Hogarth 2014 supplementary note 5: US and Canadian East Coast Tidal Data and References

All data in this note now updated to 2015 where possible, differences to the results from the 2014 paper are minimal.

This note gives references and background details of one of several regional investigations of the long term change in rate of sea level rise (acceleration or deceleration) which formed part of a systematic global study (Hogarth 2014). For this, century scale records or records from closely spaced tide gauge sites are needed, where the datum relationship is known or can be determined. This allows composite or extended time series to be created which are as long and complete as possible.

The Eastern Seaboard of the North American continent has a richly documented history of tide recording and geodetic work going back to the early 19th Century associated with charting and expansion and upkeep of major ports and harbours. This is in large part thanks to the government supported activity of the USCS which became the USCGS (United States Coast Survey and United States Coast and Geodetic Service), which amongst other things embarked on systematic scientific investigations and recording of tides and currents. There are significant amounts of as yet un-digitised data stored away in archives and municipal records, some of the early data are undoubtedly lost and many early studies and engineering reports have remained largely uncited. Much invaluable work has already been done in recovering some of the still existing early data (Talke 2014) and a large amount of 20th century and some 19th Century data is publicly available in the records of the PSMSL (Permanent Service for Mean Sea Level), UHSLC (University of Hawaii Sea Level Centre) and NOAA (National Oceanographic and Atmospheric Administration).

Here old historical records are examined and used along with more recent data in order to update or extend existing time series and create and give context to some of the longest tidal records available from the Western Atlantic. This adds to previous notes on the West Coasts of the USA and Canada, Australia and New Zealand, and the Indian Ocean. It is hoped that this effort combined with any recovered and digitised data that becomes available will allow confirmation and refinement of these preliminary results over the next few years. If so, this will add weight to the conclusion that statistically significant century scale acceleration of sea level rise, of order 0.01 mm/yr^2 over the 20th Century, is a global phenomenon.

Canada (East Coast)

The Canadian tide records available from the PSMSL have recently been updated (2015) by Fisheries and Oceans Canada and in some cases offer more complete records. As with the Pacific coast data, covered in an earlier note, there has been some rounding down to centimetre precision, and there are some differences. Where this is the case the original imperial values have been converted and used in this note, the effect on derived trends is relatively small for these sites.

St. John, N.B.

Early tide and bench mark records from St. John N. B., were lost in a fire of 1877 (Dawson 1898). Early charts were referred to a MLW (Mean Low Water) datum. Later attempts to estimate the original LW (Low Water) datum involved matching the early known MSL (Mean Sea Level) values with later MSL values from the late 1890s (as was attempted in Halifax). A new tide gauge was set up in 1892, which had problems with stability of the fixing, which had been addressed by 1894. Records were then kept up until the present, although there are gaps. Some of these early gaps can be filled with the metric annual mean values published in the PSMSL auxiliary files (from 1894), and the gaps in the 1930s and 1940s can be filled by creating a composite time series using data from the nearby Eastport tide gauge. The data from Eastport is offset using the average difference in the long overlap period between 1929 and 2015, and the differences are investigated for any anomalies. Smaller gaps in the monthly time series from St. John can be dealt with by applying a seasonal correction to the incomplete data using the differences from annual mean of each month for the entire time series. This prevents biasing the annual values due to the large seasonal variations where the monthly data is incomplete. It can be seen that the annual data from St. John shows large positive excursions in 1998 and 2014 (as well as other negatives ones) that are less amplified in the time series from nearby sites. These are large enough to have a significant effect on the derived trends even over century time-scales.

Halifax

Early tide data for Halifax was recorded on charts of Nova Scotia by James Cook, but the precision was only around 1 foot. More precise and continuous data was recorded in 1851 and 1852 on an automatic tide gauge in the Navy Yard for a regional survey by Captain Bayfield, whose detailed charts remained in use for many decades. The tidal range of these automatic tide gauge readings averaged over the entire period has also been published (Bache 1858), which for mean spring tides gives 6.0 ft. Thus MTL (Mean Tide Level, or average of MHW and MLW) would be 3 ft above the MLWS (Mean Low Water Spring) datum. Harmonic analysis of these automatic tide gauge records from 1851 and 1852 (low water spring tides below MSL = M_2+S_2+K_1+O =2.955 ft) have also been published (compare with the 3 ft derived above), as have a further two years of records from 1860 and 1861 (Dawson 1899). However whilst the elevation above CD (Chart Datum) is known for the old bench mark at the Navy Yard used for these gauges (16.08 ft), the relationship to the TGZ (Tide Gauge Zero) used remained uncertain, as the average A_0 values for 1851 and 1852 are given as 4.64 and 4.63 ft respectively, which were over one foot greater than the readings from 1896 onwards which used the original CD as the gauge zero. These early annual data (from Dawson) are available as metric mean values in the PSMSL auxiliary files and in imperial units in the Publication Scientifique No.5 (Proudman et al 1939). It was common practice to offset the zero of the gauge by some arbitrary amount below MLWS to avoid negative readings, and from the values given above this appears to be the case. From inspection it also appears that the two pairs of annual record (1851-52 and 1860-61) have different zero references. A later tide gauge set up by the Tidal Survey Branch in late 1895 used the original 1853 Chart datum as zero reference (Dawson 1895, 1898) and at the time the older tide data was offset to match the MSL derived from this later data (Dawson 1897) assuming MSL was effectively constant over decadal periods (in line with then prevailing theory). This method of datum connection is obviously not ideal for evaluating changes in relative MSL, and almost certainly the mean sea level had significantly altered between 1851 and 1896. The offset values derived by Dawson do not match the 3 ft MTL value derived from half the mean spring range, and a more appropriate TGZ below MSL offset value would be estimated by subtracting 3 ft from the A_0 value, resulting in a zero offset of 1.5 to 1.6 ft. The Canadian Almanac of 1896, published in 1895, contains tide tables for Halifax based on the early Admiralty data. The footnotes state that "*The height is measured from a datum plane which is about 1 foot 6 inches below the level of low water at Ordinary Spring Tides; which is the Datum of the Admiralty Charts*". This gives the required information to reduce the 1851 and 1852 data to the later datum. The PSMSL annual series stops in 2013 (as at end 2015) but hourly and daily values are available from the UHSLC which allow the time series to be updated to 2015. The effect of the gaps in the 2015 data (and elsewhere) can be minimised by adjusting monthly values to remove the average seasonal component, and an estimate of the MSL and MTL differences can also be derived from the available hourly data between 1895 and 1897.

Without the pre 1896 data another seven years of annual averaged tide data are available for Halifax to fill the gap in the PSMSL annual record between 1898 and 1906, from the auxiliary PSMSL data, and a composite can be created by offsetting (using mean difference in overlapping years) and adding available data from 1908 to 1919 from St Paul's Island (388km distant), improving the completeness of the annual time series and the confidence in the trend. It should be noted that the Chart Datum at Halifax was redefined in 1987 to be 290mm above the original 1852 datum. The monthly metric MSL data from the PSMSL is referred to the 1987 datum, and therefore an offset of 290mm is required to compare the PSMSL metric data with the old PSMSL auxiliary data. The derived acceleration is 0.007 mm/yr^2 for the almost complete extended data between 1896 and 2015, and 0.0102 mm/yr^2 if the corrected 1851 and 1852 points are included. The 1861 and 1862 data should be viewed with caution. The two consecutive annual values differ by 0.56 ft, and this is significantly outside the inter-annual variability for the rest of the time series.

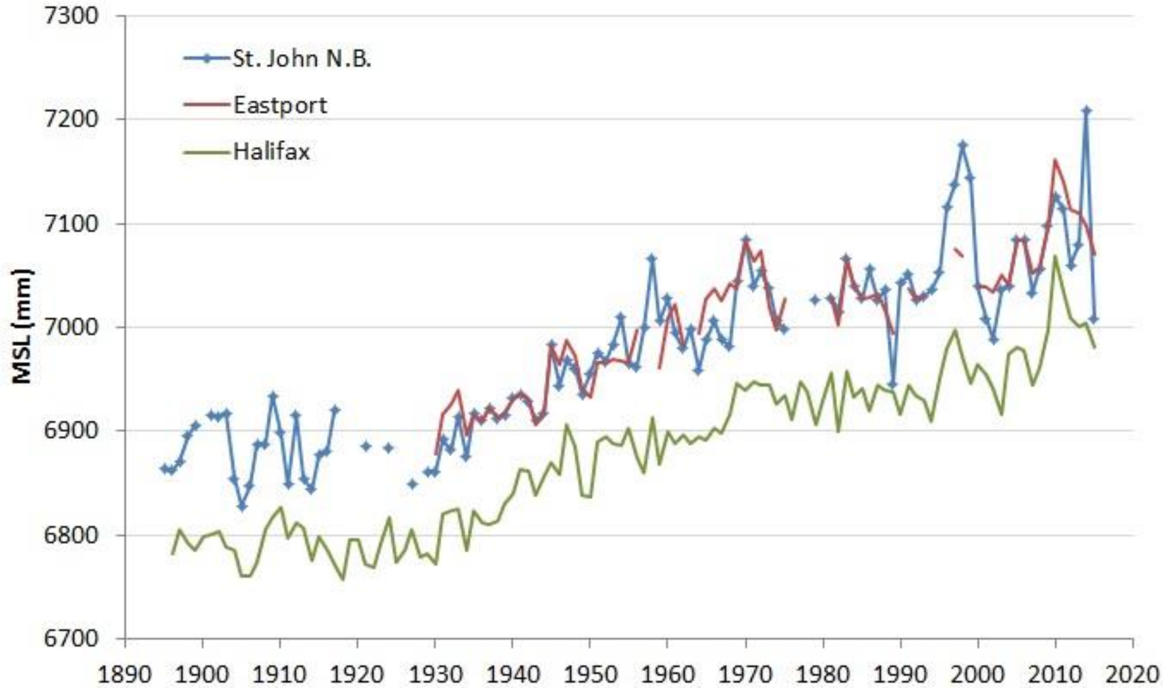

Figure 1: Plots of extended annual time series for St. John N.B., and Halifax, Nova Scotia. The data for Eastport is offset and overlaid on the St John time series to highlight possible anomalous excursions in the St John data. The Halifax time series has a -1mm/yr adjustment (VLM difference) in order to better show similarities in longer term variations.

Quebec also has a long tide (or river level) gauge record, but there are large inter-annual variations most likely caused by river flow variations that will affect even the trends derived from the longer time series. Some gaps in the early data can be filled with published data from the PSMSL auxiliary files, but some of these annual values show large excursions (e.g. 1912 and 1915) and these years were not originally used by Dawson (1917). The record from Quebec and nearby gauges also indicates significant upwards vertical land motion from post glacial rebound, to the point where relative sea level appears to be falling, as in the Northern Baltic. Details of bench marks and some historic context have been published (Dawson 1895, White 1901). Tide gauges from the St. Lawrence close to the Gulf such as Quebec, have a tidal component, but all stations upstream show the dominant river level components. The variability at Quebec was judged too high for a robust trend to be estimated.

United States East Coast

Boston (Massachusetts)

As with many other tidal time series that stretch back into or before the mid-19th Century, the earliest data is subject to a higher degree of uncertainty. A chart of Boston harbour in the 11th edition of Blunts "American Coast Pilot" (Blunt 1827) updates the earlier one presented in the 10th edition (Blunt 1822), with HW (High Water) and LW (Low Water) contours, and a note that the rise of "common" tide (ie Mean High Water, or MHW above Mean Low Water, or MLW) was 10 ft, with springs up to 13 feet. This water level information was taken from a survey by A. S. Wadsworth (U.S.N.) in 1817, but no fixed bench marks were given. A later comparison study in the 1850s concluded that the 1817 zero datum was probably mean low water, as the limited evidence from mean depth over fixed objects like rocks agreed more closely with the later MLW datum than the alternative of MLWS.

More systematic tide records were taken in Boston on instruction of Loammi Baldwin (a notable civil engineer) as part of the preparation for constructing a new dry dock at the Navy Yard in Charlestown. Daytime observations were kept for a month in October 1824 (Baldwin 1824), then from November 1824 (with some breaks) to July 1825. The intention was to set a dock datum (LW) level and measure HW levels to allow elevations of the dry dock floor and wall coping to be appropriate for the local tides and largest vessels of the day. Over this period Mean High Water was recorded as 10ft 4in above the zero datum determined at the time. From further observations October 18th to December 5th 1826 MHW was given as 10 ft 3.5 in. (Baldwin 1826). As October and November water levels were on average 0.155 ft above annual mean water level at the Navy Yard due to seasonal variations (derived from analysis of entire data set), this should be accounted for in any trend analysis. It should be noted that “low tides” in Baldwin’s 1826 report actually refer to the minimum tidal range. His zero of measurements would have been a low water datum derived from the recorded data. If the original 1824 to 1826 MHW values were referenced to an original MLW zero that was set and then maintained as the early dock datum, close to what became the “Boston Base” of 15 ft below dock coping, then the average MTL value for 1824 to 1826 would be around 5.17 ft (or 20.17 ft above the dock sill). This would be remarkably close to the later 1867 MTL values referenced to Boston Base. It is mentioned that Loammi Baldwin set the coping level several inches (three inches in some sources) above the highest recorded tide level after examination of tide records of the previous sixty years (Vose 1885, Drake 1888). In contemporary records it is mentioned that the coping was made to be level with the flood tide of 1786 (Executive Documents 1831). Most of these previous tide records would have been limited to extreme tides only. In general, the use of dock coping as an elevation reference has its origins in these considerations.

