Hogarth 2014 Supplementary Note 3: US West Coast Data, Datums and References (Jan 2016):

Introduction.

These notes show results of documentary research on US and Canadian tides gauges along the North Eastern boundary of the Pacific. Some of the more detailed work on San Francisco was carried out after points made by Stefan Talke on earlier versions of the 2014 JGR Oceans paper (Hogarth 2014), and the note on Astoria could not have progressed without the extensive marigram digitisation work and photographs of original notes in his presentation (Talke and Jay 2014). Some of the analysis shown here has been updated (to 2015) after the on-line publication of the JGR paper. The updated evidence does not affect the conclusions of that paper, but the addition of two more years of data fractionally increases the convergence in the long term trends which was discussed.

San Francisco.

Background

Early tide measurements were made in San Francisco in 1852 and 1853 at Rincon Point, Presidio and also Sausalito (Bache 1853). A tide gauge installed at North Beach in 1853 which gave a few months of data was replaced with a newer one at Fort Point in 1854. Data from this gauge marks the start of continuous tidal records from the San Francisco Golden Gate area up to the present. As such, this time series is the longest complete record from the Eastern boundary of the Pacific. However the location of the recording site has moved over this time. The PSMSL San Francisco tide gauge time series is a composite of data from the gauge at Fort Point operating from June 30th 1854 to November 27th 1877, Sausalito (on the North side of the Golden Gate), from February 19th 1877 to September 1st 1897, and Presidio from July 15th 1897 to July 26th 1927, then a short distance to Crissy Fields, Presidio from 1927 onwards.

Datum connections were made across the Golden Gate between the Fort Point and Sausalito sites when the primary tide gauge locations were transferred in 1877. From the meticulous levelling (USCS 1877) the estimated difference in tide gauge zeros was 0.464 ft (Smith 2002). From the six months of overlapping sea level data the difference was determined to be 0.42 ft (Zervas 2009). The difference between the two estimates is around 0.043 ft or 13 mm (Hayford and Baldwin 1907).

In 1897 the primary tide gauge site was moved back again from Sausalito to Presidio. The datum connections were made by comparing one and a half months of overlapping tide gauge data from both sides. The original estimated difference in tide gauge zeros for the transfer from Sausalito to Presidio using the tide data comparison in 1897 was +0.129 ft (Gilbert 1917, and noted in a 1907 letter from the USCGS - Young 1929).

The tide gauge was operating during the San Francisco earthquake of 1906, and although temporary seismic disturbances were recorded, no longer term datum shift was apparent. However the significant scale of permanent horizontal movement at the fault line raised questions about possible vertical displacements of the benchmarks and a series of precision levelling runs were completed in 1906/7 which included two independent crossings of the Golden Gate. (Hayford and Baldwin 1907, Lawson and Reid 1908). The bench marks and resultant elevations are tabulated in Smith (2002). These give an estimated elevation difference of 0.25 ft or 76.2 mm between the Presidio 1897 and Sausalito TGZ reference points, which is 0.12 ft or 36.6 mm greater than the original 0.129 ft estimate derived from the 1897 comparisons of sea level data. A difference of 30mm was however noted between the two level based water crossing results in 1906/7, suggesting relatively high levelling errors. The level based result of 0.25 ft was used to connect the datums in the PSMSL composite series (Smith 1980, 2002).

Discontinuities in the decadal scale SLR of the tide gauge data have led to alternative assessments of the datum connections at various times (Gilbert 1917, Zervas 2009, Breaker and Ruzmaikin 2011), whilst on the other hand an estimate of +0.16 ft or 48.8 mm between the two TGZ elevations (Disney and Overshiner 1925) was based on assumptions of decadal term sea level stability.

Zervas (2009) evaluated the difference in trend between late 19th century data and 20th century data - as adjusted by Smith 2002, and identified a potential datum shift which is attributed to the transfer between Sausalito and Presidio locations and possible subsequent seismic vertical displacements associated with the 1906 San Francisco earthquake. Zervas then uses the pre/post seismic benchmark elevation data from the USCGS report of 1907 (replicated by Lawson and Reid 1908) and the 1.5 month period of overlapping tide gauge data from 1897 as evidence to support such a shift. The bench mark data appears to show a differential vertical offset between the benchmarks close to the Presidio tide gauge and the benchmarks close to the Sausalito tide gauge site pre and post earthquake. Zervas suggests offsetting the pre-1898 data in Smith (2002) by -35mm as a result. This is reasonable based on this evidence.

This supplementary note provides some additional evidence which allows re-evaluation of both Smith and Zervas and which would allow the differences to be largely explained and reconciled.

San Francisco, Evidence from Bench Marks

To re-assess these datum relationships the elevation values for BM2 at Sausalito and nearby tidal bench marks were checked using the pre and post seismic height values stated in 1907 (Hayford and Baldwin 1907) and these were then compared with the same benchmarks in 1928 (Le Lacheur 1928), revised in 1943 (anon 1943) as well as the Golden Gate crossing elevations given by Smith (2002) and the modern bench mark data sheets (modern elevations are referenced to NGVD 29 in this analysis). The 1928 precision levelling includes elevation values relative to MSL for BM2 at Sausalito, and for BM6, BM9, BM166 and BM173 at Fort Point and Presidio. The 1943 report gives elevations for the Presidio benchmarks as well as BM180 which is the primary tidal benchmark today (2014). Some of these original benchmarks still exist and therefore can be given precise modern elevations, referenced to the NGVD 29 MSL datum for the region. Therefore it is possible to link the NGVD 29 MSL datum, older precise net datums, and the current bench mark information to BM2 in Sausalito and the other early tidal benchmarks. Thus differential movement of individual bench marks compared with their neighbours over time or relative movement between groups of benchmarks can be investigated. Any levelling error in crossing wide rivers or areas of water on successive surveys would introduce differential offsets between groups of bench mark elevations on either side of the crossing.

There is evidence that this is the case for the Presidio and Sausalito bench mark differences under discussion. The 1928 precision levelling elevations (Le Lacheur 1928), which pre-date the construction work on the Golden Gate Bridge and piers, compared with the 1906/7 elevations for the same benchmarks, reveals a consistent differential across the Golden Gate of approximately -35mm (Presidio to Sausalito side, Figure 1), but also confirms the relative stability of the groups of benchmarks on either side and the scale of actual levelling discrepancies between adjacent bench marks.

Similarly for the 1943 revised elevations and recent NGDV 29 referenced elevations (mainly from levelling work in 1991) if these are also compared with the 1906/7 elevations.

This implies that either the 1906/7 elevations include an error due to the water crossing, or the later revisions do. As the two independent Golden Gate crossings in the 1906/7 precise levelling disagreed by 30mm, the former is assumed.

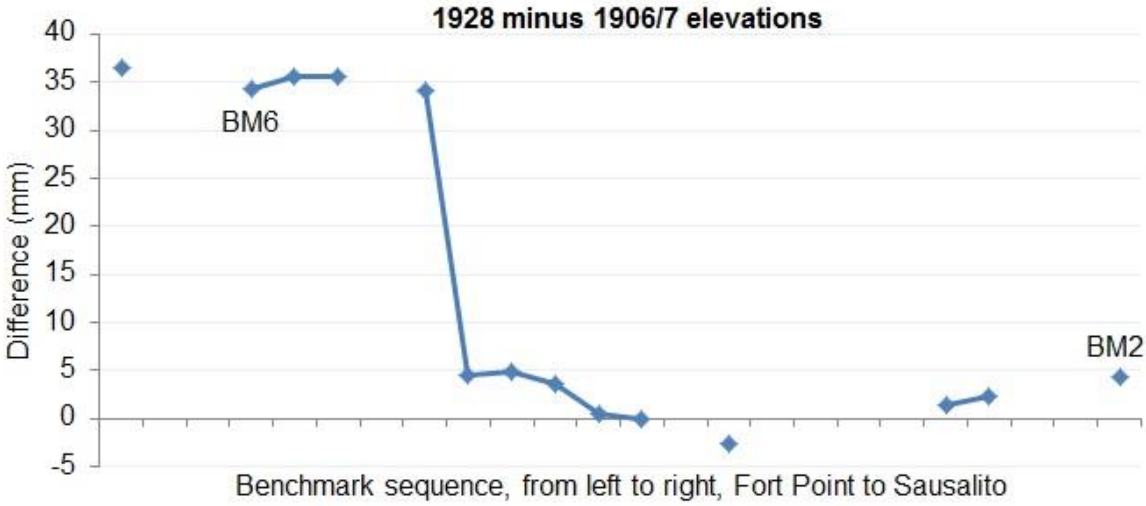

Figure 1: Differences between 1928 and 1906/7 levelled elevations at each benchmark in approximate levelling run order. The step of 30 to 35mm is at the water crossing.

This difference is of similar magnitude but opposite polarity to the average difference between the apparent pre and post 1906 elevations (Hayford and Baldwin 1907). The pre/post 1906 elevation differences are therefore largely resolved if the 1906/7 elevations are corrected using the 1928 (or later) elevation data. This correction also effectively closes the difference between the relative elevations derived from the independent 1897 sea level data and the 1906/7 levelling work.

If the 1928 precision levelling elevations are compared with the 1877 bench mark data series (which are referenced to the Fort Point 20 ft mark in the 1877 levelling campaign between Fort Point and Sausalito, Smith 2002) then the differences are small, although there are only two surviving benchmarks, BM2 (Sausalito) and BM6 (Presidio) with continuity back to 1877.

The preliminary conclusion is that there was no significant relative vertical movement between the Sausalito and the Presidio bench marks, anywhere between 1877 and 1991 (consistent with the assumptions of Smith 2002), but nevertheless a correction of around 30mm would be required for the relative elevations in Smith (2002) which is consistent with the conclusion of Zervas (2009). This is primarily due to errors in the post seismic 1906/1907 levelling at the Golden Gate crossing. These errors have now been quantified.

The actual elevation difference values (difference of differences) if we look at BM6 (BM15 was moved around 1926) on the Fort Point side and compare to BM2 at Sausalito, are 8.8mm for the 1928-1877 elevations, 5.8mm for the 1943-1877 elevations, and 15mm for the NGVD 29–1877 elevations. These residual differences are of the same order as the original levelling error bounds.

San Francisco, Evidence from Sea Level Measurements:

For this note, independent evidence is provided by connecting the measurements of monthly MSL taken at Sausalito from March 1977 to October 1979 with the 1881 tide gauge zero at Sausalito and comparing this with the MSL data from the Presidio over an identical period from 1977 to 1979. The 1881 tide gauge zero elevation at Sausalito is offset by 0.279 ft from the modern Sausalito TGZ using the recovered BM2 elevation (Smith 2002). It was assumed that any long term sea level changes are common to both locations, which allowed a connection to be made between the 1881 TGZ in Sausalito and the modern TGZ at the Presidio, by comparing the 1977 to 1979 MSL data from both locations and estimating the vertical offset required to align the data (figure 2). This gave 0.172 ft or 52mm.

