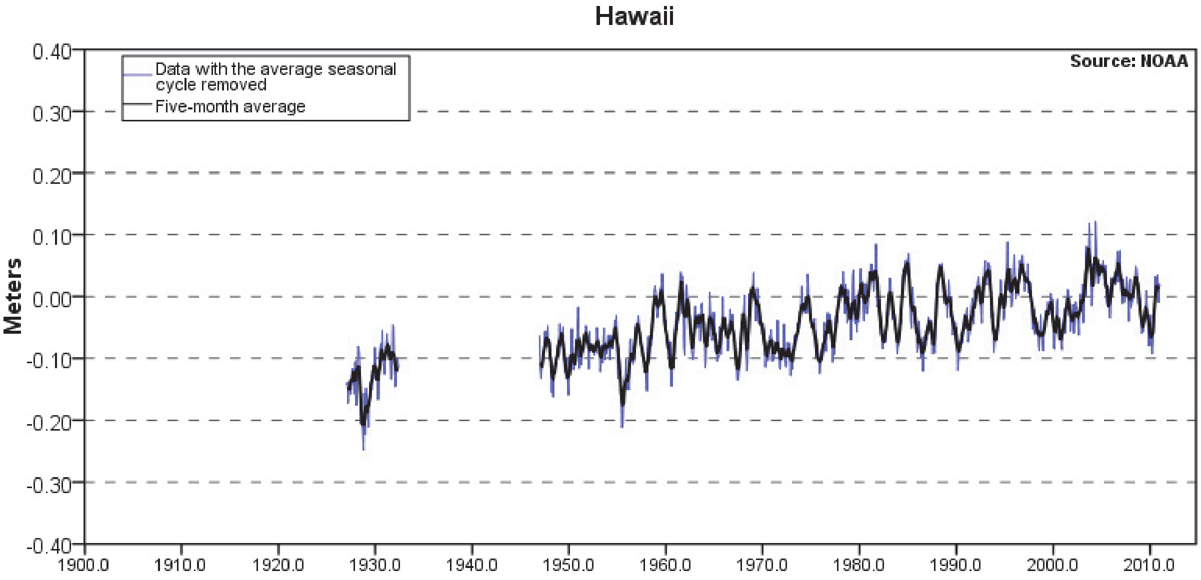
0.45
0.30
0.15
0.00
-0.15
-0.30
-0.45
-0.60
1900.0
1910.0
1920.0
1930.0
1940.0
1950.0
1960.0
1970.0
1980.0
1990.0
2000.0
2010.0


Hawaii
Source: NOAA
Data with the average seasonal cycle removed
Five-month average
Meters
0.40
0.30
0.20
0.10
0.00
-0.10
-0.20
-0.30
-0.40
1900.0
1910.0
1920.0
1930.0
1940.0
1950.0
1960.0
1970.0
1980.0
1990.0
2000.0