Construction of the docks at Charlestown was started in June 1827, and the dock was opened in June 1833. The smooth level top of the granite coping on this dry dock was (from the plans) set “30 feet” above the dock sill, with the intention that ordinary high tide would be “5 ft” below the coping (Monthly Record 1831, Stuart 1852) based on the tide measurements. A summary of MTL of three years gaugings from 1830 to 1832 taken during construction was published by Loammis brother George (Baldwin 1864). This was 9.54 ft below the dock coping (or 20.46 feet above the dock sill on the dock tide scale). Curiously this differs from the average of MHW and MLW (4.7ft and 14.695 ft below coping respectively) of 20.3 ft over the same period given in the same document. Either way, there is already a divergence between the expected nominal MLW as a permanent dock datum of 15 ft below coping and actual MLW, which varied considerably year on year. Tides were also recorded by the British Admiralty at the dry dock using the coping level as reference, for the international effort on tide levels undertaken 8th to the 28th June 1835 (Whewell 1836, Baldwin et al 1837). The later harbour survey of 1837 by Baldwin also referred water levels to the coping, but the tide data was not published.

The dock as originally constructed included six tide gauges consisting of copper or bronze numerals and scale marks denoting feet above the sill of the dock set into the granite facing stones of the dock walls, inside and outside the gates. The top level of the coping was originally the 30 ft mark of these scales. Initially High and Low Waters were recorded as observed directly on these gauges (Pourtales 1859). A portable tide staff would normally be used so as to allow readings to fractions of feet, and this would be referenced to the coping level, or bench mark “30”. The USCS (United States Coast Survey) chart of Boston Harbour for 1847 notes under the tidal datum levels that “*The coping of the dry dock at the Navy Yard Charlestown is adopted as a permanent plane of reference for these and future observations*”. For the 1846 data used on the 1847 chart MLW is given as 15.3 ft, and MHW as 25.7 ft above the dock sill. MLW is also recorded as being 14.7 ft below the coping level, so mean tide would be 9.5 ft below coping. By 1853 MLW was recorded as 14.78 ft below coping, and by 1856 it was 14.76 ft. These are very close to the values from Baldwin, suggesting the original dock datum was also at around this level.

The tide staff was moved to another position 400 ft East after it was noted in 1857 that widening of the joints between the granite facing blocks near the dock gates had caused stretching of the inlaid copper (or bronze) tide scale of up to 2 inches in a single foot (Schureman et al 1928). Shortly after this the dock was extended in 1858-1859 to accommodate larger vessels, which involved dismantling the wall and altars at the head of the dock and rebuilding them 65 feet further inland, with new massive granite block side walls filling the gap. The rear section of coping was levelled with the older side sections near the original position of the rear wall of the dock.

The coping and wall near the outer part of the dock at BM1 was also rebuilt in 1859, as it was noted that the top level of the coping inclined slightly inland (Mitchell, October 1860 reported by Schureman 1928). These repairs involved resetting of the coping blocks and the scale of the inlaid gauge “so as to make the top of the wall read 30 feet as before”. By comparing with the fixed tide staff which had at some point been previously levelled to BM1, Mitchell noted that the coping of this outer section had been set lower by 0.07 ft at this time and this would affect subsequent tide readings (Bache 1861).

Mitchell goes on to state that even after the repairs, the coping still inclined over the entire length of the dock so that the outer section was over 0.1 ft higher than at the head of the dock. Therefore before the repairs BM1 would have been at least 0.17 ft above the coping at the rear of the dock.

In a report of 1860 (written 1859) a tide measurement datum was selected as 20 ft below coping on the dry dock, this suggests that a standard 20 ft "common" tide staff was in use by this time, with 20ft mark set at or close to coping level.

The tide gauge was moved a few paces in 1861 due to obstructions reading low water, and then silting became such an issue (Pourtales 1862) that a new box gauge was fitted in the tide gauge building on May 28th 1861 just South West of the dry dock entrance, where a self-registering gauge (set up by the Harbor Improvement Commission) had also been fitted in 1860 (Ferrel 1871, Schureman 1928). The zero was set to the same level as the old staff gauge. The box gauge readings were taken from 1860 to the end of September 1866. A survey of the river in 1861 tabulates tide readings from the navy yard tide staff using using a nominal MLW of 5.5 ft above zero (Totten et al 1862). If the accepted MLW was 14.69 ft below coping at that point, this implies that the 20 ft mark on this tide staff would have been 0.19 ft below BM1. Judging from the actual MLW up to 1861 of 5.27 ft this would place the 20 ft mark slightly above BM1, as indicated by Mitchell. A new box gauge was fitted in 1862, and the self-recording gauge was handed over to the Coast Survey observer (U.S.C.S. 1864), although the USCS reports state that the actual subsequent tide records are taken from the box gauge.

Monthly and annual mean HW and LW as well as MTL were published for the period July 1847 to June 1865 (Ferrel 1871). These have been transcribed into electronic format for this note.

Just South of the Navy yard, a short series was recorded at the India Wharf by G. Baldwin from September 1867 to May 1868. This data used the Boston Base as reference and was connected to the Navy Yard datum by levelling and simultaneous water levels. Monthly HW and LW have been published (Freeman 1903) and these have also been transcribed.

From 15th August 1867 to February 1877 tide data was recorded on a newly installed Saxton self-recording gauge fitted in the next dock South West of the dry dock. As the dock coping at BM1 was being repaired again, Mitchell set a new benchmark "BM2" on top of the coping at the head of the dock, and determined that the TGZ of the now relocated reference 20 ft tide staff was 19.433 ft below this (Schureman 1928). BM2 was later measured as 0.176 ft or 54 mm below BM1 when levelled in 1868. Further repair work was done at the entrance to the dock 1869-1870, again including rebuilding work of the section with the tide scale and BM1 coping stones. In late 1869 Mitchell was instructed to adjust the tide staff so that the 20ft mark was level with the dock 30 ft mark, or old BM1. He carried out this instruction by February 1870 once the dock repairs were complete. The vertical difference between BM2 and BM1 at this time was carefully recorded as 0.155 ft. The self-recording gauge was moved across the slip-way July 19th to 21st 1870, but a few days afterwards a vessel collided with the tide staff and it was reinstalled again with the 20 ft mark level with BM1 (July 26th). The self-recording gauge was moved back again in June 1876. Records were taken from 1867 until February 1877. There is then a gap in continuous tidal recording (or in available records) at the Navy Dock site from 1877 to 1902.

In 1878, one lunar months readings were taken by the US Engineers at the Navy yard (on a gauge established by the Massachusetts Harbor Commission) between November 5th and December 3rd (Shailer 1878). MHW was 9.89 ft, MLW 0.38 ft, so MTL was 5.135 ft (compare with the later 1902 readings reported by Freeman to the same Navy Yard base). As the average water level for the peak month of November over the annual mean is around 0.155 ft, then again the seasonal tidal variation should be considered. In an engineering report of 1883, it is stated that the low water mark on the tide staff was 5.4 ft above zero, and this mark was 14.7 ft below the coping, thus by this point the 20 ft mark of the staff would be approximately 0.1ft below BM1 due to further elevation of the coping.

A new 15 foot gauge was set up in 1902, with TGZ 14.54 ft below BM2, which at this time was measured at 0.36 ft or 110 mm below BM1. Tidal data from the Navy yard from 1902 to 1911 has been published with some gaps (Freeman 1903, Schureman 1928), but annual mean tide levels are available and missing months and partial years can be adjusted for by using the average seasonal MSL variation.

After another gap in continuous recording at Boston, a tide gauge was installed at the Commonwealth pier 5 in 1916 (Journal of the Boston Society of Civil Engineers 1916), with the intention of monitoring subsidence as well as sea level (prompted by Freeman), but this operated intermittently and was discontinued by 1921. The USCGS, keen to again have a permanent station in Boston, installed a new standard tide gauge at the site, set new bench marks, and levelled the gauge zero back to standard city bench marks (Auld 1921). This was operational from May 1921. The tide gauge zero was originally referred to a 12 foot tide staff at the site, but this was replaced with a 15 foot staff installed in September 1922, with the 15 ft mark level with the old 12 ft mark (Schureman 1928). The published tidal values were referred to the zero of this later tide staff which was 21.45 ft below BM7 near the pier. This TGZ is the same datum used in the current PSMSL time series, which runs from 1921 to the present.

Several of these tide gauge data series from 1847 onwards were reduced to common datums and published in a USCGS report on Boston Harbour (Schureman et al 1928). Although the shorter time series is mentioned from 1846, Schureman summarised annual HW and LW as well as annual mean tide levels for 1847 to 1877, and 1902 to 1911 at the dry dock, then monthly MTL and MSL values from August 1921 to December 1926 from the Commonwealth Pier No. 5. This latter series (from 1921) continues up to today (2015) and is available from the PSMSL or NOAA.

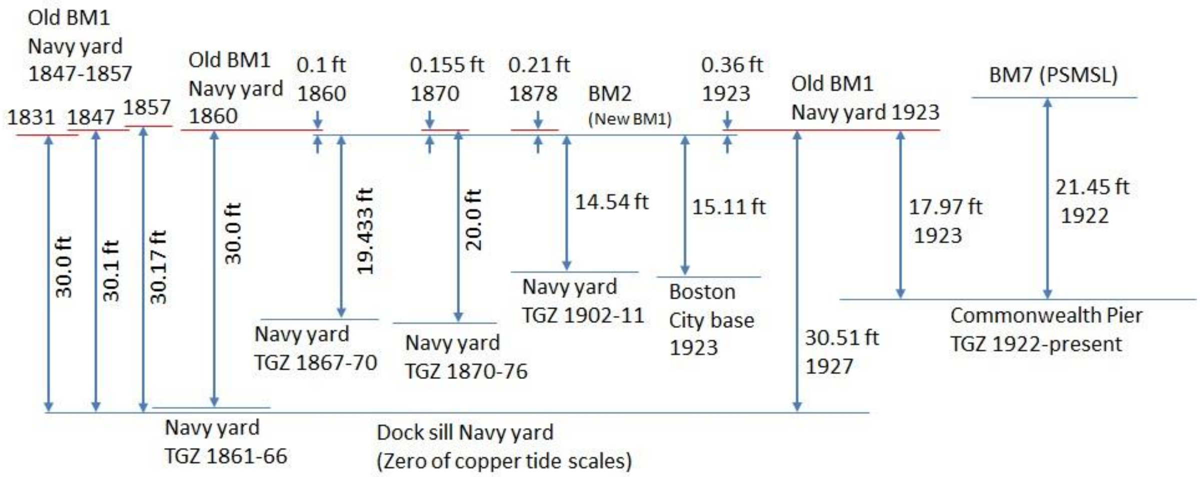

Figure 2: Stick diagram for Boston showing various TGZ and datum relationships. The elevation changes in BM1 resulted in a cumulative change of +0.5 ft over time between 1831 and 1923.

To create a composite time series from these various data series:

i. The Navy Dock time series must be accurately connected to the Commonwealth Pier 5 time series datum. The relationship between the two respective tide gauge benchmarks (BM7 near Commonwealth Pier and BM1 at the Navy Yard) was established in 1923 by first order levelling (Schureman 1928, pg 15). However the bench mark elevation changes in respective locations between the time of setting up of the gauge at the Navy yard (1902) and the later Commonwealth Pier tide gauge (1921) should be considered. Whilst benchmarks Tidal BM6, BM7 and J12 near the Commonwealth Pier appear to show similar small subsidence of order -0.5mm/yr between the 1920s and 1980s, judging from repeat levelling, BM2 appears relatively stable over the period of interest (1902 to 1923). No additional correction was therefore applied for the 1923 datum connection back to BM2 in 1902.

ii. As the Commonwealth Pier data is MSL, and the Navy Yard data is recorded as MTL, the average MSL-MTL difference of 0.16 ft or 49 mm at the Navy Yard must be accounted for by adding this average offset to the Navy Yard series (the equivalent MSL-MTL at the Commonwealth pier is 0.12 ft).

iii. Any average height difference at different locations due to net water flow in estuarine or embayed environments should be factored in. Ideally simultaneous water level records would allow average equivalent MSL differences to be determined (Johnson 1929). The respective mean sea levels at the Navy Yard are reported as slightly higher than at the Commonwealth Pier, the difference amounting to around 0.11 ft (Elliott 1938) or 33.5 mm. Whether due to levelling error or actual mean sea level differences, this offset should be subtracted from the entire Navy Yard time series, assuming dredging or other factors have not significantly affected relative water levels over this time.