This is somewhere between the original (and Zervas) estimate of 0.129 ft derived from the 1.5 months of overlapping tidal data and the 0.25 ft estimated from the 1906/7 levelling (Smith 2002). It is interesting that it is within a few mm of the estimate of 0.16 ft given in Disney and Overshiner (1925). The difference to Smith 2002 is -0.078 ft or -24 mm. This is also very close to the -20 mm correction proposed by Breaker and Ruzmaikin (2011) based on estimated differences in tidal height at the two locations.

Assuming BM2 at Sausalito has been un-disturbed, this tide gauge data comparison over longer periods carries more weight than the result from 1.5 months of simultaneous tidal observations in 1898 (which could be affected by seasonal prevailing winds noted in the bay). This result would of course also completely resolve the significant difference in long term MSL trends for the two sites estimated by Zervas (2009).

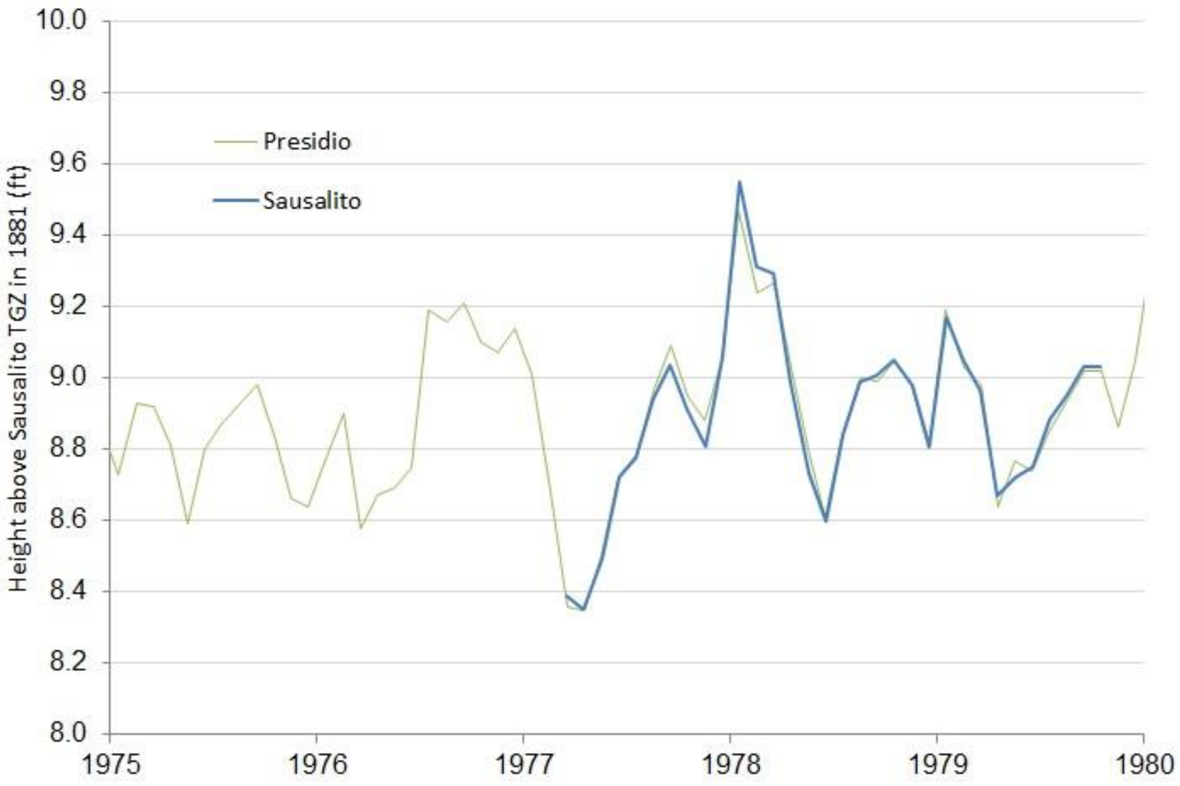

Figure 2: Monthly MSL at Presidio and Sausalito (referred to BM2) in order to link with the common 1877 to 1898 data. The overall relative tide gauge zero offset required to align the Sausalito data as shown is 0.172 ft or 52mm.

San Francisco, Achieving Closure using Fort Point

The final check is to close the loop by connecting the Fort Point and Presidio bench marks (and tide gauge zeroes) directly, and comparing the elevation difference to the independent summed elevation differences estimated for the transfers from Fort Point to Sausalito and then back to the Presidio. The two results should be close, and a direct connection would of course reduce the uncertainty level associated with the crossings.

BM6 at the Presidio was included in the 1877 levelling campaign connecting Fort Point and Sausalito, and allows connection of the modern BM180 elevation above TGZ with the Fort point bench mark elevations (BM2, 3 & 5) above Fort Point TGZ in 1877. This is achieved by using the difference in elevation between pairs of bench marks in the same levelling runs, and linking backwards in time using older elevation values at the same bench mark to link to other nearby bench marks (which may now be lost) which have contemporaneous recorded elevations. For example (keeping the units in feet for convenience):

BM180 (elevation above MSL, NGVD29) – BM6 (MSL, NGVD29) +BM6 (MTL, 1877) – BM5(MTL, 1877) +BM5(TGZ, 1877) = BM180 (elevation above Fort Point TGZ in 1877)

10.41 – 12.87 + 12.819 – 48.472 + 57.128 = 19.015 (ft) BM180 above Fort Point TGZ in 1877.

If this is compared to the modern elevation of BM180 above the Presidio TGZ (18.947 ft) the difference is +0.068 ft or 21 mm, so the Fort Point TGZ in 1877 is estimated to be 21 mm below the Presidio TGZ using these bench mark elevations.

Depending on whether the Fort Point to Sausalito TGZ elevation difference is taken as 0.464 ft from levelling, or 0.421 ft from six months of overlapping tide gauge data, then the closing elevation difference going from Fort Point to Sausalito, and back to the Presidio is either:

0.421 - 0.215 – 0.172 = 0.031 (ft) or 10.4 mm, or if 0.464 ft is used, then the remainder is 23.5mm

Therefore, within precision levelling uncertainty levels, these results are consistent using independent methods.

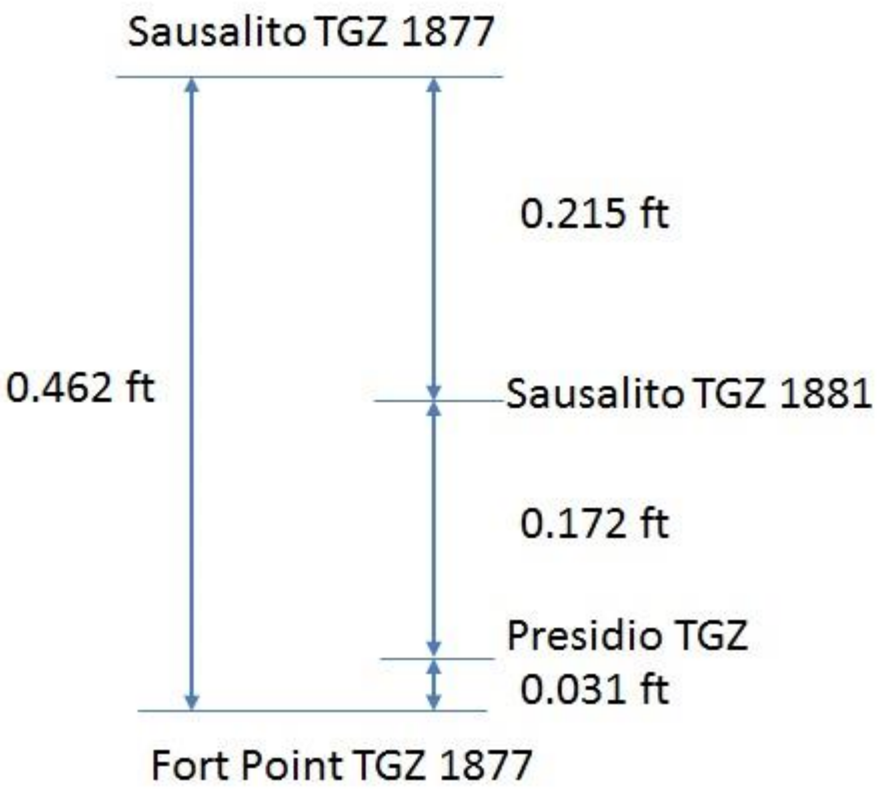

Figure 3: Stick diagram showing the suggested datum connections between the various tide gauge zero points from San Francisco derived from this analysis.

Subsidence at Fort Point

Early benchmark elevations were referenced to a sea level related datum derived from tide gauge data. A nearby primary tidal benchmark would be commonly referenced to either the TGZ (tide gauge zero), or a known LLW (Lower Low Water) or MSL (Mean Sea Level) datum. Other benchmarks in a local survey would then be referenced to the primary bench mark, for example for benchmarks 2, 3 and 5 at Fort Point (Anon 1873). The bench marks are then used to check any changes in elevation of the tide gauge (or the structure it is affixed to). From the tide gauge origin, elevations (and any MSL related errors) would then propagate throughout any local survey net. This is a separate issue to bench mark stability.

The jetties at both Fort Point and Sausalito were found to be subject to subsidence, and various attempts were made to correct for this using bench marks, levelling and other local tide gauge data, as well as by physically relocating the tide gauge. Some of the early attempted corrections are recorded in the original tidal registers (reproduced in fine detail in Talke et al 2013). These (figure 4) are based on an assumption of a constant rate of settling of the jetty pilings over time. These old records plus original hydrographic sheets have allowed better estimates of the rate and timing of the subsidence (Dedrick 1983, Smith 2002). The corrections in the 1854 to 2014 PSMSL series are based on Smith (2002). It is questionable whether to include the pre 1858 records in any analysis of the San Francisco sea level (Muftakhari et al 2013) as the subsidence and corrections are relatively large. In this analysis the information is included as records of bench mark and short range levelling data do at least exist and correction can be attempted based on this.

Possible settling of individual benchmarks is also investigated by comparing neighbouring benchmarks and ensuring that relative elevations were consistent. This revealed for example that BM64 at Fort Point (close to the South pier of the bridge) has settled over successive levelling compared to surrounding benchmarks. The post 1928 elevations also show some apparent settling over time at the Lime Point bench marks, which may be associated with the building of the North Pier of the Golden Gate Bridge (completed in 1937) and associated loading related subsidence. The North pier is adjacent to the Fort Baker site where many of the Lime Point bench marks are situated.