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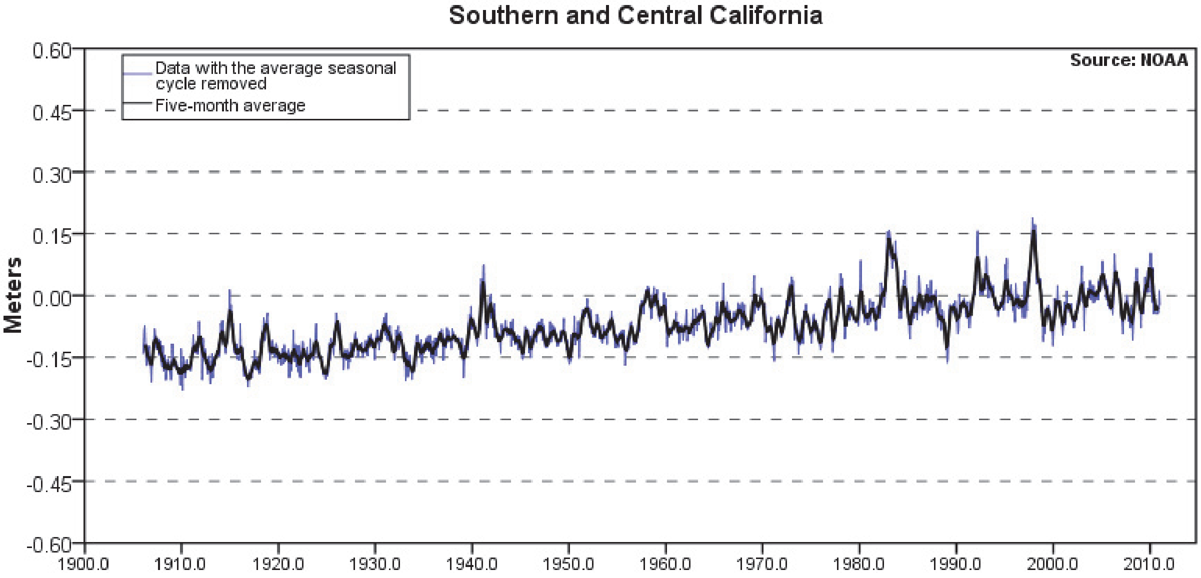
Southern and Central California
Source: NOAA
Data with the average seasonal cycle removed
Five-month average
Meters
0.60
0.45
0.30
0.15
0.00
-0.15
-0.30
-0.45
-0.60
1900.0
1910.0
1920.0
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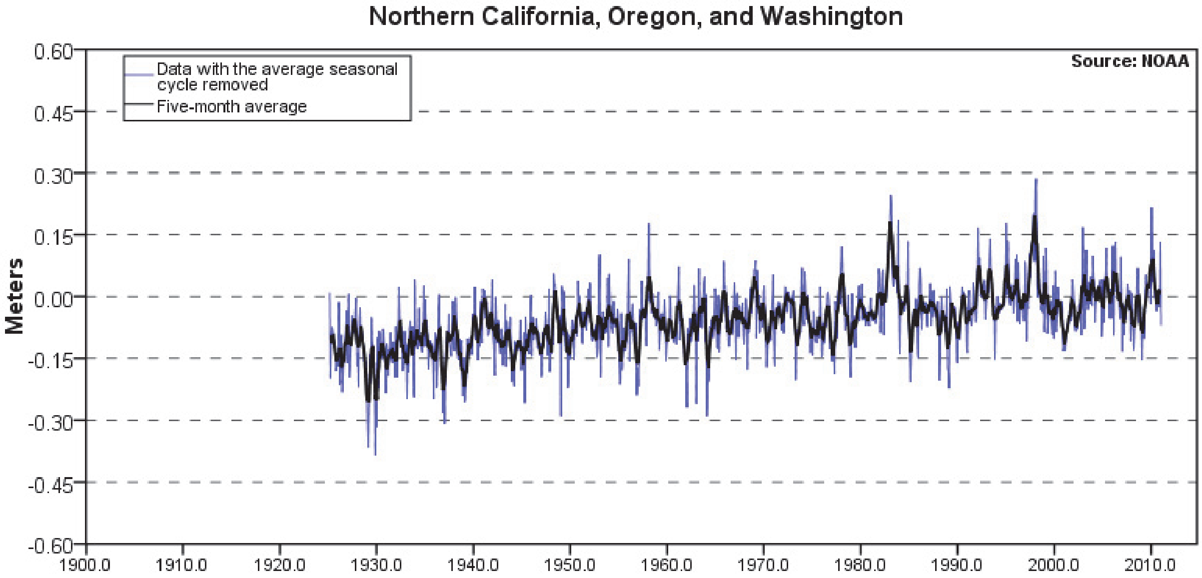