The resultant corrected composite series bridging the gauge location change should ideally be double checked with data from a nearby station which has continuity over the data gap. Fortunately the data series from Baltimore starts in 1902 and runs to the present, and a difference plot with the corrected Boston data using average annual values shows good agreement, at less than 3 mm mean difference between the 1902-1911 Navy Yard data and the later data from the Commonwealth Pier (figure 3).

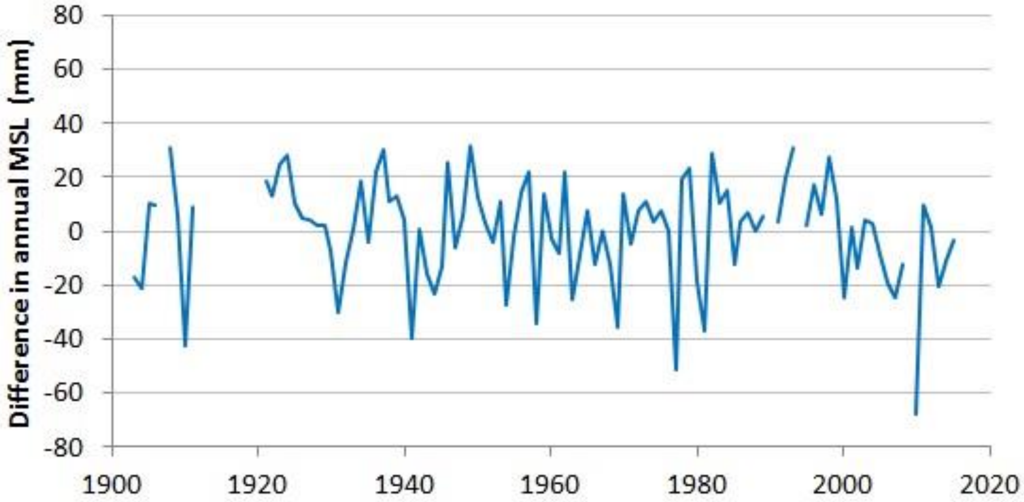

Figure 3: Difference plot of Baltimore (PSMSL) minus new Boston composite (annual values, overall scale factor and offset added for visualisation purposes). The Navy Yard section is from 1902 to 1911. If the estimated datum connection is robust then there would be no average offset between this section and the later Commonwealth pier section.

iv. The final and more challenging issue is to account for changes in datum elevation over time at the Navy Docks prior to 1902. The elevation of BM1 relative to the dock sill was found from levelling to be 30.51 ft in 1927, 30.47 feet in 1903, 30.33 ft in 1878, and assumed to be 30.0 feet when constructed in 1831 (Schureman 1928, Freeman 1903). This change is non-linear from the bench mark information, with large initial changes, then very little relative change from around 1900 until at least 1934. Here, the modern datum as used by the PSMSL (Commonwealth Pier MLLW in 1922) and time series is used as a starting point. The correction for bench mark movement relative to the connection of BM1 to the Commonwealth pier in 1923 appears close to zero around 1910, but then follows any step changes with various tide staff adjustments or re-locations as well as the slow coping level uplift due to frost, moving backwards in time, resulting in a cumulative correction of around -0.5 feet by 1831.

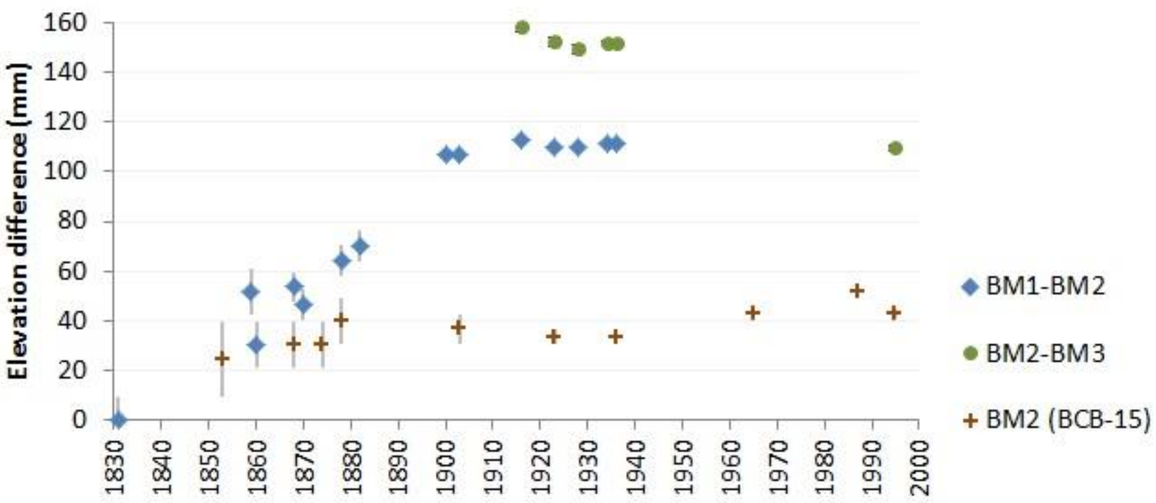

Figure 4: Plot of benchmark elevation differences and a plot of BM2 elevation (offset) at the Navy Yard, showing the relative changes in elevation of BM1 (and also of BM3 more recently) and relative stability of BM2.

As noted in 1857, over the years the effects of sea water and winter ice, (this author also suggests repeat stress due to the hundreds of tons pressure on the dock gates was a factor) caused the joints between the dock wall granite facing blocks, particularly on the more exposed seaward side near the dock gates to expand, having the effect of stretching parts of the scale and raising the elevation of the coping level and the original BM1 compared with nearby bench marks. Initially this relative movement was thought to be due to settling, but it became accepted during the 1880s that frost was responsible for the expansion of joints in some granite dry docks over time (Burchell 1890) and this was investigated in some depth at Boston by Freeman (1903). He measured the distance between the foot markings on the six gauges at the dock to estimate specific joint movement which he believed must have occurred since dock construction and correlated this with changes in bench mark BM1 elevation relative to BM2 and compared both of these to surrounding bench marks and the dock sill and floor. From this he estimated a trend of increase in elevation of the coping stones relative to the sill over time between 1831 and 1902. As the self-registering tide gauge or tide staff outside the dry dock was referenced to BM1, or the coping of the dock, and earlier recorded data was checked against the copper numerals, this undoubtedly meant that there had been systematic errors in relative sea level measurements over time. Freeman then attempted to adjust the recorded sea level values to try to compensate for this joint expansion. This note will follow this methodology.

As further levelling work has been carried out since 1902, additional evidence is now available (Schureman et al 1928, bench mark and levelling records, and modern bench mark sheets). This is complicated before 1878 due to the recorded resetting of the coping stones (during repairs 1859 to 1860, and 1869 to 1870) and also by enlargement of the dock to cope with larger vessels and the necessary movement and resetting of some of the dock bench marks when the rear dock wall was dismantled and rebuilt in 1859.

Schureman accepted Freeman was correct in stating that BM1 has moved 0.46 ft since the coping stones were first set. However Freeman assumed that only a small amount of elevation change in BM1 had occurred before 1847, whilst Schureman (1928) thought it possible that most of the elevation change had already occurred before 1847, and that as the changes were in any case uncertain, no corrections were attempted for the early data he tabulated. This latter is inconsistent with the available information and would make a large difference to the composite time series. The evidence from Freeman, from direct measurement of the true height of the tide scales and BM1 above the dock sill in 1902, plus the previous levelling and repeat measured difference between BM1 and BM2 tabulated by both Freeman and Schureman, and later bench mark sheets, is summarised in figure 4. This differs slightly from the continuous uplift suggested by Freeman (pg 555), by including both stated step changes when the coping was reset. By interpolating between the points, a best estimate of the year by year elevation change can be derived. This can then be linked to the dates when the tide gauge staff was moved and re-referenced to BM1. As in Freeman, it is assumed that the tide staffs were set and not altered once installed (unless such alterations are recorded). This results in a table of estimated corrections for the tide gauge data. It should be noted that the correct 1867 to 1870 TGZ offset was clearly not accounted for by Freeman in his chart, (pg 568) as shown in figure 5.

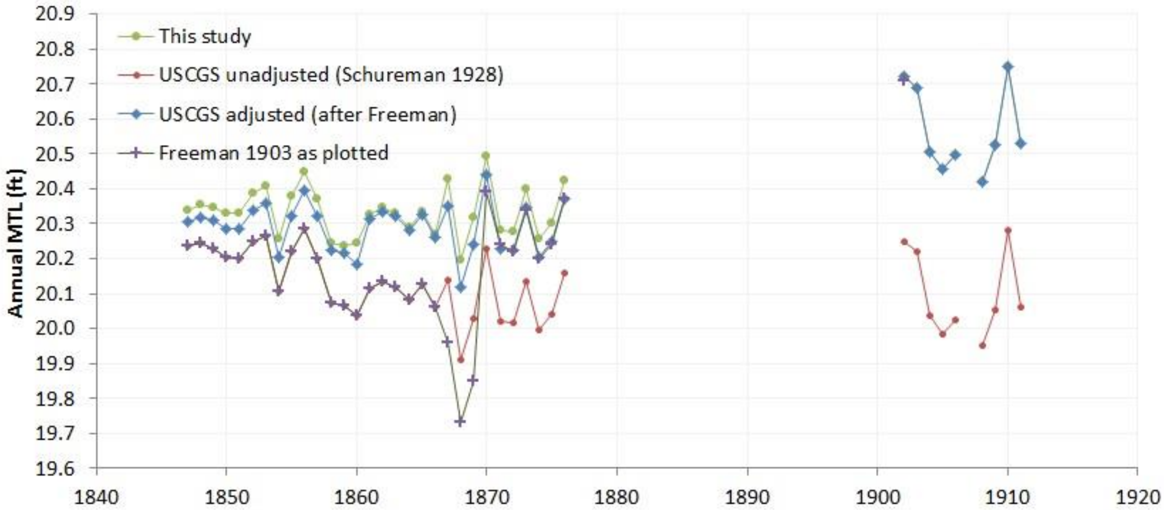

Figure 5: Plot of the Boston Navy Yard annual MTL data above dock sill. Freeman 1903 (partially corrected) as plotted in his report (purple), the correctly reduced for TGZ but unadjusted values published in Schureman (red), and the same values adjusted with uplift corrections after Freeman (blue) and the corrected values from this study (light green).

Correcting the data from 1847 to 1866, the primary bench mark used is BM1. It is assumed that the actual change in BM1 elevation above dock sill between 1831 and 1857 is linear, starting at 30.0 ft and ending around 30.17 ft. If a portable tide staff was used placed over the dock edge with a shoulder resting on the coping (one possibility from existing practice), so that the 30 ft mark was level with the coping, then the required corrections will directly track the rise in elevation of BM1. If the portable staff was attached to a pile or other structure not fixed to the coping, then the correction will involve a number of unknown steps when the gauge was renewed and possibly re-levelled to BM1. The latter seems possible as some annual reports mention degradation of the staff gauge which is consistent with constant immersion, and a “Common tide gauge” is also referred to (ie a standard length tide board marked in feet and tenths). Later tide staffs (1861 onwards) were certainly attached to pilings. The minimum case would be a staff zero remaining fixed between 1847 and 1857. After the change in location in 1857 it is assumed that the elevation is maintained at the 1857 value of coping elevation. For the box gauge data from 1860 to 1866 it is assumed that BM1 is used at the estimated 1859 BM1 elevation before repairs (30.17 ft referred to dock sill). The monthly data from 1847 to 1866 (Ferrel 1871) can be checked against the later monthly data from India Wharf given in Freeman (1903). Correcting the Navy yard data (it is assumed that the India Wharf MSL is closer in elevation to the MSL at the Commonwealth Pier), eliminates a visible datum step in the uncorrected data. The resultant plots of Navy yard MTL data corrected for elevation change, by whatever method, all show improved match to the later India wharf data over the uncorrected versions, and all show less interannual variation. It should also be pointed out that although there is still uncertainty about the tide staff zero elevations between the 1847 and 1857 values, the end points are better defined and the possible alternative set of corrections will all have a similar significant effect on the overall acceleration of the composite time series compared to the uncorrected version.