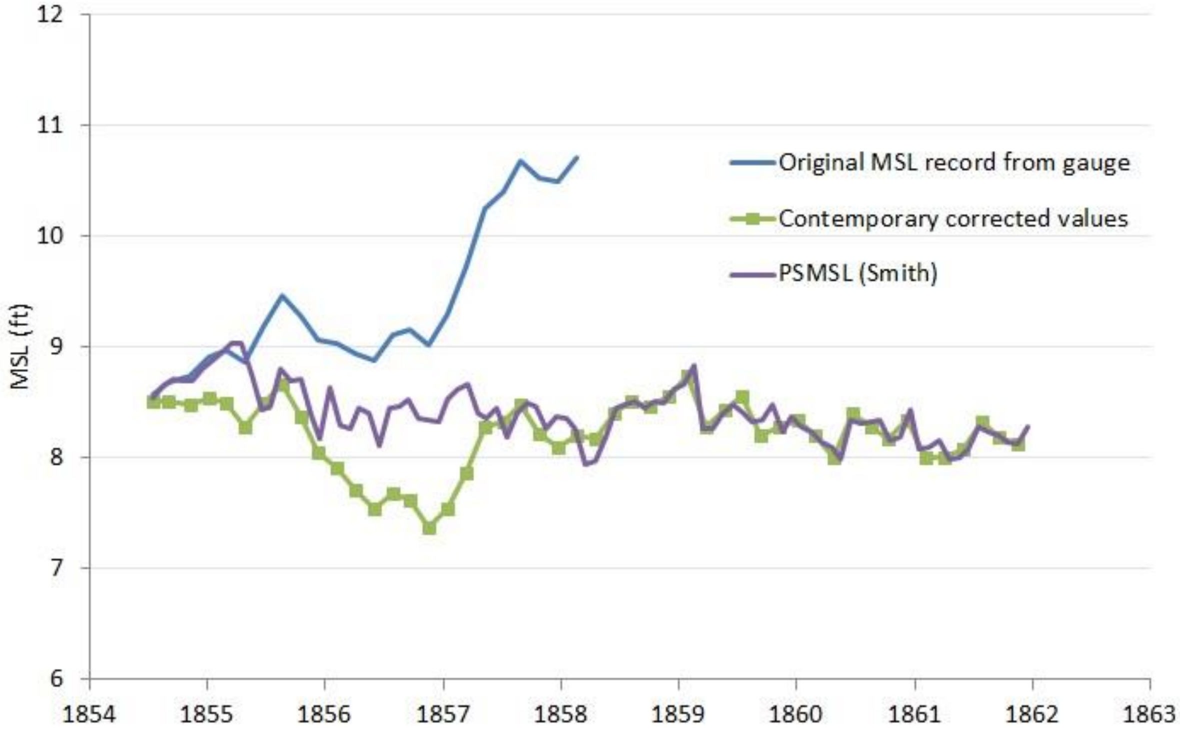

Figure 4: Original recorded values from tide gauge at Fort Point, plus the attempted contemporary correction for settling of the jetty between 1854 and 1858 using simple linear scale factor, and the PSMSL values from Smith 2002 which are based on more detailed levelling information.

Corrections for Sausalito

The tide gauge at Sausalito and zero reference was reset in 1882 (Smith), and this was noted based on contemporary levelling of the tide gauge to local bench-marks. The old hand written records (photographs in Talke 2013) show that contemporary corrections were made based on assumptions of a constant settling rate of approximately 0.05 ft/yr, or 15.3 mm/yr between 1877 and 1882. The monthly MSL values in the RLR data from PSMSL are from Smith, who used corrections based on the change in TGZ elevation. The corrections required at Sausalito are an order of magnitude less than at Fort Point.

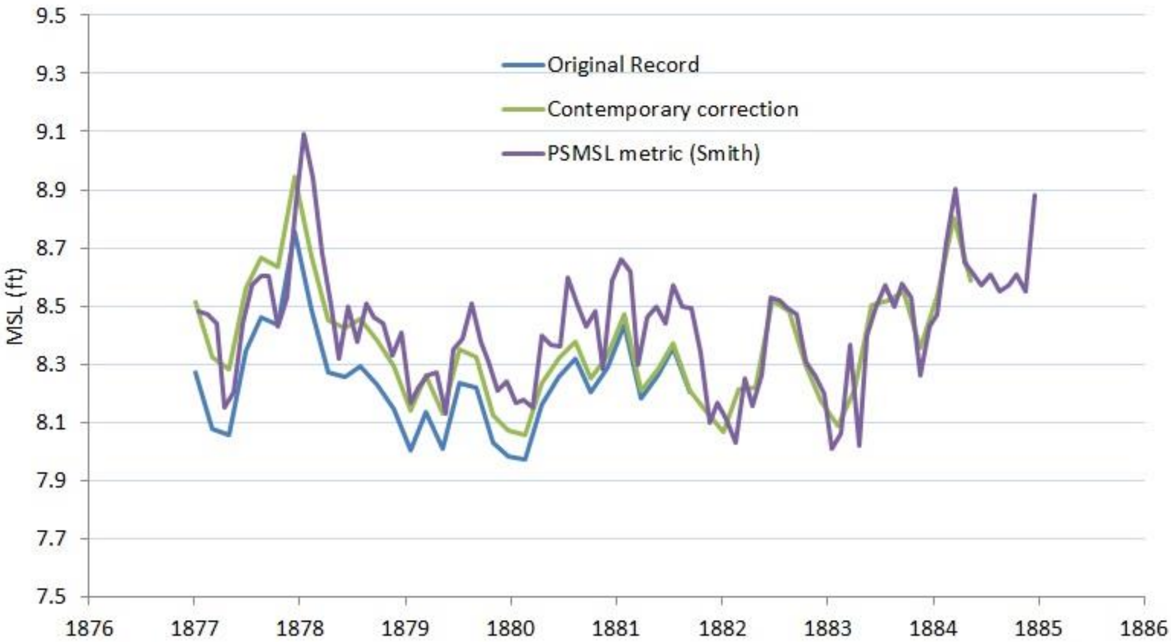

Figure 5: Showing the original tide gauge record, contemporary corrections based on a linear interpolation between levelled values in 1877 and 1882, and the corrections from Smith 2002, (PSMSL).

San Francisco: Conclusions

Shortly after the 1906 earthquake surveyors and geologists were cautious about interpreting the pre and post seismic elevation differences as due to seismic activity, and suggested that levelling errors were possible (Hayford and Baldwin 1907, Gilbert 1908). This is supported by the fact that similar magnitude differences between pairs of the City surveyors results and the USCGS results, both taken either before or after the earthquake, are also reported at a small number of other local bench marks at the time.

Gilbert (1908) also suggests that the potential datum shifts in the MSL time series occurred in June 1899 and April 1904. This is admittedly difficult to estimate even from the hourly data available from UHSLC, but his estimate does not correspond to the timing of transfer of tide gauge or known seismic events. It is also possible that these observations represent real variations in sea level over these time scales due to ENSO or shifts in PDO regime.

It is of course possible that multiple vertical shifts in land level have occurred at the Sausalito site during the decades of (mostly) slow lateral slip experienced at the nearby San Andreas fault. It is also possible that long term "tilting" (Balazs and Douglas 1979) could affect SLR results even over the small distance between Presidio and Sausalito. However, the available evidence is consistent with relative vertical stability of the tidal benchmarks across the Golden Gate at century timescales, and therefore supports the basic assumptions in Smith (2002). The bench mark analysis, the availability of the recent Sausalito data and the recovery of BM2 and continuity of BM6 independently support a datum connection within a few mm of the suggested correction of Breaker (2013).

San Diego

Tide data was recorded at La Playa tide gauge site near the Quarantine from September 1853 until September 1st 1872, when the gauge was removed. The original tidal bench mark from 1853 "tidal 1" as well as the primary reference "tidal 4", were still in existence when a new gauge was installed at the site in February 1906. The elevation history allows connection of these bench marks to recent datum levels (Gannett and Baldwin 1908, Bowie and Avers 1914, Birdseye 1925, Le Lacheur 1928). The gauge was moved 8 km to the Municipal pier in 1926 (originally referenced to BM13, the primary bench mark is now BM12). The PSMSL continuous records start in 1906 with a short break for this transfer. A gauge was also set up at La Jolla in 1924 and the data was used to provide a sea level datum overlap period to help link the two San Diego sites.

Early annual MSL data from San Diego has been published for 1860, 1861 (Thompson 1877) and 1869 to 1871 (Ferrel 1882), referenced to the La Playa tide gauge zero, and complete annual data from 1854 to 1872 has been published in work on apparent subsidence in Southern California (Wood and Elliott 1978) who linked the old and new datums.

The effect of extending the annual MSL data back by 53 years (although with a significant gap) is to change a statistically zero acceleration value of -0.0018 mm/yr^2 using the available PSMSL series from 1906 onwards, to a positive acceleration of +0.0056 mm/yr^2. Although the trend analysis is compromised by the effect of the data gap, it uses all available information from this gauge.

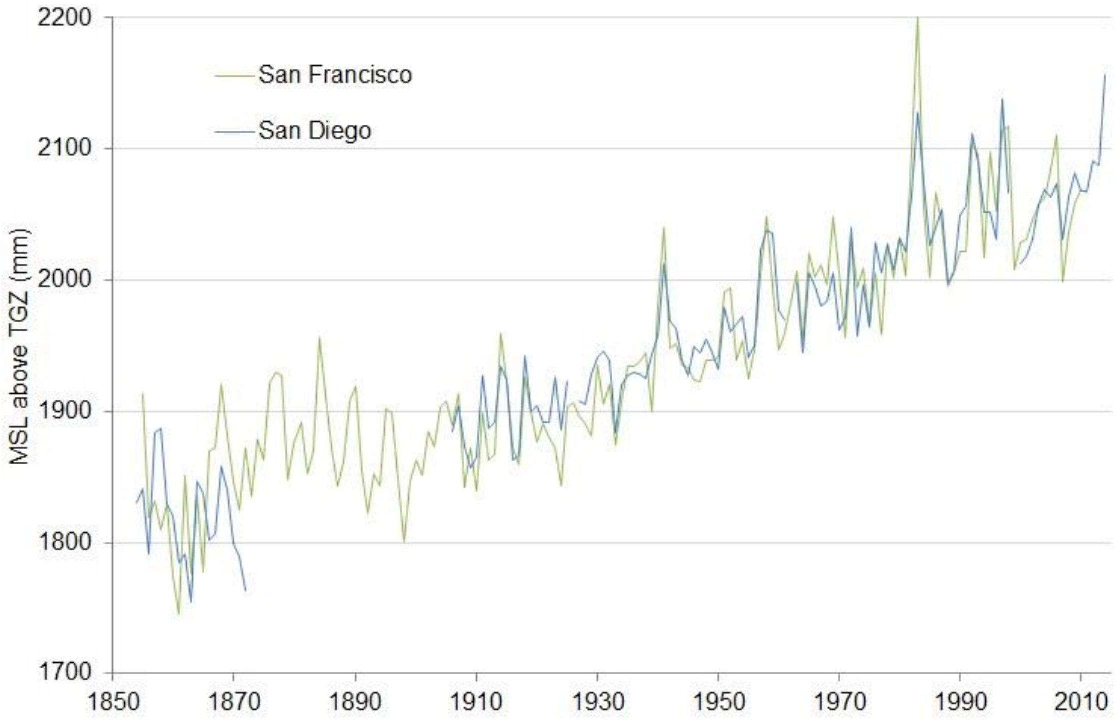

Figure 6: Corrected annual MSL data for San Francisco and extended MSL data for San Diego, adjusted for estimated relative vertical land motion (using MSL at year 2000 and San Francisco trend as reference).