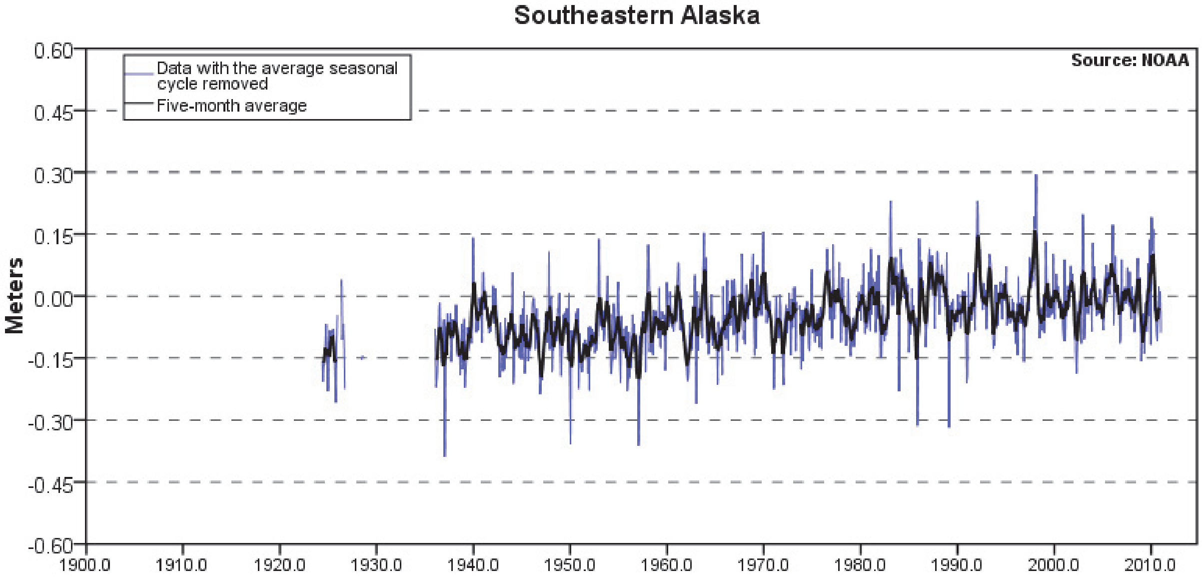
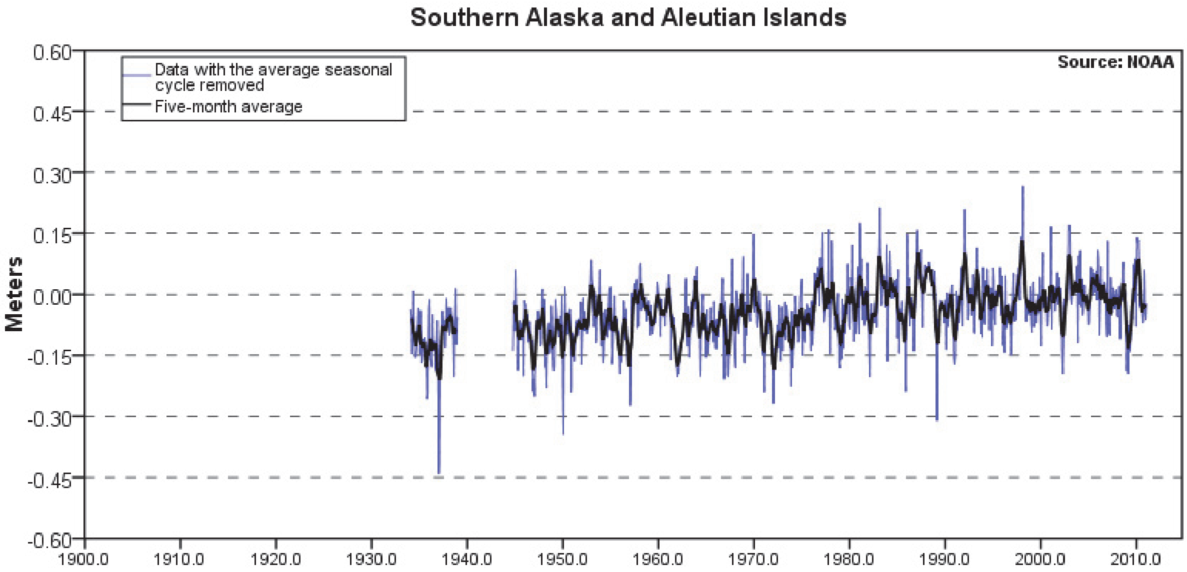


Northern California, Oregon, and Washington



Southeastern Alaska


Southern Alaska and Aleutian Islands
Source: NOAA
Data with the average seasonal cycle removed
Five-month average
Meters
0.60
0.45
0.30
0.15
0.00
-0.15
-0.30
-0.45
-0.60
1900.0
1910.0
1920.0
1930.0
1940.0
1950.0
1960.0
1970.0
1980.0
1990.0
2000.0
2010.0