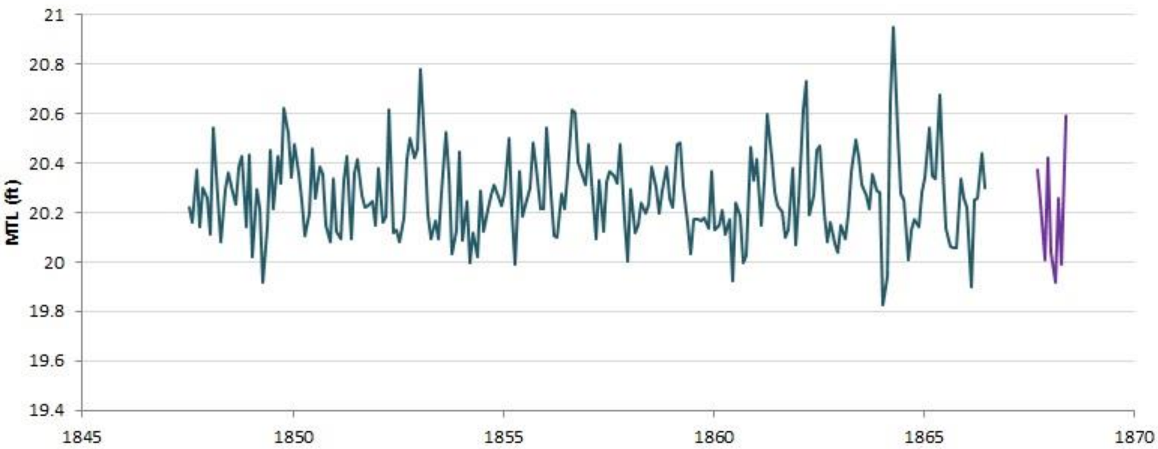

Figure 6: Monthly MTL for Boston 1847 to 1866 derived from MHW and MLW (Ferrell 1871), and data from India Wharf (purple). The data is corrected for estimated changes in BM1 elevation assuming step changes each time the tide gauge staff is known to have been tied to BM1. Referenced to Dock sill datum. Mean seasonal variation over the time period removed.

Whilst it is clear that BM1 has risen significantly in elevation compared to BM2 over many years, it is not clear that BM2 has substantially altered elevation relative to other surrounding survey points between 1867 and 1903, or even up to the 1990s. Both the chiselled square and the broad arrow of BM2 still exist (2015) as set in 1867. It was noted at an early stage that the visible change of coping level appeared limited to the outer section of the dock (and BM1).

It is also possible that the top of the wall at the head of the dock (and BM2) has not significantly changed in relative elevation since 1859, when the dry dock was extended and the rear dock wall was moved and rebuilt using the original granite stones. It is also likely that the coping was set at the same level as previously, or level with the remaining old coping near the original rear section of the dock. The elevation would also be important to maintain, as this coping height and the nearby “City bench mark” were known reference points from an important 1854 city survey by Harris. This suggests little elevation change had occurred when BM2 was later levelled at 15.11 ft to Boston base. This relative stability of BM2 will be assumed for this discussion.

Unfortunately BM1 is assumed destroyed when the outer section of the dock was extended in 1947/48 and only some of the lower original granite blocks were retained. The tide staff for the data series from 1867 to 1870 is referenced to BM2, and also linked to the elevated BM1. In 1870 the tide staff was again referenced to BM1, but the elevation difference between BM1 and BM2 was also measured at various points in time, and the movement of BM1 can therefore be estimated.

Using all of the corrections discussed previously, the overall effect on the composite series compared to the uncorrected data is significant, and driven largely by the rise in elevation of BM1 over the years.

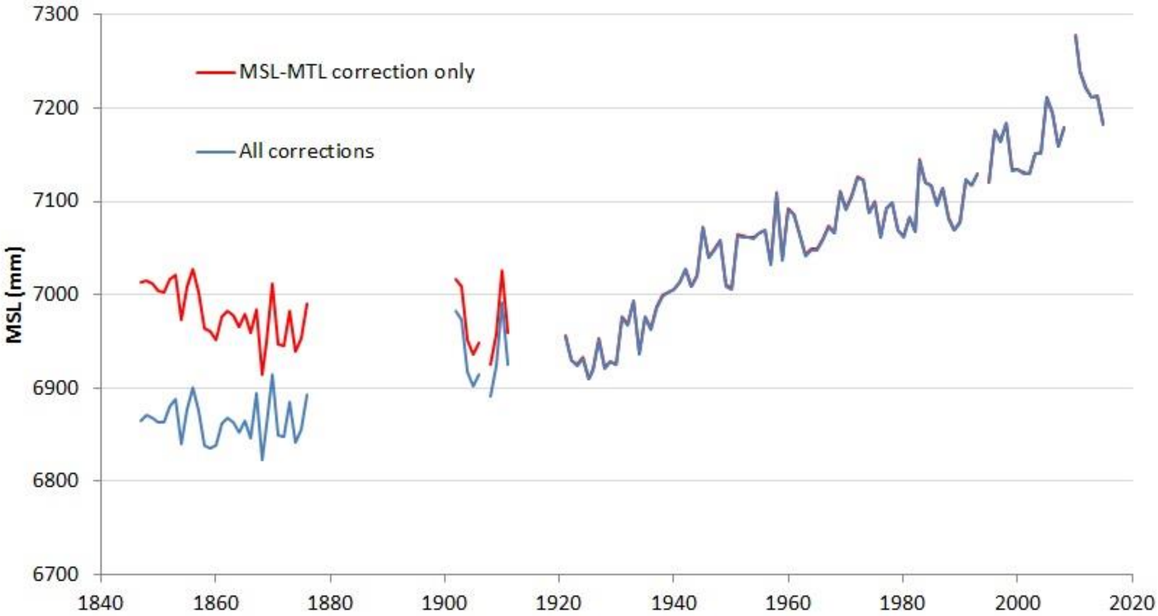

Figure 7: Chart of original annual 1847 to 2015 MSL data from Boston. Red, (as implied in Schureman 1928), with only the correction for MSL-MTL at the Navy Yard applied, and blue, the same original data with corrections applied for MSL-MTL, absolute MSL height differences, and the significant cumulative component of elevation change at BM1. Both offset to match PSMSL RLR datum for Boston.

Estimating the datum for the early (1820s) tide gauge data

The USCS chart of Inner Boston Harbour of February 2nd 1847, based on data from 1846 gives MLW as 14.7 below the coping of the dock, and MHW as 4.3 below coping level. However the Coast Survey of 1847 had supposedly given a MLW value of 15 feet below coping (Commission report 1853 pg 43), which suggests rounding has occurred. City survey records of 1851 put the base of "city water levels" at 84.729 ft, MLW as 14.7 ft, and "Marsh Level" (or MHW) 5.089 ft below the dry dock coping respectively (Boston City Engineer 1900). The marsh level elevation of 5.09 ft below dock coping was given in 1851 in a water board document (Cochituate Water Board 1851). The stated difference of 10 ft between MLW and MHW (marsh level) goes back to at least a survey of 1817 and was assumed by Baldwin (1826). The measured tidal range at the Navy Yard is given as 10.1 ft in the USCS 1853 tide tables and 10.0 ft in the USCS tide tables of 1854 from actual observations (Bache,1854,1855). Another early survey had worked back from the city and ran a spur to the dock coping and arrived at an elevation of the coping of 5.054 ft above "marsh level". In a survey carried out by C. H. Harris in 1854 starting at the head of the dock, "Boston Base" was *set* to be 15 feet below the top of the coping (in the corresponding position on the coping to where BM2 was set in 1867) or 15 feet above the dock sill (equivalent to nominal MLW). The difference between the City Water Level base and the Boston base as defined by Harris (estimated from the difference between elevations of the same bench marks in the two records) shows the older is between 0.06 and 0.13 ft higher than the newer. This would imply that the elevation of the coping at the head of the dock in 1854 could have been 15.06 to 15.13 ft, measured to the same base as the earlier surveys. In an 1859 plan of the Brookline reservoir Tide marsh level is stated as 9.91 feet above Mean Low Water or City base, and the coping level was again stated as 5.09 ft above marsh level (Bradlee 1868). This merely confirms that the accepted level of Boston Base for much city survey work was 15 ft below the coping. All of these surveys were before the rebuilding of the rear of the dock in 1859. By 1859 the accepted actual MLW datum at the Navy yard was 14.76 ft below coping at BM1, this was revised to 14.69 ft by Mitchel in 1860. The definition of MLW at the Navy yard remained as 14.69 below BM1 for many years, right up until the 1930s, despite awareness of the recorded movement of BM1. The actual tidal range at the Navy Yard was recorded as higher than at the Commonwealth pier, and therefore by accounting for the variation in tidal range caused by the Lunar nodal cycle, it can be suggested that the MLW and thus original dock datum in the mid 1820s would be similar to that in 1846/47, as implied in the references.

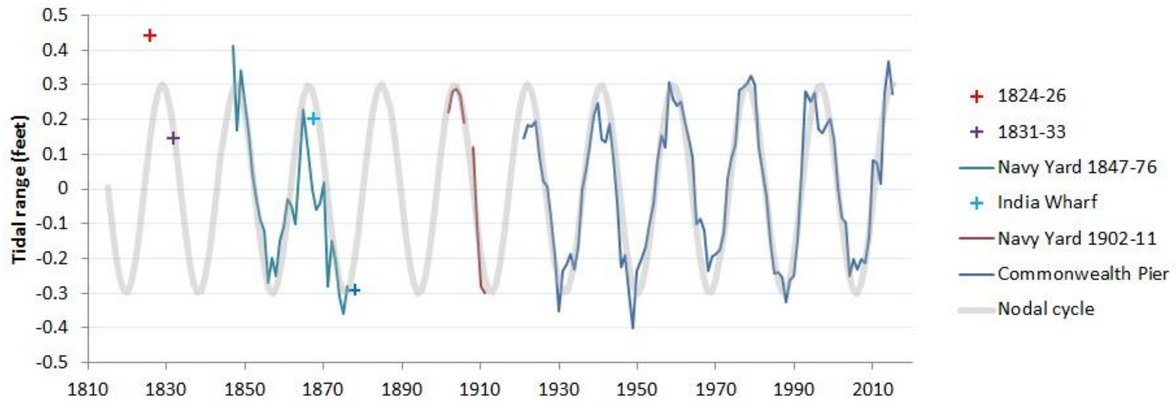

Figure 8: Annual variation in mean tidal range compared to mean for the Navy yard and Commonwealth Pier, showing all data where range values are available. The influence of nodal tide will cause variations of 0.6 ft in tidal range (MHW-MLW) and 0.3 ft in MLW which explain some of the apparent differences seen in MTL in different observation periods.

The original data series linked purely by levelling (as implied in Schureman 1928) with only the MSL-MTL correction shows relatively high acceleration of 0.035 mm/yr^2. The new extended composite with all corrections applied shows a much reduced acceleration of 0.014 mm/yr^2, with slightly reduced formal uncertainty due to the longer time period.

This value converges much more closely (within the error bounds) with the estimated global average of 0.01 mm/yr^2 as well as showing improved long term, decadal and inter-annual correlation with nearby extended time series such as New York and Baltimore (figure 9).

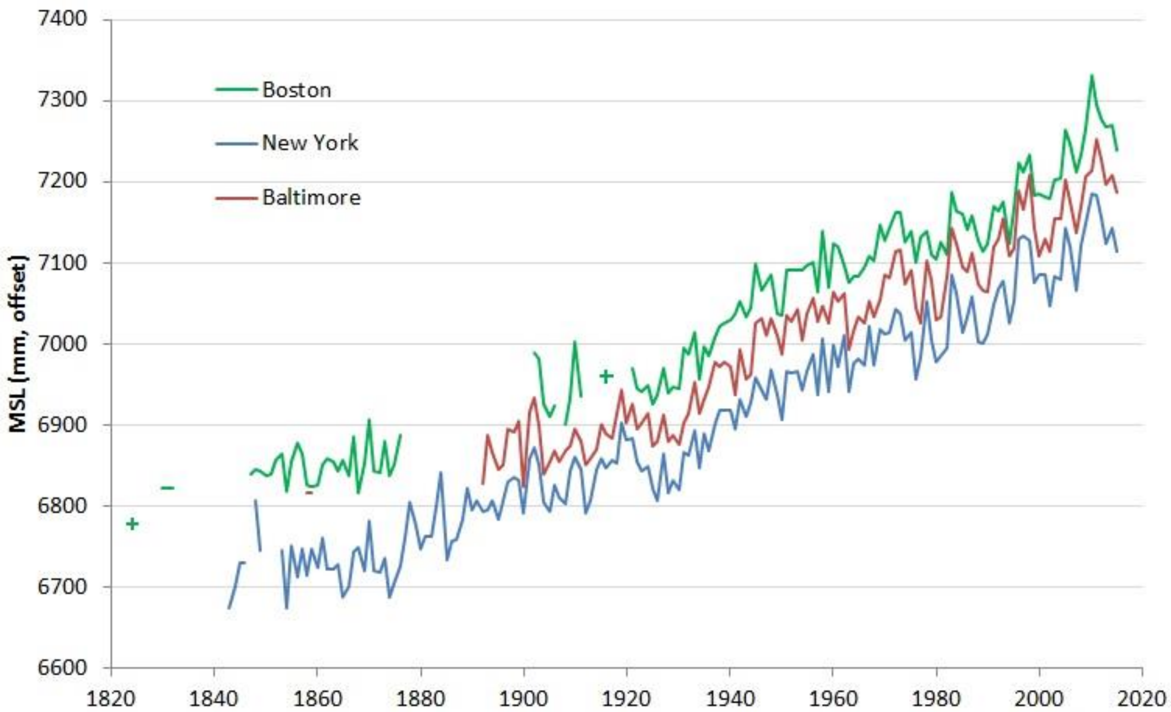

Figure 9: Corrected extended time series from Boston, compared with extended series from Baltimore, and New York also from this study. The Boston data has an additional scale factor of 0.5 mm/yr added to match the linear trend from New York and Baltimore for display purposes only.