Los Angeles

Tide gauge data from San Pedro, Los Angeles, was recorded as early as 1854, but only a few months of data are available. A further short period of data is available for 1878. The data series available from the PSMSL is complete from 1924 onwards.

Although it is debatable that there is validity in a trend derived from an extended series where two short period values are added and gaps are large, these extra values can help constrain the longer term trend. This has proved useful in seismic studies, as early relative levelling information is available, and it is evident that the long term vertical land motion at Los Angeles shows relative uplift compared to both San Diego to the South and San Francisco to the North. Assuming such uplift is relatively linear at century scale, then in the case of Los Angeles it is interesting that the small positive SLR acceleration trend estimate of 0.0030 mm/yr^2 from the 1924 onwards PSMSL annual series increases to 0.0075 mm/yr^2 using the extended data. The SLR acceleration values from all three sites therefore tend to converge compared with the unextended data. However the Los Angeles data series was not used in the global analysis (Hogarth 2014) due to the quality control requirements for greater than 75% completeness. The data is however shown here for reference.

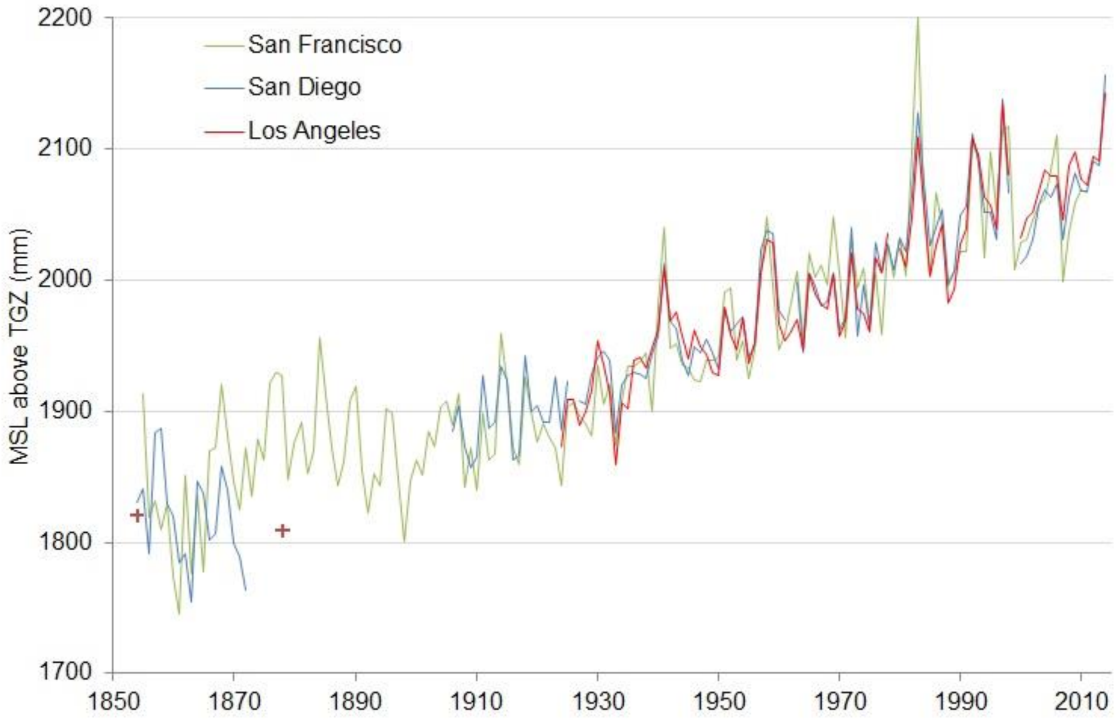

Figure 7: Corrected annual MSL data for San Francisco and extended MSL data for San Diego and Los Angeles, linear trend adjusted for estimated relative vertical land motion (using MSL at year 2000 as reference).

Astoria, Oregon

A self recording tide gauge was set up at Astoria water front in 1853 (Bache 1854). Readings were taken until at least 1876. A gauge was noted as operating in 1879 and 1883. A tide gauge was re-established at Astoria in 1888 by the US Engineers, but removed to Fort Stevens in 1899. A new primary gauge site was set up in 1925 around 7.3km upstream of the Columbia river at Tongue Point. The PSMSL monthly MSL data from Tongue Point is almost complete from 1925 to the present. Annual MSL data from the old Astoria site for 1874, 1875, and 1876 is tabulated by Ferrel (1882), and the entire time series and bench mark notes from 1853 to 1876 has been recovered in a comprehensive marigram digitisation effort by Talke and Jay (2014). All of this early data is referenced to the TGZ (tide gauge zero) of the old gauge which was at Astoria waterfront. The datum level was established as MLLW (Mean Lower Low Water) referenced to this TGZ, which in turn was referenced to bench marks BM1 (Astor point) and BM A 32 (USE A-1) with elevations recorded in the superseded bench mark data sheets. BM1 has yet to be recovered, and BM A 32 was destroyed when the old post office and custom house was demolished in 1931, whilst a further bench mark F 31 which does still exist is known to have settled from levelling records. The datums between old Astoria and Tongue point were not successfully linked (Talke and Jay 2014).

However the elevation of BM A 32 was referenced to the Astoria MLLW datum from 1875/1876 as well as to a regional first order level net levelled back to the Fort Stevens tide gauge and adjusted MSL value in 1920 (Avers 1926, Cole 1930). This potentially allows a connection back to the 1873 to 1876 tidal data as well as to the Tongue Point tide gauge bench marks and the tide gauge zero there. These bench marks were referenced to the MLLW from one year of recorded river level data at Tongue point, but also to the same first order “MSL” level net (Cole 1930). This gives an offset of 2.713 ft between the two tide gauge zeros.

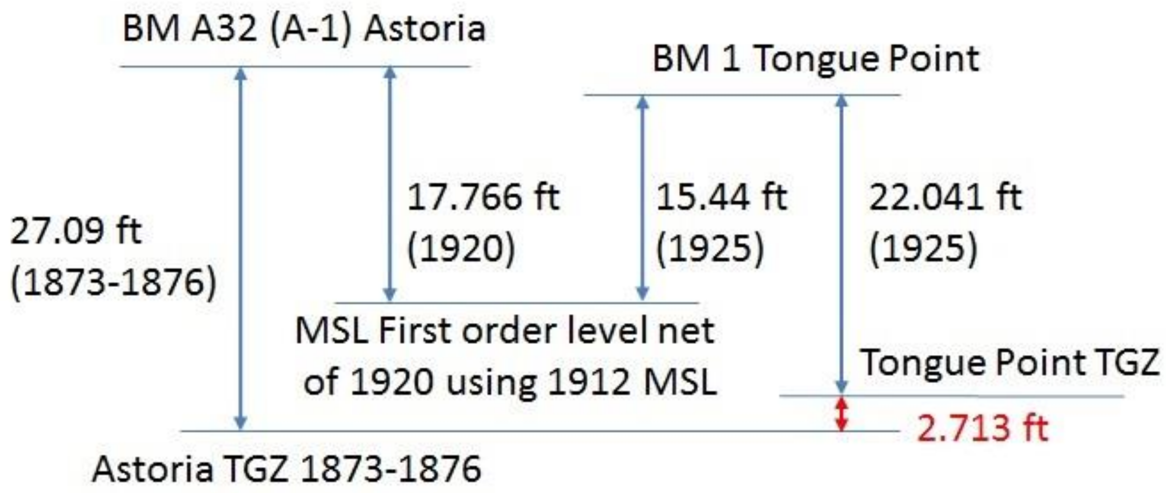

Figure 9: Stick diagram for Astoria showing preliminary estimate of datum connection between Astoria and Tongue Point from this work.

The bench mark BM A 32 was close to a group of other bench marks. The nearby BM F31 still exists and is known to have settled since 1920 (Rappleye 1932). To assess whether the BM A 32 benchmark had also settled, or whether there was localised subsidence which might affect any elevation connection to Tongue Point, (Burgette et al 2009) then the differences between old and newer elevations can be checked. If the difference between the 1920/1925 adjusted elevations and the 1930 adjusted elevations are plotted in the same order as the level runs, then a pattern emerges. This implies that settling or localised subsidence has occurred between 1920 and 1930 in the levelling net near the tidal bench marks for Astoria which is worst case near F31. Further settling here is confirmed by comparing with the NGVD29 and later NAVD88 benchmark data sheet elevations. The other anomalous elevation is isolated to a single bench mark (C31, sixth from left in figure 8a).

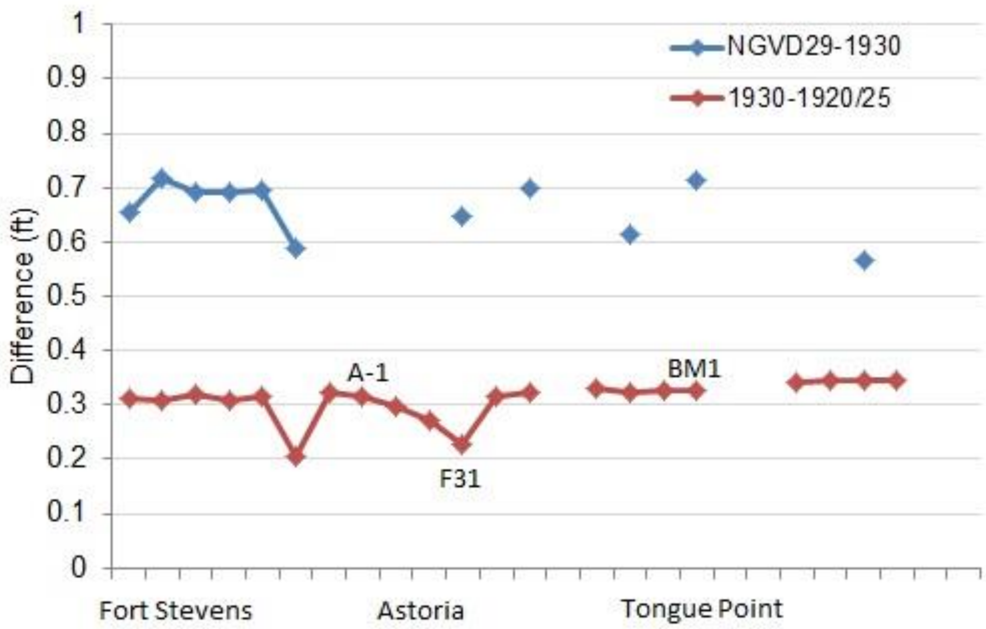

Figure 8a: Bench mark elevation differences for levelling runs moving inland from Fort Stevens. The datums are different for the different periods, but localised relative vertical movement of individual bench marks shows as deviations from a constant difference.

BM A32 (USE A-1) appears to be a better choice in terms of relative stability if using the 1920 and 1930s elevations to connect Astoria to Tongue point. To minimise error it is important to make these connections using elevations measured at similar times to the link of the earlier 1873 to 1876 datum to the benchmarks in 1920. Although the elevation differences between the 1920 levelling and the 1930 leveling at A32 and BM1 are small, it appears there is also either a small systematic bias in the early levelling runs, or a differential vertical motion or “tilt” over the distance from the coast upriver to Tongue Point. This appears magnified as greater time differences between recorded elevations are used (figure 8b). The dates for the NAVD88 and NGVD1929 elevations used here are given on the latest bench mark data sheets.