The improved correlation gives some confidence that the various independent corrections are reasonable and that the derived trends are likely to be a significant improvement over the ones derived from uncorrected data.

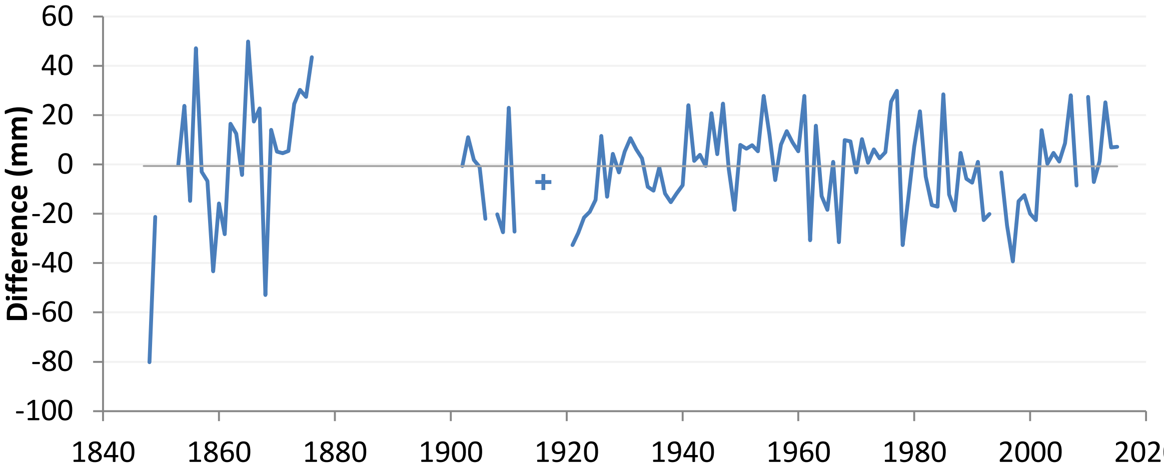

Figure 10: Difference plot of extended Boston and New York time series, (offset and slope adjusted for visualisation purposes). This result from two independently derived series gives some confidence in the methodology. The higher variability in the early data may be reduced if the original marigram or tidal register records are re-analysed in the next few years.

Providence, Rhode Island

The tide record from Providence R. I. was not used in the original global study as it did not satisfy the criterion for completeness, however, the investigation and background work is summarised in this note as an example of results that can be obtained even with sparse data.

Early tidal measurements in Providence harbour were taken by Lt. General Rosecrans in 1853, and a record of high and low waters from April 12th to May 31st has been published (Bentley 1880). The mean low water was stated to be the same as the Cushings chart of Providence Harbour of 1834, but the zero of the gauge was actually LLW in both cases. The mean high water (5.85 ft on the gauge) from this record was then adopted as the City reference datum or Providence High Water Mark in October 1867, and benchmark information is given for the Cushings Low water datum (Paine 1874). Several other short sections of tide record were published in the Harbour Commission reports, which were referred to bench marks where modern elevations are not available or the bench marks have not been recovered. For example 10 days of daytime half-hourly readings in October and November 1870 were recorded for a staff gauge set up on Hills wharf (Russell 1871), daily data is given for a lunation in October and November 1872 from Bishops Point, and for the Butler Hospital wharf in April and May 1873. Fortunately contemporary engineering or city reports refer the mean levels to earlier records and datums (Bentley 1873, 1874). Records from the U.S.C.S. self-recording gauge on the Gas Company Wharf from August 4th to the 31st 1872 were also given, and monthly means for the longer period from May 22nd to December 28th 1873 from Hills wharf were published (Warren 1874 & Bentley 1879). A record of tides was continued with this gauge until Sept 16th 1882 (Bowie 1927), but no further published details have been found. Simultaneous observations taken every 20 minutes in daytime, and HW and LW in the night and Sundays were recorded by the Harbour Commissioners from three gauges near India Point from September 4th to October 7th 1878 and these were published (Shedd et al 1879). The 1878 India Point data were referenced to a bench mark on the bridge abutment 11 ft above the zero set by the Coast Survey in 1874. The self-recording gauge set up on Hills wharf was later moved a short distance to the City wharf. Daytime observations from a staff gauge set up by the harbour commission near the self-recording tide gauge on the City wharf were recorded October 3rd to November 29th 1879, and the record was compared with that from the tide gauge. Simultaneous records from November 1879 were published for 4 other sites (Bentley 1881). A new self-registering gauge manufactured by Longs was installed by the city engineer at the Point Street bridge in 1885 and a description given (Gray 1886). This was maintained and continuous records kept up to at least the 1920s, although the data was only occasionally summarised and published for short illustrative periods in the annual reports. A more recent study (on phytoplankton blooms) which cites a few days of the tide data given in the city reports (Nixon 1989) states that these original city tide records have now been lost. Copies of marigrams showing several periods of around three days each of what were considered to be typical tidal variations are however given in the annual reports for 1888 and 1890, a single similar diagram is given for wind induced high tide in 1894, and extreme tide levels are given for 1907 to 1909. The USCGS also had records from a gauge running from Oct. 22, 1886, to June 2, 1890, and also the year 1892 (Bowie 1927) but these have not yet been recovered. The Harbour commissioners tried to reconcile the different tidal ranges at different times in the late 19th Century, as their preferred datum was either the MHW or MLW. The 18.61 year nodal cycle of amplitude around 0.4 ft at this site (and higher towards Pawtucket) explains some of this variation, although it was also noted that the USCS automatic tide gauge used in 1879 on the City Wharf showed a lower tidal range than simultaneous observations from a co-located tide staff. It can be seen that overall, if reduced to a common datum, the data sets show closer agreement using MTL, rather than HW or LW (as might be expected).

The current records in the PSMSL are from another gauge set up in 1938 near the State Pier. These run to 1947 when funding ran short, then there is a nine year gap until records from a new gauge set up in 1956 on the State Pier No.1 with agreement of the USCGS (public works report for 1956) run up to the present (2015). This gap can be mostly filled using data from the Newport tide station in the outer part of Naragansett bay. The Newport data must be offset, and a small scaling correction is also added so as to account for the apparent VLM difference implied in the MSL difference plot. The data from Newport also allows a composite monthly time series to be created extended back to 1930. The eight month section of data from 1873 can then be used to extend the annual time series.

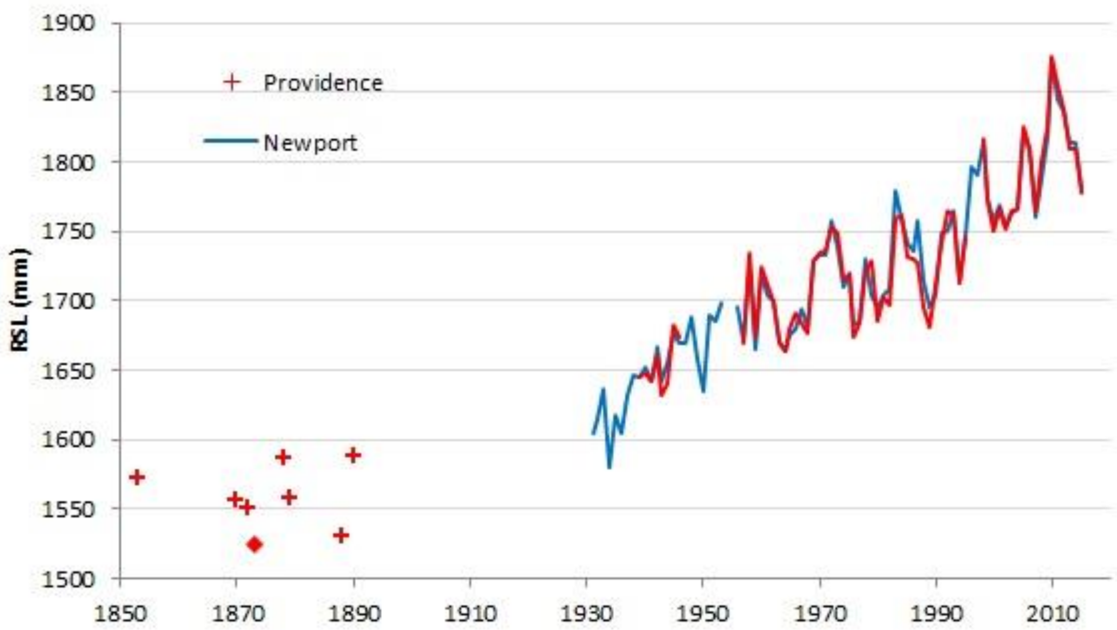

Figure 11: PSMSL annual time series for Providence R.I. (red) overlaid on Newport (blue). The red diamond is an almost complete year of MSL from providence, the red crosses are means of short time series (often lunar months).

The remaining short sections of data, mostly from lunar monthly periods, can be reduced to the same local datum using the published information, although the levelling run connections are not given in detail.

Consistent relative connections for the various data sets can be gleaned from the annual city and harbour commission reports (with a little care):

- Zero of gauge from Rosecrans 1853 data is LW reference of Cushings 1834 chart (most likely LLW).
- MHW from Rosecrans 1853 data is adopted as City datum (Providence Mean High Water)
- MLW city datum is 2.24 ft on the 1870 gauge at Hills wharf, and MLW “agrees with” city MLW
- The MHW of the 1872 (Gas Company wharf) data is 0.06 ft above the MHW of 1853 (City datum)
- The MHW of 1879 (City wharf) data is stated to be 0.01 ft different to Roscrans MHW city datum
- BM at abutment of India Point Railroad Bridge 11.909 ft above reference for the 1879 data.

- BM top of SE corner of West abutment of Point St Bridge is 12.29 ft above MLW for 1879 data.
- 1879 MLW is 0.091 ft above the MLW determined from the 1873/4 Coast Survey BM on the Pier of India Point Bridge, and 0.171 ft above the MLW from BM on the abutment of the same bridge. The Bench mark on the India Point Bridge abutment was originally given as 12.08 ft, and the BM on the pier of India Point bridge 10.04 ft above the Coast Survey MLW reference of 1873/4. The original BM elevation difference of 2.04 ft was revised to 1.96 ft in 1879. Butler Hospital wharf 1879 MTL is 0.144 ft below City wharf MTL (1879 water level comparison)
- Butler Hospital wharf Tide gauge in 1879 in same position as 1872, and MLW is 0.03 ft lower.
- The city MHW and MLW levels relative to the TGZ were adopted at the October 1879 levels (10.06 ft and 5.33 ft respectively) and marked on the published Point Street Bridge tide gauge marigrams.

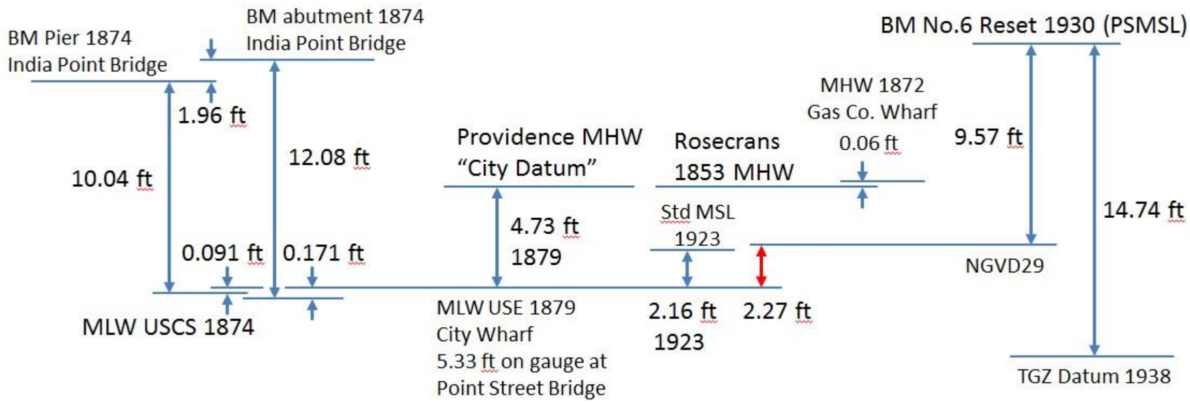

Figure 12: Stick diagram showing some of the estimated datum connections used to connect the modern TGZ to the 19th Century data from Providence R. I.