If localised differences in uplift or subsidence rates between Astoria and Tongue Point have occurred since the 1920s and the datum link, then this would affect any acceleration values derived from the composite series. Also if the bench marks are unstable, then this too could affect the local vertical reference frame and any connections to the tide gauge zero point. Burgette et al (2009) provides evidence that some relative movement (upwards) has also occurred for the old primary Tongue Point bench mark “Tidal 1” (BM1), and refers instead to “Tidal 7” (set in 1939) as a more stable bench mark using “Tidal 11” (set in 1959) to check. However the recent benchmark sheets suggest from repeat levelling that whilst there has been possible vertical movement at “Tidal 1”, there has also been possible settling at “Tidal 7”. For this note the relative bench mark elevations over successive levelling runs were compared to try to highlight any patterns of differential movement over time. From this it can be inferred that the bench marks near the tide gauge at Tongue Point were relatively stable in the 1920s and 1930s (figure 8a), including “Tidal 1”. The situation is slightly more ambiguous since then.

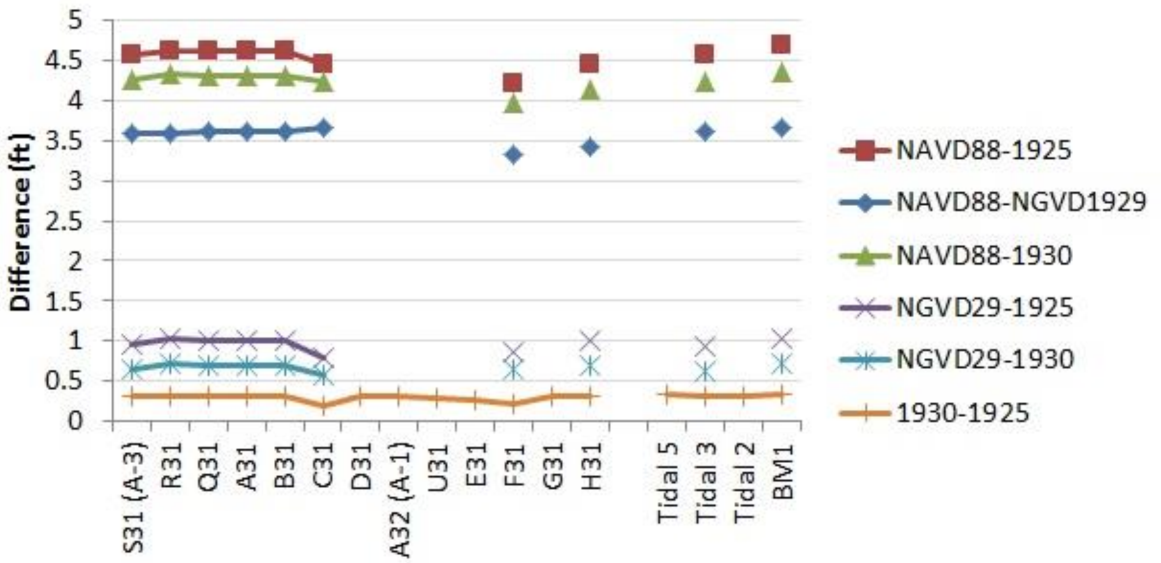

Figure 8b: bench mark elevation differences from early repeat levelling surveys in 1920s and 1930s through to the 1980s and 1990s for the NGVD 29 and NAVD88 adjusted nets. The levelling run to Tongue Point was originally a spur from the road route levelling lines. “Tidal 7” NAVD88 – NGVD29 elevations are 3.41 feet which is towards the lower limit for the other bench marks shown.

An additional factor in the case of Astoria is the slope of the river. This would have the effect of raising the mean river level measured at Tongue Point relative to Astoria, which is several kilometres downstream. Likewise this would be higher than the river level at Fort Stevens. An estimate of the slope of the river can be derived from the historical tidal plane information. For Astoria the half tide level (HTL) derived from the tidal records 1873 to 1876 is 0.16 ft higher than the first order levelling connection to the MSL datum. However the HTL above MLLW recorded on benchmark 13.26 in 1926 at the Port of Astoria was 4.22 ft. At Tongue Point HTL derived from one year of tidal records 1925/1926 is 0.23 ft above the first order levelling connection to the MSL datum. As the actual difference between measured mean tide level and the mean river level is similar (around 0.05 ft) at both locations, the excess difference value of 0.21 ft above gives an estimate of mean upstream elevation of the water surface in 1926.

More recent studies (Evans 2011) have modelled the variation of tidal MLLW in the river compared to the NAVD88 datum (see also Buijsman 2003). This gives an estimate of the difference in MLLW of the *current* river level between the Port of Astoria and Tongue Point of approximately 68mm or 0.223 ft. The tidal range may change moving upstream between these points, and has almost certainly changed with time. HTL at Astoria in 1873 to 1876 was given as 4.36 ft above MLLW (Cole 1930), but was recorded as 4.22 ft in 1926 (Avers 1932) at the newly built Port of Astoria (inscribed on benchmark 13.26). HTL at Tongue Point for the year ending in 1926 is given as 4.25 ft relative to local MLLW. The difference of 0.03ft subtracted from 0.223 ft is 0.193 ft. Although the MLLW values are estimates and the tidal range is most likely to have changed due to dredging over the past century and a half, the river level difference values between the two points are close using both approaches. This suggests an estimated offset of approximately 0.2 ft should be subtracted from the Tongue Point mean water levels when trying to create a composite series from the older Astoria tidal data.

An additional factor due to the site being non-coastal is non-tidal variations in river level due to seasonal and inter-annual variations in water flow, and also any long term trends in average water volume. These factors have been shown as likely to affect the linear trend in river level (Burgette 2009, Talke and Jay 2014) and result in inter-annual divergence from coastal tide gauge records such as that from San Francisco.

Whilst the overall composite record from Astoria compares reasonably well with the long records from San Francisco (figure 10), and gives some confidence that the datum connections are approximately correct, it must be emphasised that the datum connection estimate and early river level data for Astoria are preliminary (the High Water and Low Water levels are as originally tabulated), and further independent quality control checks and analysis are ongoing (Talke, personal communication, 2016).

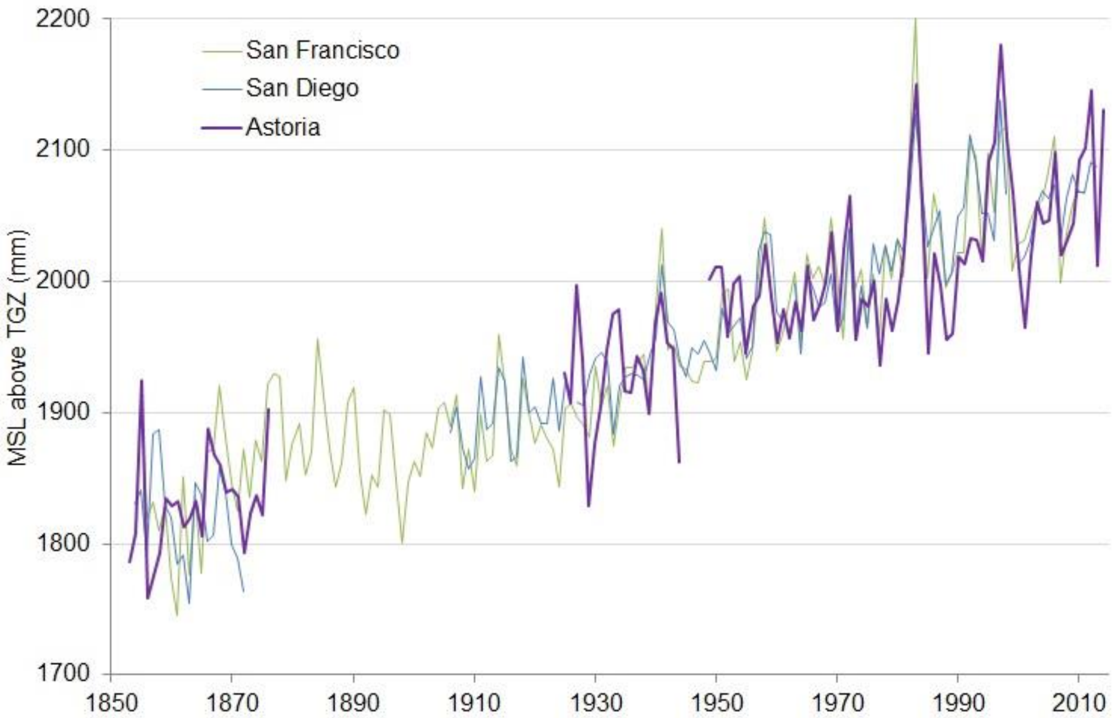

Figure 10: The tidal river level at Astoria including the preliminary corrections overlaid on the annual MSL record from San Francisco and San Diego, with GIA adjusted to match the long term linear trend differences for the period of recording at Tongue Point (the difference being around 2mm/yr).

Seattle

The PSMSL record from Seattle is virtually complete from 1899. Earlier records are available from Port Townsend. There are annual values from 1874 to 1876 (Ferrel 1882), but the vertical datum has not yet been tied to other sites to allow connection with modern records. The PSMSL annual record for Seattle starts on a negative decadal scale peak (1898/1899) for the West Coast of the USA and this slightly negatively biases the derived second order component. However, as can be seen from figure 11, the annual time series is strongly correlated with San Francisco and this is likely to follow a similar pattern moving backwards in time. The data from Seattle provides some correlation with the non-linear decadal behaviour evident in the early San Francisco data. Further evidence which gives a small degree of additional confidence that this behaviour represents real sea level variation is to be found in extended records from Vancouver and Victoria.