Connecting the modern tide gauge zero datum to the old city datum (or Providence MHW) requires bench mark information where elevations to both datums are given. The elevations of bench marks in Providence in the 1926 report (Cole 1926) are given to the local MLW datum, and also to the "standard" sea level datum (which after minor adjustment would later become NGVD29) as determined by levelling. Some of these bench marks were also listed in later post 1929 adjustments (Clifford 1934) and some still survive and have modern elevations to NGVD29 (modern bench mark data sheets). Thus the local "city" MLW datum (still used around 1923) can be connected to NGVD29, although the spread of difference (old to new) elevations should be considered.

Seasonal corrections based on the average annual variation should be applied to any monthly mean water levels. MTL values derived from the published HW and LW readings were corrected and directly compared with average MSL values taken from published hourly (or more frequent) observations. MSL is estimated to be 0.14 ft below MTL (at Providence) from a direct analysis of the observations. It is not known if the April-May (1853, 1873) and October-November (1870, 1872, 1878, 1879) sections of data were deliberately chosen so as to minimise the effects of seasonal variation, but an analysis of this variation over the entire recording period shows that these months are closest to the annual mean and therefore should require least correction.

The overall plot including the mean values, adjusted to the same datum as the PSMSL metric data, and adjusted for MTL and MSL differences where appropriate, is shown in figure 13. This is sanity checked by comparing with the time series from New York. An offset and scale factor derived from analysis of the difference plot of the section of overlapping quality controlled data (New York-Providence) from 1938 to 2015 is also applied to the older data from Providence (which has been independently reduced to the same datum as the modern data). Here the distribution of the individual data points at the two sites appears correlated. This suggests that the datum connections and other corrections are reasonable, but higher resolution comparison data can be used to more directly compare the limited sections of data from Providence.

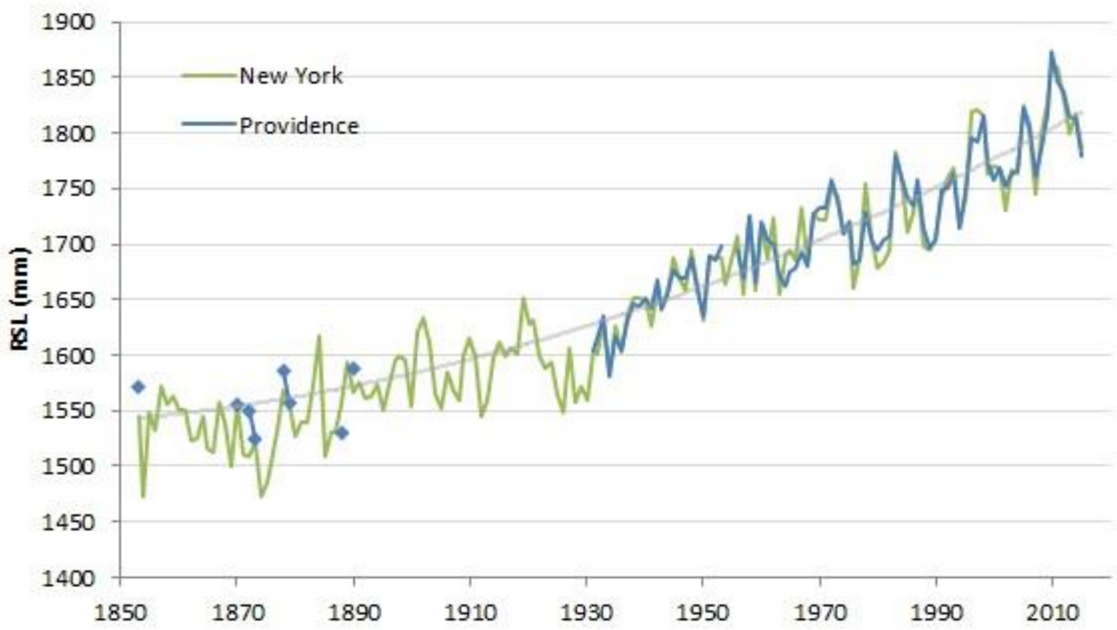

Figure 13: The composite time series from Providence overlaid on the time series from New York, with offset and scaling factor of -0.78m/s applied derived from minimising differences in the overlap period from 1931. The distribution of the early data points in Providence appears less random.

If monthly MSL data from New York (PSMSL) is compared with the short (mainly single lunation) sections of corrected MTL and MSL data from Providence, the mean water levels are very similar. This suggest that the elevation connections at this site are well within expected error bounds given the precision of the original data records (0.1 ft or 30 mm)

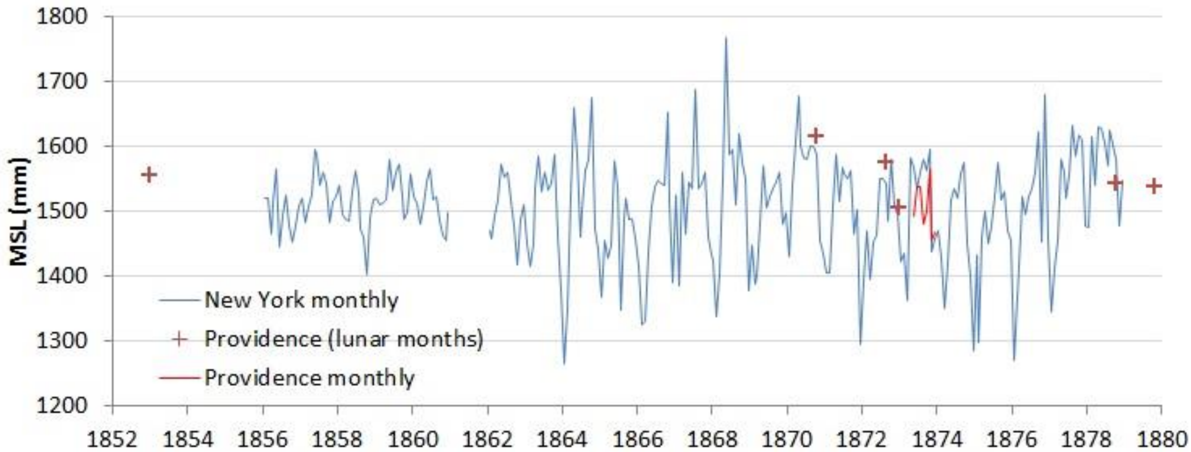

Figure 14: Monthly MSL from New York compared with the estimated MSL derived from short time series at or near Providence. The data is reduced to the same datum using the 1938 to 2015 data.

The un-extended data from Providence (without infill) from 1938 has a derived acceleration of 0.035 mm/yr^2 (which over a century would be anomalously high) but with high uncertainty bounds. Creating an extended complete composite time series back to 1930 and infilling with data from Newport reduces the derived acceleration to 0.0084 mm/yr^2 with reduced uncertainty. Extending back using the data to 1873 does not change the trend, but adding in the other shorter series (several months-worth), gives an indication that the trend would increase slightly (a non-weighted derivation would be 0.0146 mm/yr^2.

New York

Tides were recorded at the site of the Brooklyn Navy Yard from September 20th to October 17th 1826 as part of a site investigation for possible dry dock construction (Baldwin 1826). Tides were also recorded at Sandy Hook from as early as 1835, as summarised on USCS (United States Coast Survey) charts from 1844, and mean HW (High Water) and LW (Low Water) values are given with benchmark information by the USCS for 1853. Tidal diagrams of high waters and tidal range were published for several tidal stations in the US including Sandy Hook, New York (Brooklyn) Navy Yard (and Boston) for the 8th to the 28th June 1835 (Whewell 1836). A mean high water value averaged over three years is mentioned from Brooklyn Navy Yard from 1840 to 1843 (Burr 1904). High and Low waters as observed on a Tide Pole were recorded by the USCS at Governors Island from before 1844, and in 1844 a self-recording tide gauge made by Wightman was also operating at this station (Bache 1844). This was later to be replaced by a Saxton gauge (Bache 1845). The gauges on Governors Island had regular problems due to icing in Winter, and in these instances were backed up by records from the Navy Yard. The bench mark BM_1 at Governors Island was mentioned in 1853 (Bache 1854) whilst the Navy Yard coping was used as a bench mark from the time of the Yards construction. The early Governors Island data from 1844 still exists and has been analysed (Talke 2014 and personal communication) but is not yet processed and archived in the PSMSL.

The early tide data is referred on the charts to either a MLW (Mean Low Water), or MLWS (Mean Low Water Springs) or the LLW (Lowest Low Water) tidal datum, which in some cases was given as a distance below the bench mark, allowing connection to later data. The difference between MLW and MLWS at Governor's Island was given as 0.4 ft (Bache 1855). These tidal datums were occasionally adjusted as more data accumulated and the values were refined.

Published annual average HW, LW and half tide levels for Governors Island are available for 1856 to 1874 (Ferrel 1878) and MSL from hourly co-ordinates for 1876 to 1878 (Ferrel 1886). The tabulated USCS data had at this time not been corrected for changes in the tide gauge zero level of around 1.1 ft around the middle of 1861 and nearly 2 ft in 1871, due to uncertainties surrounding benchmark information. Tuttle (1904) extended this annual data series back to 1846 but was unable to resolve the large frequent datum jumps prior to 1853. In 1872 the MLW mark was stated as 2.21 ft above the zero of the gauge (Mitchell 1874), and BM_1 16.899ft above this zero.

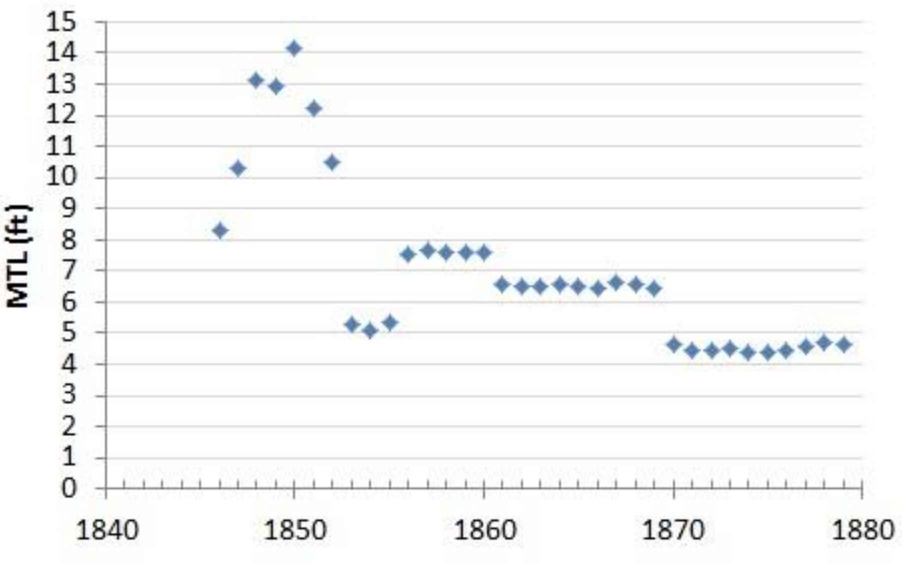

Figure 15: Plot of the Governors Island unadjusted MTL data tabulated by Tuttle (1904), derived from USCGS reports and other contemporary records clearly highlighting the large datum steps.

From 1853 onwards Tuttle estimated the large 1855, 1861 and 1871 datum shifts (figure 15) using assumptions of similar mean sea levels before and after the datum step changes, which would undoubtedly reduce the datum uncertainty but is an unsatisfactory methodology when analysing long term changes using composites of short sections of data (Ferrel 1878). Later work used the original records to produce a time series for Governors Island from 1856 to 1879, which is used in the early section of the composite "Battery" data series currently available in the PSMSL. Tuttle also linked the tidal data from the Governors Island, Sandy Hook, and Fort Hamilton time series using bench mark elevation and tide level information, and published early shorter time series (for example from the Battery at Pier A, and at Yonkers) some of which are available as monthly MTL values in the IAPO report of 1936 (Proudman et al 1939). The Governors Island half tide level had also been used as a reference for levelling work in the Great Lakes in the 1850s and earlier canal construction.

A USCGS levelling campaign of 1886/7 in the New York area (Schott 1889) used a datum defined by measurements of average sea level (half tide level) from 1876 to 1881 at Sandy Hook and contemporary elevations of local bench marks above this level (Schott 1883). This was based on the assumption that a site near the open ocean would be less subject to meteorological or river flow effects. Levelling lines were run through the Fort Hamilton tidal bench marks and spur lines were run to the Governors Island bench marks through a crossing at Brooklyn. Connections were also made to the primary tidal bench mark at Willetts Point. The forward/backward levelling errors were estimated to be very low (at mm level over a few km). However, these elevations were supplemented by simultaneous tide gauge readings at several sites. Judging from the levelling, the water level readings averaged over a period of 28 days in October 1886 at Governors Island were lower than the equivalent readings at Sandy Hook by 0.213 ft or 64.9mm. Differences of similar order magnitude were recorded at all seven inner harbour tide gauges used, and at the time this was put down to possible changes in the wharf level (and starting point bench mark) at Sandy Hook due to ice action between the time of the water level recordings and the later levelling, and as a result a correction of 0.176 ft was suggested in order to reconcile these differences.