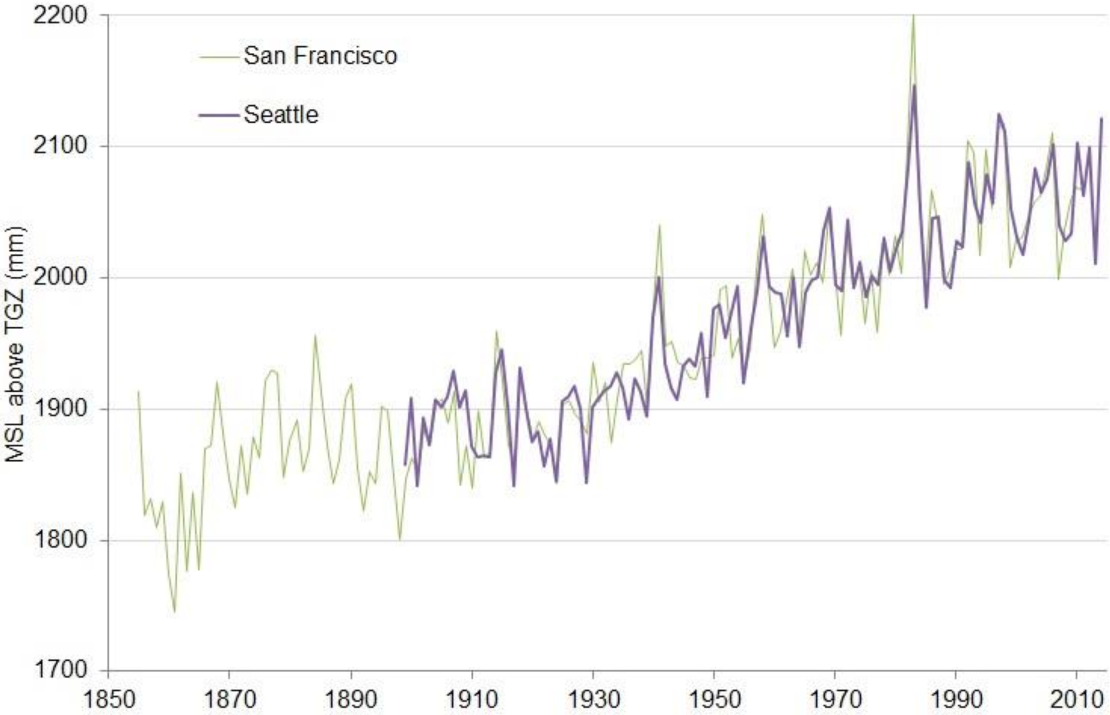

Figure 11: Annual MSL values from Seattle, corrected for differences in GIA and overlaid on the San Francisco time series. The strong inter-annual, decadal and centennial scale correlation is reflected in the subjective match of the time series shown here.

The contribution of Canadian records to the MSL record of the Eastern Pacific.

It should be noted that the 2015 tidal data PSMSL updates from Fisheries and Oceans Canada have some late 20th century datum adjustments compared with earlier data from Canada (used in Hogarth 2014) and some rounding to cm. precision. This note has been updated with these later datum adjustments but retains the original precision. The records from Georgia Sound include a number of old Canadian tide gauge records (Dawson 1906, 1923) which are not represented in the annual PSMSL series, but some of which are in the ancillary annual records. Data and some datum determinations were recorded at Victoria even before 1880, but these and some of the datum connection records were lost when the records from Victoria were destroyed by fire.

Figure 12: Zoomed in chart of some of the old data from the Canadian West Coast with datums adjusted to minimise mean differences. The 1895/96 datum connection for Victoria appears doubtful.

Dawson (1906, 1923) details the attempt at recovery of the pre-1905 Public Works Datum, which relied on a single water level connection. Re-assessing this datum connection using the Sands Head data from 1895 onwards and early annual data from Vancouver (PSMSL ancillary files, and Dawson), which cover the period when the datum connections were lost (figure 12), shows that there is still some doubt about the two years of MSL data from Victoria for 1895 to 1897. It is possible that the old Public Works Datum from Victoria is much closer to the even older Hudsons Bay Company Datum (see Dawson 1906 and 1923), the difference of the two being originally accepted by Dawson as 0.35 ft. Offsetting the 1895 to 1897 Victoria data by this amount does resolve the mean differences between Victoria and Sand Heads, as well as giving a more consistent difference to the early Vancouver data and data from more distant stations with continuous records. Until pre-1905 benchmark records from Victoria can be recovered elsewhere, this comparison with nearby stations appears to offer a more consistent datum connection than the single water level connection used in 1905.

The PSMSL record from Victoria from 1909 onwards is however essentially complete (hourly readings are available from the UHSLC). The bench mark 737-J-1905 (Tidal Survey Bench Mark), was established in granite bedrock in 1905 at 15.4 feet above the tide gauge zero, which was the tidal survey datum (Dawson 1923). This bench mark is still used today with the same elevation above TGZ. The tidal bench mark of 1919 (738-J) also still exists, although there has been some very small movement or levelling differences over time. This continuity justifies using the Victoria time series as a buddy check for the other older tide gauge data where gaps exist after 1909. This indicates a probable small (around one and a half inches or 35mm) issue with the Vancouver data between 1909 and 1923 (a datum query has also been recently noted in the 2015 PSMSL updates), as in figure 13, which also uses an independent buddy check from the Point Atkinson metric time series from 1914 onwards.

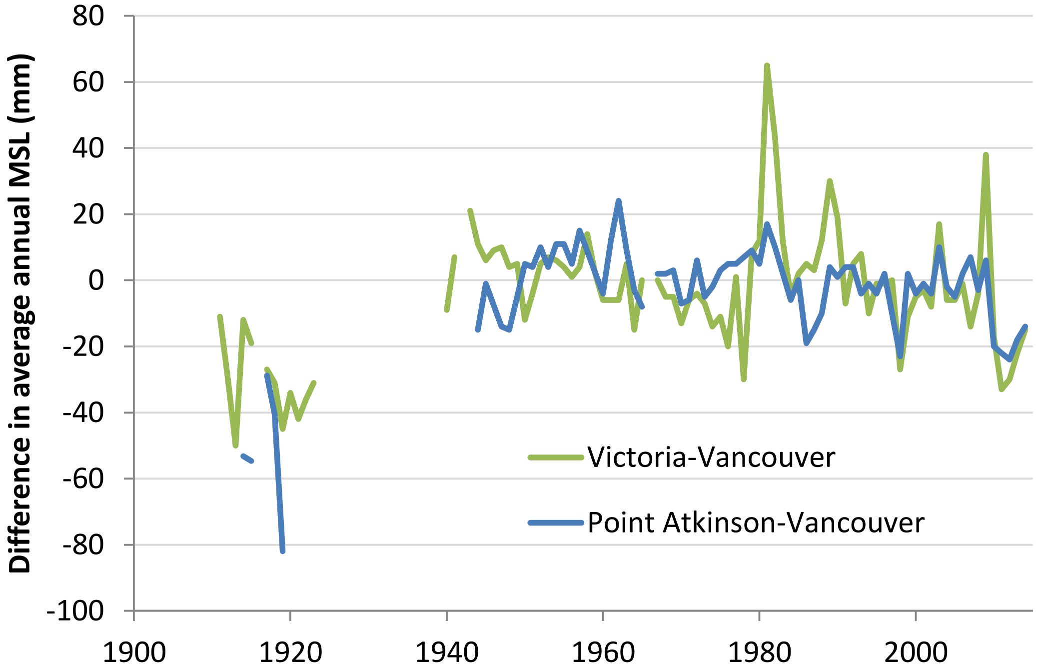

Figure 13: MSL Difference data (both offset to mean zero for the 1940s to 2014 data) highlighting the possible datum issue with the Vancouver data from 1909 to 1923.

It is reasonable therefore to attempt to correct the long record from Vancouver and then extend it with the old PSMSL ancillary data by minimising differences in the few years of data overlap using least squares and comparing with the early adjusted record from Victoria (double checking with the record from Sand Heads). As Sand Heads is close to Vancouver, and there is annual data from Sand Heads from 1895, with gaps to 1903, then data from 1914 to 1920, and 1944 to 1959, this allows sufficient temporal overlap for the creation of an extended composite time series.

The results are shown in figures 14 and 15, which separately show the extended and corrected Victoria and Vancouver/Sand heads composite data overlaid with the times series from San

Francisco. The linear sea level trends are adjusted to match the San Francisco data using overlapping data from 1920 onwards. This highlights the longer term inter-annual and decadal similarities. The significant differences in actual unadjusted RSL trend (figure 16) are due to GIA and tectonic movement, and are assumed to be linear over the century scale in these comparisons.

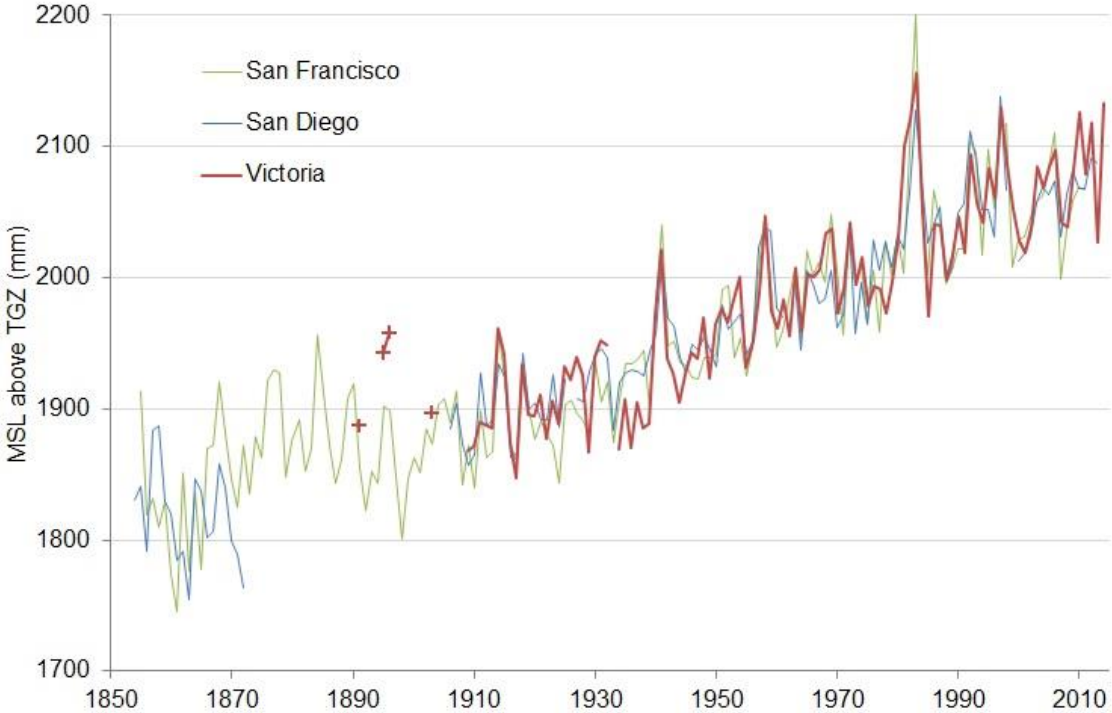

Figure 14: Extended data from Victoria with a linear slope offset of 1.40 mm/yr applied to match the trend from San Francisco in order to display the high correlation and highlight the suspect 1895/96 datum connection for Victoria.