Further New York datum adjustments were also made. The “Battery Datum” (Mean Low Water at the Battery) was raised by 0.24 ft in 1898 (Koop 1916) after 12 years of recording at Pier A indicated the original datum was too low. The published “Pier A” time series runs from 1886 to 1903. The USCGS datum of mean sea level at Sandy Hook as transferred to New York Harbour bench marks on the levelling run beyond BMF_1 at Raritan Bay was adjusted downwards by 32.3 mm or 0.106 ft in the same year after a reassessment of the 1881 and 1886-87 levelling differences (Hayford 1900, pg 402-404). This resulted in re-adjustment of the elevations of the bench marks at Governors Island and the Battery above the Mean Sea Level Datum at New York by an additional 0.11 ft over the previously accepted 1886 values (Marshall 1912). The relationship between the adjusted Battery datum and adjusted MSL datum was given as -2.09 ft in 1912, and later adjusted again to -2.103 ft (Koop 1913, Marshall 1918).

To create an accurate composite time series for New York, the sections of data from different sites need to be connected and these datum shifts accounted for. Fortunately, the data from Governors Island (up to 1879) and the later data from the Battery sites (June 1920 to present) can be connected to bench marks where the current and historical elevations are recorded and the sites are close enough to have allowed direct precise levelling connections. The difference between tide gauge zero elevations is estimated to be 0.211 ft or 64.3 mm from the levelling, so to reduce the Governors Island tide MTL gauge data (referenced to the tide gauge zero) to the most recent Battery Tide gauge zero requires adding an offset of +64.3 mm. As these observations are averages of high and low waters, or MTL, then to estimate equivalent MSL a correction for the MSL-MTL difference (from a comparison of averages of 10 years of MTL and MSL) at this site of +22.3 mm is added resulting in a total offset estimate of +86.3 mm.

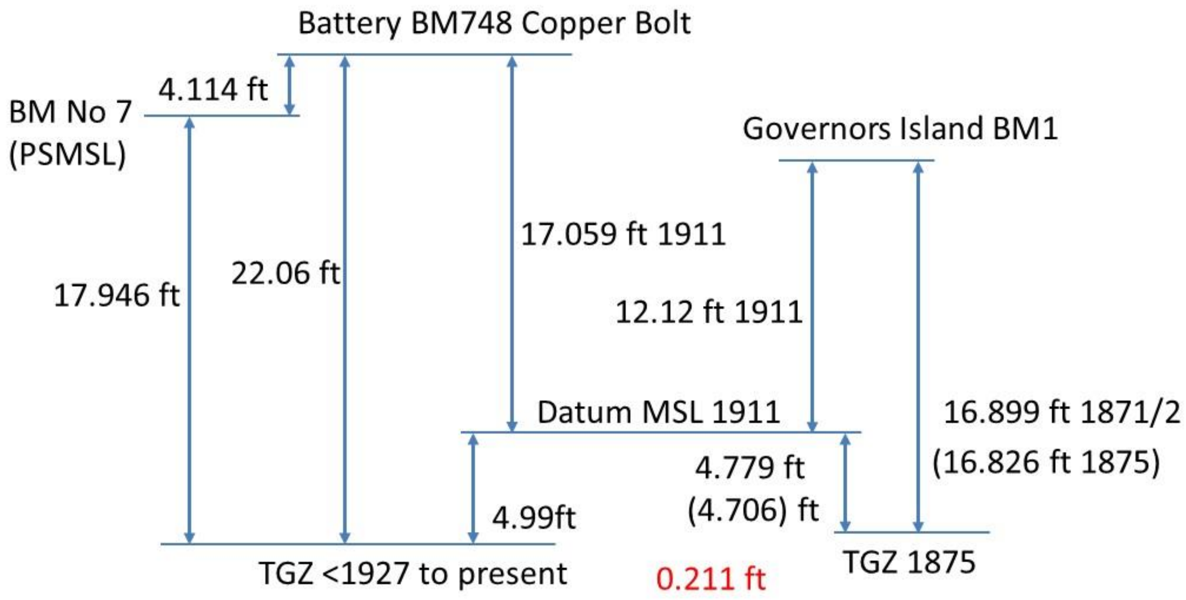

Figure 16: Stick diagram of benchmark and tide gauge relationships between the Battery and Governors Island in New York.

The data from the Battery is itself from two sites. From 1920 to May 1927 data was recorded at the Barge Office Pier (this is available as a metric monthly Mean Tide Level series from the PSMSL) and from September 1927 onwards the gauge was relocated at the current site at the end of Whitehall Street. The original data was referenced to the same TGZ of 5.000 ft below the accepted transferred Sandy Hook MSL datum (Buckley 1924). The metric PSMSL "Battery" series from 1921 onwards and the monthly values from NOAA are identical to the USCGS historical records.

The time series from Fort Hamilton, from 1893 to 1932, also suffered a break in the records when the first site was destroyed by fire on December 5th 1920 (Marmer 1925). Data was then taken from a nearby gauge set up by the US Engineers. The tide gauge zero was levelled to the same benchmarks used for the USCGS site which allowed continuity. Monthly MSL (from hourly values) referred to the tide gauge zero are published for the complete years 1893, 1902, 1911, 1920 (Marmer 1925), and 1900, 1910, and 1930 (Marmer 1935), whilst further monthly published MSL data is available from December 1926 to March 1928 (Johnson 1929). A full monthly time series of MSL referred to 5 ft below the Sandy Hook Mean Sea Level Datum is available from 1893 to 1920, and monthly MTL is available from 1893 to 1932 (Schureman 1934). Annual MSL referenced to the tide gauge zero is also available for the period 1893 to 1920, whilst from 1921 to 1932, the published MSL data is estimated from HW and LW readings by adding 0.04 ft to the MTL values to account for the average MSL-MTL difference at this site (Marmer 1935). The MSL-MTL offset is also similarly given as 0.038 ft or +11.6 mm (Cole 1922 pg 5). This small offset must be added to any MTL data if this is to be combined with MSL data with the same datum and used for annual or longer scale studies. The estimated difference between the Fort Hamilton tide gauge zero and the 5 ft below Sandy Hook MSL datum is 0.92 ft or 280 mm.

The datum connection for Fort Hamilton to the Battery can be estimated using either bench mark elevations and levelling, or from tidal water level data where there is temporal overlap. The original Fort Hamilton Tidal Bench Mark, BML was 42.194 ft above the Tide Gauge Zero. This TGZ was 17.951 ft below the Governors Island Bench Mark BM_1 from levelling in 1887. Subsequent levelling of the same elevation difference gave 17.971 ft in 1898 and 18.019 ft in 1900 (Tuttle 1904). The bench mark BML was believed destroyed in 1901. BM1 at Fort Hamilton, (also known as BM180) was the 12 foot mark at the top of the tide gauge staff, and was 6.04 ft above an MSL measured over 19 years at Fort Hamilton (considered at the time to be equivalent to the Sandy Hook MSL). This tide gauge was destroyed in the fire of 1920. BM2 at Fort Hamilton (also known as BMA or BM181), was 8.855 ft above this MSL datum. Johnson (1929) in a study in 1928, records that BM181 is 14.1 ft above the Fort Hamilton TGZ, and 8.86 ft above the MSL datum at Sandy Hook. This means that the MSL datum is 5.24 ft referenced to this 1928 TGZ. However the earlier TGZ was 14.815 ft below BM 181, making the MSL datum 5.96 above the lower original tide staff zero that Marmer uses. This benchmark BM181 still exists as “181 NYBE +A” (from benchmark description) with adjusted elevation of 8.83 ft to NGVD29 (7.71 ft to NAVD88). The difference of differences between modern and 1911 elevations (Koop 1916) at Fort Hamilton BM181 and the Battery BM 748, is just over 20mm.

The direct comparison of tide gauge data gives differences within the uncertainties of the datum links estimated from levelling. There is no overlap period of simultaneous tide gauge data to link the early part of the Fort Hamilton data (1893 to 1932) with the earlier data from Governors Island (1844 to 1879). There is data with three years of overlap from Sandy Hook from 1876 to 1892, which can be linked to data from the Battery Pier “A” from 1886 to 1903 and West 57th Street from 1885 to 1903. However there are significant divergences between the earlier data from these latter two sites. The metric data from 1921 onwards in the PSMSL records (from NOAA) is referenced to the “5 ft below MSL at Sandy Hook” datum (as in Schureman 1934) which was eventually adopted as the basis for the NAD27 datum and the re-adjusted NGVD29 MSL datum. In several published composites of the Battery and Fort Hamilton time series the two series are directly connected assuming this MSL level is the same at both stations. This estimate was based on assessments of relative water levels over relatively short periods. Longer term levelling and simultaneous water level records can be used to investigate this assumption.

The later data from Fort Hamilton has overlap with the Battery data over the period 1920 to 1932. The Fort Hamilton data from 1930 to 1932 appears less stable than the preceding data judging from difference plots, but this still allows ten years of data overlap where the average monthly differences appear relatively constant. If the MSL data from the Battery (PSMSL, Schureman 1934) and the MSL data from Fort Hamilton, which is referenced to the same Sandy Hook MSL datum (Schureman 1934) are plotted, it is clear that a ten year comparison (up to 1930) shows a consistent offset of around 15 to 20mm, (figure 17a). The offset required to minimise this difference is +11mm (figure 17b).

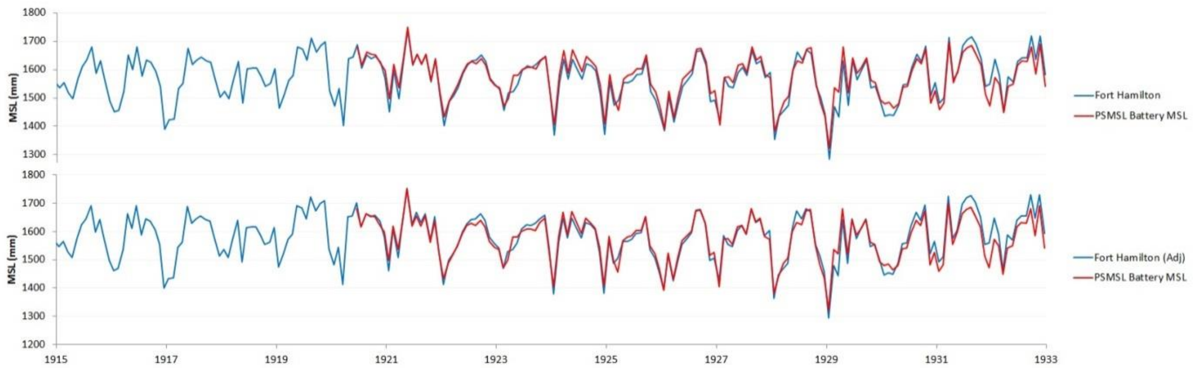

Figure 17: Fort Hamilton and Battery monthly MSL data: above, (a) as tabulated in Schureman 1934, and (b) below, +11mm offset applied to the Fort Hamilton data to minimise the ten year average difference.

If the monthly difference values are plotted, it can be further shown that adding this offset also improves the difference in the short overlap of data from Pier “A” prior to 1921.

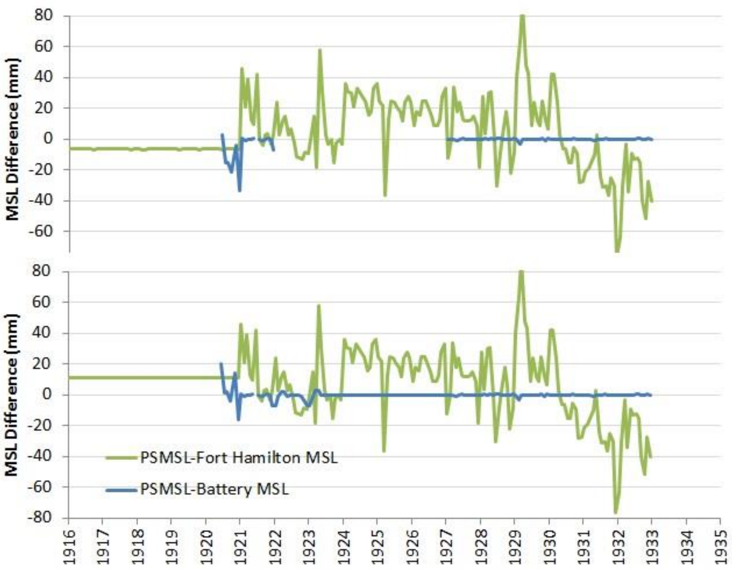

Figure 18: Difference plots of (a) the PSMSL composite minus the unadjusted Fort Hamilton and original Battery time series, and (b) the adjusted Fort Hamilton series and resultant revised composite. Ideally the flat portion of each difference plot should have the same mean value as the variable portion if the offset value is correct.