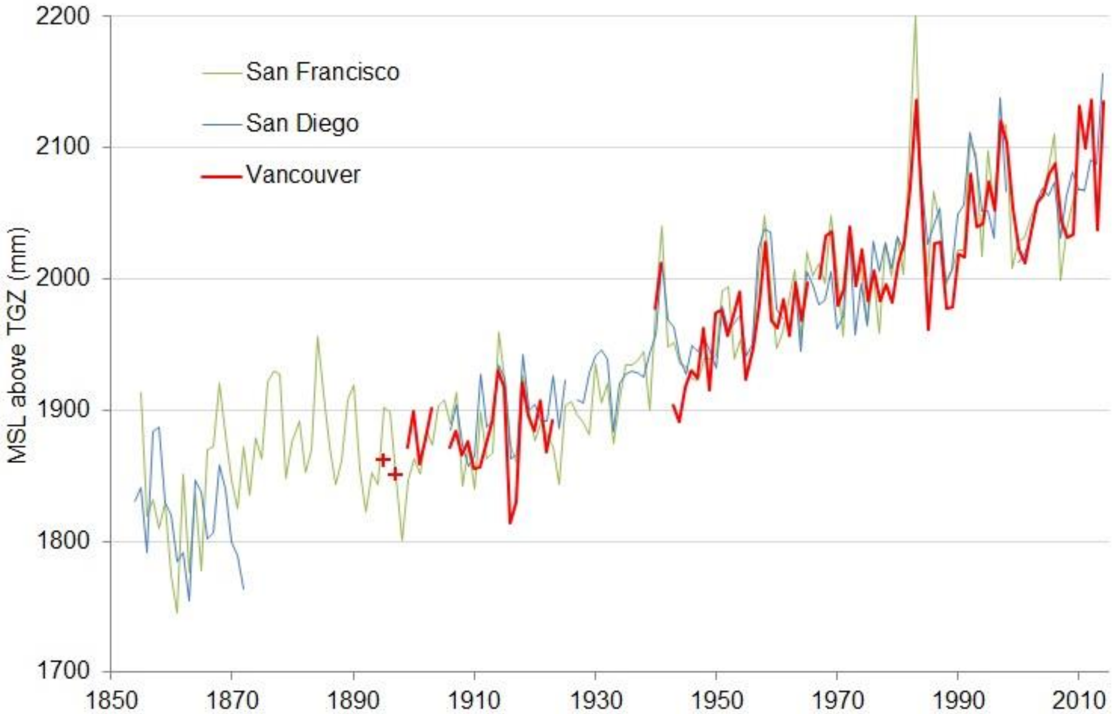

Figure 15: Extended annual MSL data from Vancouver also with a linear slope offset of 1.27 mm/yr applied to match the trend from San Francisco in order to display the high correlation. Here the earlier 19th Century data values appear consistent with the San Francisco data.

Similar comparisons can be made for Tofino, which can be extended from 1910 back to 1905 using the PSMSL ancillary data from Clayoquot, and Prince Rupert which has data from 1907 but can be extended back to 1903 (and some gaps filled) using temporally overlapping early published data from nearby Port Simpson. Both PSMSL time series currently have gaps from the 1920s to the early 1930s.

Trends and effect of Land motion

The time series for all tide gauge sites shown in the previous sections have been adjusted by adding a linear trend so as to match the trend for San Francisco, but this is simply to better show correlation. The actual linear trends of relative sea level which includes a component of VLM (vertical land motion) are shown in figure 16. Here the trend differences caused by different vertical land motion across the subduction zone appear linear over century time scales. Plotting the differences in RSL once the linear trends have been matched shows that variations from linear differential movement appear small. These small differences (cm scale) may be due to small remaining tide gauge datum issues or real variations in vertical land motion.

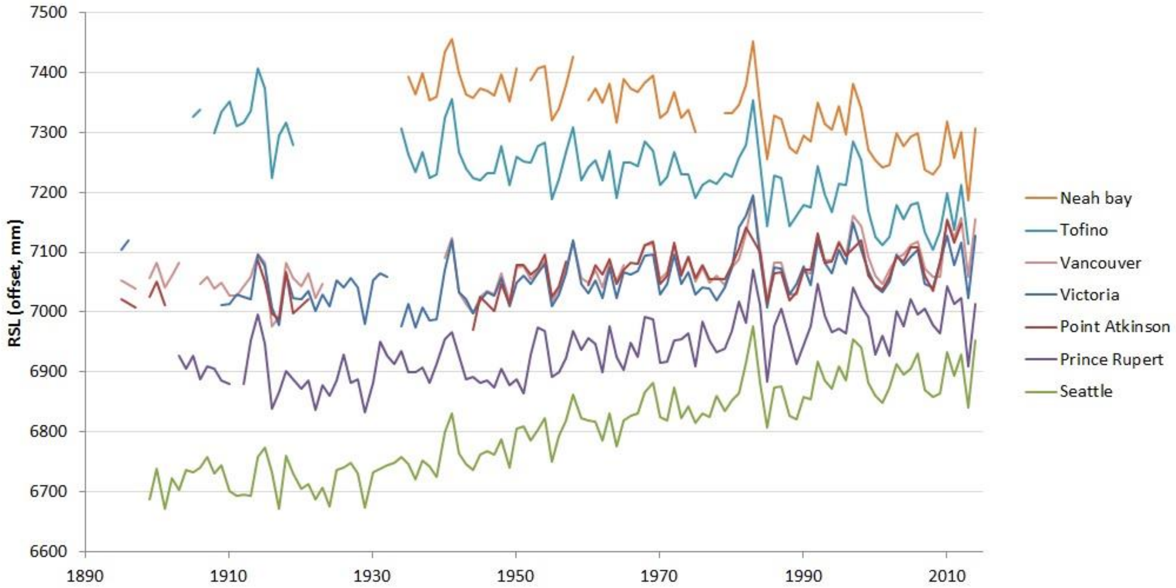

Figure 16: Relative sea level trends (RSL=MSL-VLM) as recorded in the PSMSL for some of the tide gauge sites. Seattle RSL trend is 1.98mm/yr, Victoria is 0.53mm/yr Vancouver is 0.53mm/yr Point Atkinson is 0.69mm/yr, whilst Tofino is -1.55mm/yr and Neah Bay is -1.74mm/yr (Neah bay is 190km from Seattle and 93km from Victoria)

Tide Gauge Site	RSL (mm/yr)	RSL uncertainty ± (mm)	NASA CGPS VLM (mm/yr)	CGPS uncertainty ± (mm)	Total uncertainty ± (mm)	120 yr MSL estimate (mm/yr)
Prince Rupert	1.06	0.17	0.81	0.23	0.40	1.87
Tofino	-1.55	0.15	3.32	1.19	1.34	1.77
Neah Bay	-1.74	0.25	2.71	0.23	0.48	0.97
Victoria	0.53	0.16	0.62	0.16	0.32	1.14
Vancouver	0.53	0.17				
Seattle	1.98	0.12	-1.20	0.10	0.22	0.79
San Francisco	1.84	0.25	-0.34	0.37	0.62	1.50
Los Angeles	0.89	0.15	0.20	0.55	0.70	1.09
San Diego	2.08	0.12	0.20	0.66	0.78	2.28

Table 1: RSL from extended data sets (trends calculated for 1890 onwards), CGPS derived estimates of VLM, using nearest CGPS site with lowest uncertainty over longest period (all >five years and most < 30km distance) and corrected MSL estimates at each tide gauge site.

Recent VLM can be estimated within an absolute geocentric reference frame from CGPS (Continuous Global Positioning System) stations which have been recording geodetic position information for several years. Various processing methods are used to reduce GPS errors, one of the main differences is in the estimates for corrections for vertical discontinuities (due to instrumental changes or seismic motion). For this note the NASA JPL time series and correction estimates are used. If the corrected data is plotted, it can be seen that the average 120 year MSL trend is around 1.4mm/yr. Some caution is justified here as at some sites GPS stations which are closely spaced give divergent VLM results (for example Point Loma near the original San Diego tide gauge site has station P475 giving 0.24 ± 0.553 mm/yr for 8 years since 2008, whilst almost collocated PLO3 gives -2.389 ± 1.00 mm/yr for a 9 yr record from 1997).

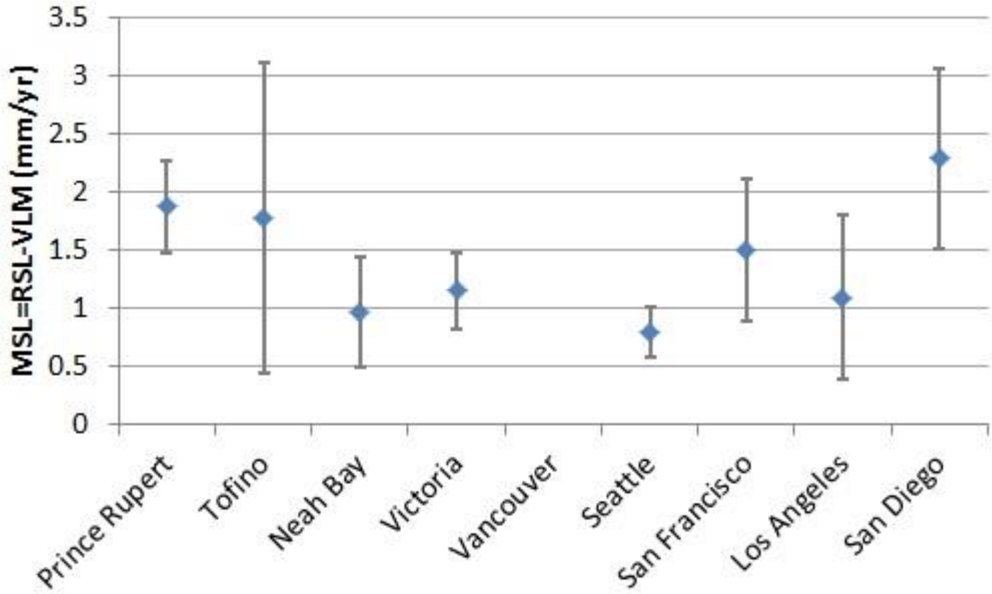

Figure 17: Estimates of MSL for the tide gauge sites, corrected using GPS derived estimates of VLM.

It is generally assumed that GIA (Glacial Isostatic Adjustment) is linear at century timescales, but it is less safe to assume that long term vertical land motion is linear near an active subduction zone, and the CGPS stations have only been operating since the 1990s so cannot give information about VLM before this. However any divergence or relative differences should show up in difference plots between tide gauge sites with continuous long time series. These comparisons reveal cases of both long term linearity and small but consistent step like differences. A monthly difference plot of Prince Rupert minus Vancouver has a very low second order component (an order of magnitude less than that in the individual time series), but on the other hand difference plots of Victoria or Vancouver minus Tofino show small divergences in the early 20th Century data, which is probably reflected in the late 2015 queries against the early datums noted in the PSMSL.

The above issues could mask any century scale non-linearities in the long term mean sea level rise, although if the vertical land motion is linear, or small, then it will not affect any second order component. If there is a significant second order component in the average East Pacific sea level (ie acceleration or deceleration) then it would be expected that longer time series would have slightly different overall linear MSL trends than for shorter time series, but it should be remembered that as the time series are shortened, the uncertainties in MSL trend increase in a non-linear fashion, this is one reason to use longer times series in trend analysis, even when error bounds in the older data need to be adjusted to allow for suspect datum offsets.

To help quantify any acceleration in MSL, a second order fit is estimated for the extended data sets, acceleration being twice the second order coefficient. It is not suggested that a quadratic fit is an appropriate model for actual MSL rise (especially when the time series might be incomplete and given the cautions above), but it is a simple test for long term growth in rate that allows easy comparison with previous studies. As with other regional and indeed the global tide gauge data sets, extending the data and setting some accepted arbitrary criteria for completeness results in increased convergence towards a small but consistent positive acceleration. For the data here the average is 0.01mm/yr^2. This is consistent (identical) with the value derived from century scale time series from the extended global data set. The same criteria for annual series completeness is used of >75% overall, except for Los Angeles which is 57% since 1854, but 74% complete over the last 120 years.

Tide Gauge Site	Start Year	% Complete	Acceleration (mm/yr^2)
San Diego	**1854**	**78%**	**0.0066**
Los Angeles	**1854**	**57%**	**0.0086**
San Francisco	**1854**	**100%**	**0.0128**
Seattle	**1899**	**99%**	**0.0051**
Victoria (uncorrected as at 2015)	**1891**	**88%**	**(0.0156)**
Victoria (corrected using Sand Heads)	**1891**	**88%**	**0.0086**
Vancouver (using buddy checks)	**1895**	**79%**	**0.0126**
Tofino composite	**1905**	**86%**	**0.0132**
Prince Rupert composite	**1903**	**99%**	**0.0144**

Table 2: Estimated century scale MSL acceleration values derived from the extended and corrected data discussed in this note.

For Astoria, although there is a large gap in the record and the datum connection between Tongue Point and Astoria is tentative, the derived estimate of acceleration using the additional data in this note (given here for comparison, but not used in the global analysis) would be 0.0034 mm/yr^2.

It is interesting that the small positive acceleration also appears consistent for nearby tide gauge sites even where the vertical land movement is in opposite directions (for example Tofino and Victoria), suggesting it is indeed independent of the land motion and due to real changes in MSL over this time period.

Monthly, daily, or higher frequency data is used to give the best estimates to fill partial annual values, and seasonal variations are taken into account when interpolating monthly values if small gaps exist (using NOAA derived seasonal variation estimates as at 2015). The datum height values from earlier published records have been used (even if not noted here for some individual sites) to double check datum connections where possible.

Once the datum information for some of the Canadian sites is independently verified (2015 PSMSL notes), some of the uncertainties in the extended data sets discussed here can be reduced further. It is obvious that any non-linear trend values are highly sensitive to datum connections where data gaps exist, but it is hoped that this work and recovered data sets can now be built upon or further corrected to improve long term regional trend estimates. As ever, this is work in progress.

References

Anon (1943). *Tidal Bench Marks: San Francisco Bay Region* USCGS (T21), US Government Printing Office.

Anon. (1873). Descriptions of Bench-Marks at Tidal Stations. *Report of the Superintendent of the United States Coast Survey showing the Progress of the Survey During the year 1870*, Government Printing Office. (Appendix 10), 92-97

Anon. (1877) Tidal Observations. Progress of work in Section 10, *Report of the Superintendent of the United States Coast Survey showing the Progress of the Survey During the year 1877*, pg 51. Government Printing Office.Washington

Association d'Oceanographie Physique (1939). Monthly and Annual Mean Heights of Sea-level up to and including the year 1936. Publication Scientifique No. 5. 224 & 226.

Avers, H. G. (1926). First-Order Levelling in Oregon. USCGS Special Publication 122, US Government Printing Office. Washington

Bache A. D. (1854) On the tides of the Western coast of the United States – Tides of San Francisco Bay, California. Appendix 28, *Report of the superintendent of the coast survey showing the progress of the survey during the year 1853*. USCS. R. Armstrong, Washington.

Balazs, E. I., & Douglas, B. C. (1979). Geodetic leveling and the sea level slope along the California coast. *Journal of Geophysical Research: Solid Earth (1978–2012)*, *84*(B11), 6195-6206.

Birdseye, C. H. (1925) *Spirit Leveling in California 1896 - 1923*. U.S.G.S. Bulletin 766. Government Printing Office, Washington.

Bowie, W. (1914). *Hypsometry: Precise leveling from Brigham, Utah, to San Francisco, California.* USCGS Special Publication No.22. US Govt. Print. Off. Washington

Bowie, W. & Avers, H. G. (1914). *Fourth General Adjustment of the Precise Level Net in the United States and the Resulting Standard Elevations*, USCGS Special Publication No.18. US Govt. Print. Off. Washington.

Bowie, W. (1936). Vertical Movements of Earth's Crust as Determined by Leveling. *The Journal of Geology*, 387-395.

Breaker, L. C., & Ruzmaikin, A. (2011). The 154-year record of sea level at San Francisco: extracting the long-term trend, recent changes, and other tidbits. *Climate dynamics*, *36*(3-4), 545-559.

Breaker, L. C., & Ruzmaikin, A. (2013). Estimating Rates of Acceleration Based on the 157-Year Record of Sea Level from San Francisco, California, U.S.A. *Journal of Coastal Research*. 29, (1), pp 43-51. doi: 10.2112/JCOASTRES-D-12-00048.1

Bromirski, P. D., Flick, R. E., & Cayan, D. R. (2003). Storminess Variability along the California Coast: 1858–2000. *Journal of Climate*, *16*(6).

Buijsman, M. C., Sherwood, C. R., Gibbs, A. E., Gelfenbaum, G., Kaminsky, G., Ruggiero, P., & Franklin, J. (2003). Regional Sediment Budget of the Columbia River Littoral Cell, USA. Open-File Report 02-281. U.S. Geological Survey.

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 (1978–2012)*, *114*(B1).

Cole, L. A. (1930). Tidal Bench Marks, State of Oregon. USCGS Special Publication 163, US Government Printing Office. Washington

Dawson, W. B., (1906) Tide levels and datum planes on the Pacific Coast of Canada. Sessional paper no. 21c.A. Supplement no. 1 to the Thirty-eighth annual report of the Department of Marine and Fisheries. Ottowa.

Dawson, W. B. (1923). Tide levels and datum planes on the Pacific Coast of Canada, from determinations by the Tidal and Current Survey up to the year 1923. Department of Marine and Fisheries. Ottowa.

Dedrick, K.G., (1983) Use of Early Hydrographic Surveys in Studies of California Estuaries. *Coastal zone '83: proceedings of the Third Symposium on Coastal and Ocean Management*, Town and Country Hotel, San Diego, California, June 1-4, 1983, Volume 3 pp 2294-2314

Disney, L.P., Overshiner, W.H., (1925). *Tides and Currents in San Francisco Bay.* U.S.C.G.S. Special Publication 115, US Government Printing Office.

Ferrel, W. (1882). Discussion of the tides of the Pacific coast of the United States. Appendix 17 *Report of the Superintendent of the United States Coast and Geodetic Survey showing the Progress of the Survey during the Fiscal Year ending June 1882*, pp 437-450 Government Printing Office. Washington.

Gannett, S. S., & Baldwin, D. H., (1908). *Results of Spirit Levelling in California 1896 to 1907 Inclusive*. U.S.G.S. Bulletin 342, Government Printing Office. Washington.

Gilbert, G. K. (1917). *Hydraulic-mining debris in the Sierra Nevada* (U.S.G.S. professional paper No. 105). US Government Printing Office.

Pourtales, L. F., (1858). Report to the superintendent by Assistant L. F. Pourtales in charge of the field and office work relating to Tidal Observations. *Report of the Superintendent of the United States Coast Survey showing the Progress of the Survey During the year 1858*, Government Printing Office. (Appendix 29), 208

Hayford, J. F., & Baldwin, A. L. S. (1907). The earth movements in the California earthquake of 1906. *Report of the Superintendent of the Coast and Geodetic Survey*. Government Printing Office. (Appendix 3), 67-99

Lawson, A. C. (1908). *The California Earthquake of April 18, 1906: Report of the State Earthquake Investigation Commission, in Two Volumes and Atlas* (No. 87). Carnegie Institution of Washington.

Le Lacheur, E. A. (1928). *Tidal Bench Marks State of California* USCGS Special Publication 141, US Government Printing Office. Washington

Moftakhari, H. R., Jay, D. A., Talke, S. A., Kukulka, T., & Bromirski, P. D. (2013). A novel approach to flow estimation in tidal rivers. *Water Resources Research*, *49*(8), 4817-4832.

Rappleye, H. S. (1932). *Levelling in Oregon*. USCGS Special Publication 177, US Government Printing Office. Washington.

Roberts, E. (1872). Report of the Committee appointed for the promotion of the extension, improvement and harmonic analysis of Tidal Observations (Thompson, W., Adams, J. C., Oldham, J., Parkes, W., & Admiral Richards). *Report of the Forty First Meeting of the British Association for the Advancement of Science*, Edinburgh, August 1871. British Association for the Advancement of Science, J. Murray. London.

Roden, G. I. (1966). Low-frequency sea level oscillations along the Pacific Coast of North America. *Journal of Geophysical Research*, *71*(20), 4755-4776.

Smith, R. A. (1980). Golden Gate tidal measurements: 1854-1978. *Journal of the Waterway Port Coastal and Ocean Division*, *106*(3), 407-409.

Smith, R. A. (2002). *Historical Golden Gate tidal series*: NOAA Technical Report NOS CO-OPS 035.

Talke, S. A., & Jay, D. A. (2013). Nineteenth Century North American and Pacific Tidal Data: Lost or Just Forgotten?. *Journal of Coastal Research*.

Talke, S. A., & Jay, D. A. (2014).Water levels and extremes in the Columbia River Estuary since 1853. Presentation given January 28th 2014. Portland State University.

Theberge, A. E., (2005). *150 Years of Tides on the Western Coast: The Longest Series of Tidal Observations in the Americas*. US Department of Commerce, National Oceanic and Atmospheric Administration, National Ocean Service, Center for Operational Oceanographic Products and Services.

Thompson, W., Adams, J. C., Oldham, J., Parkes, W., & Admiral Richards. (1877). Report of the Committee appointed for the promotion of the extension, improvement and harmonic analysis of Tidal Observations. *Report of the Forty Sixth Meeting of the British Association for the Advancement of Science*, Glasgow September 1876. British Association for the Advancement of Science, J. Murray. London.

Wood, S, H., Elliott, M., R. (1978). Early 20th-Century Uplift of the Northern Peninsular Ranges Province of Southern California. *Tectonophysics*, 52 (1979) 249-265

Young, W., R. (1929). *Report on Salt Water Barrier Below Confluence of Sacramento and San Joaquin Rivers, California*. Reports of the Division of Water Resources, Bulletin 22, Vol 1. Pg 264.(0.291 ft offset Fort Point zero datum)

(2011) Lower Columbia River DTM Summary Report, Appendix A, Lower Columbia River Chart Datum Modeling. David Evans and Associates, Inc.

(1918) Engineering Institute of Canada. pp. 414-5. *Engineering Journal, 1918: Revue de L'Ingénierie*. London

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http://babel.hathitrust.org/cgi/pt?id=mdp.39015070308294;view=1up;seq=25 Victoria BC datums

http://www.ngs.noaa.gov/cgi-bin/ds2.prl?retrieval_type=by_pid&PID=SC0478 Tongue Point Bench Mark Tidal 7

http://www.geocaching.com/mark/datasheet.aspx?PID=SC0482 Tongue Point Bench Mark Tidal 1