This small offset is slightly different to the independently derived -6 mm offset used for the Fort Hamilton MSL data in the NOAA composite supplied to the PSMSL. It is interesting that the difference of 17mm is close to the difference between using modern NGVD29 adjusted and older elevations, to the precision of the MSL-MTL correction values applied to the 1920 onwards Fort Hamilton data (the precision is 0.01 ft or 3 mm).

The remaining gap in the extended New York composite time series is covered by available data from Sandy Hook from 1876 to 1892 (Schott 1883, Christie 1891, Tuttle 1904), which gives 4 years of overlap with the Governors Island time series. The possibility of differential vertical land motion (or coastal subsidence) at coastal sites such as Sandy Hook compared with the inner bay was discussed with evidence and opinions on both sides from the 1860s well into the 20th Century (Mitchell 1880, Koop 1915, Johnson 1917) until the weight of accumulated evidence from the tidal records became clearer (Marmer 1948). An up to date difference plot using data from Sandy Hook minus either 80 years of overlapping data from the Battery, or almost 70 years of overlapping data from Willetts Point, gives average relative subsidence at Sandy Hook of 1.10 mm/yr or 1.59 mm/yr respectively. It is likely that the inter-annual variations between Willets Point and the Battery time series could affect multi-decadal trends to a small degree, but more detailed investigation is needed. However the first order trend differences are significant for Sandy Hook, suggesting there is indeed relative subsidence at this site. As any subsidence at Sandy Hook is possibly due to a process of sediment loading (millions of tons accumulated here annually) which has been ongoing for as long as historical charts and records are available (Bache 1856), this rate is assumed real and linear over the tide recording period, and thus it is reasonable at this stage to compensate the early Sandy Hook tide gauge data for this relative VLM to create a more accurate composite with the inner bay data. The relative VLM also helps explain some of the recorded levelled bench mark elevation differences relative to Sandy Hook over time.

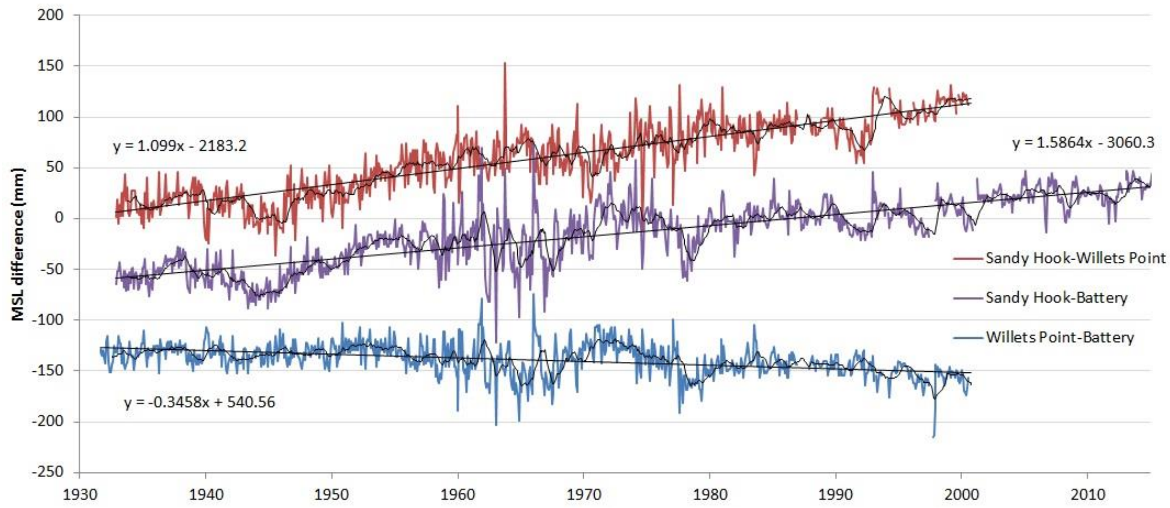

Figure 19: Difference plots of monthly MSL time series from the new York area, suggesting long term vertical land motion between the New York Inner harbour tide gauge sites and Sandy Hook.

The original composite time series available from the PSMSL for New York is the longest un-extended time series from the region, starting in 1856 and running to the present (2015). The acceleration of the original series is 0.0106 mm/yr^2, whilst the infilled, adjusted and slightly extended series is 0.0132 mm/yr^2. Both of these values are well within the error bounds for the global average.

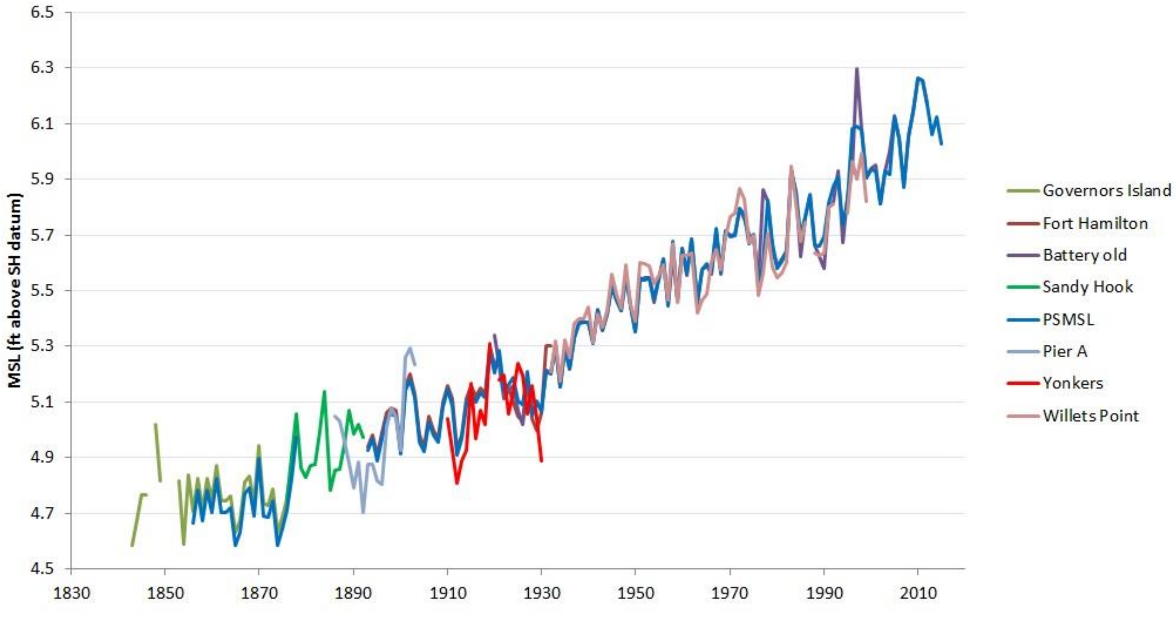

Figure 20: Some of the derived and available annual MSL data from New York, reduced to the original Sandy Hook "5 feet below MSL" datum and overlaid.

Philadelphia

Philadelphia is around 160km upstream of the Delaware river mouth, and is therefore subject to run-off driven river level as well as tidal variations. Dredging a wide deep water channel for large vessels was mostly complete by around 1890 in the portion of the river from Philadelphia to the Ocean. Records suggest that mean low water changed from the 1870s to the 1890s after this dredging. Tides were recorded at several places in Philadelphia and on the Delaware (Zeskind and Le Lecheur 1926), but the composite series available in the PSMSL was from a self recording tide gauge on the old pier at the end of Chestnut Street between July 1900 and January 1921, and then transferred to

Pier 9 in the city from June 1922 onwards. As such, this is another site with long and almost continuous records of tidal data. The City datum has a long history, William Penn is said to have set this datum by placing a metal spike above mean high water at the foot of Chestnut Street in 1682.

The first few years of the published Mean River Level time series in the PSMSL record up to 1903 appear at least 100mm higher than succeeding years. In isolation, this has the appearance of a datum shift. It is known that the City low water datum was changed in 1907/8 (Mayors message 1907) and that from the first data returned from the gauge in 1900 it was apparent that MLW was around 1 foot different to the previously accepted value (Gardner 1875, Mayors reports). For this work an independent check was taken using tide gauge records from Arch Street Pier No 4 North, which were recorded almost continually from 1901 to 1921 and published annually in the Mayors messages (1901 to 1921). This Municipal Arch St. site was transferred to the New Chestnut St. Pier in 1922 and continued until at least 1933. These records were given as annual mean HW and LW values below the city datum and also later at higher resolution in chart form. These “forgotten” records (only a few months of data from Arch Street are mentioned by the USCGS) were transcribed for this work and show similarly high relative values to the Chestnut Street data in 1901-1903. The datums for the two annual time series can be connected directly by comparison, but also checked by levelling. BM35 (referenced in the PSMSL RLR diagram) set in 1931 has an elevation of 6.55 ft above NGVD29 (originally based on MSL at Sandy Hook), and 12.474 ft above the tide gauge zero of 1900. The estimated elevation of Philadelphia City Base to MSL at Sandy Hook is given as 5.5456 ft below the City Datum in the Mayors report of 1904 (1905, Vol II, pg 418). This datum link was from a net containing a significant number of benchmarks and levels and therefore has higher confidence than earlier levelling from point to point runs. To connect the Arch Street data (referenced to City Datum) to the 1900 Chestnut Street tide gauge zero, an estimated offset of 12.474-6.55+5.546 = 11.469 ft should be added (figure 21). It should be noted that this connection is only used here to reference the Arch Street data and City Datum, but results are close enough to give confidence in the levelling data.

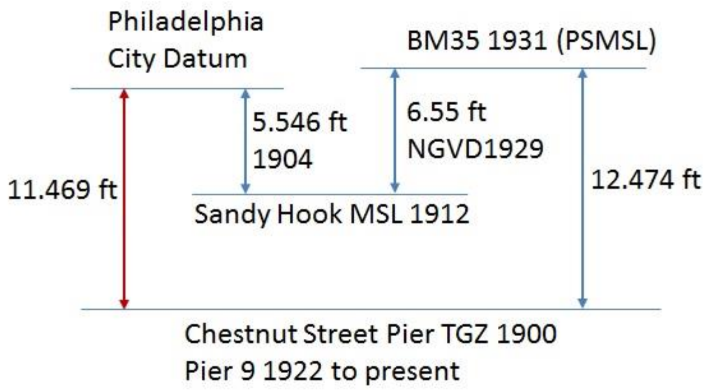

Figure 21: Stick diagram showing vertical datum and tide gauge zero relationships for Philadelphia in the early 20th Century. This is used to allow direct comparison of the Arch Street data

The overall composite time series is fractionally extended with MTL data derived from MHW and MLW values from 15 months 1891-2 from the Pier at Washington Avenue, to the same datum as the Chestnut Street data. The average difference between MSL and MTL which is given as 0.16 ft for this site (Zeskind and Le Lecheur 1926, pg 25), must be added to allow this extra year to be included in the MSL time series. This same offset is already incorporated in the early section of the PSMSL metric data from Chestnut St., which is actually offset MTL data). A further annual data point is given from HW and LW values for 1871 referred to the City datum (Gardner 1875). These values are from before the significant dredging of the river channel, and so should be viewed with caution. Nevertheless, it seems likely from the plotted data that some of the difference thought at the time to be due to dredging could simply be due to relative MSL rise.

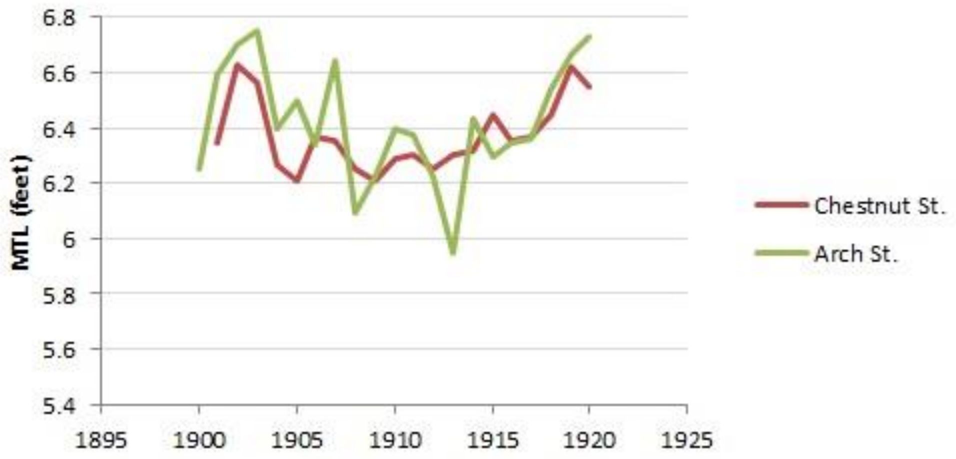

Figure 22: Annual MTL from Chestnut Street (PSMSL) and Arch Street tide gauges reduced to same tide gauge zero used by PSMSL, showing the common significant excursion from 1901 to 1903.

Likewise comparing with the Boston or New York time series also shows a common positive excursion around 1902, and therefore the effect is a real reflection of local mean sea level variation.

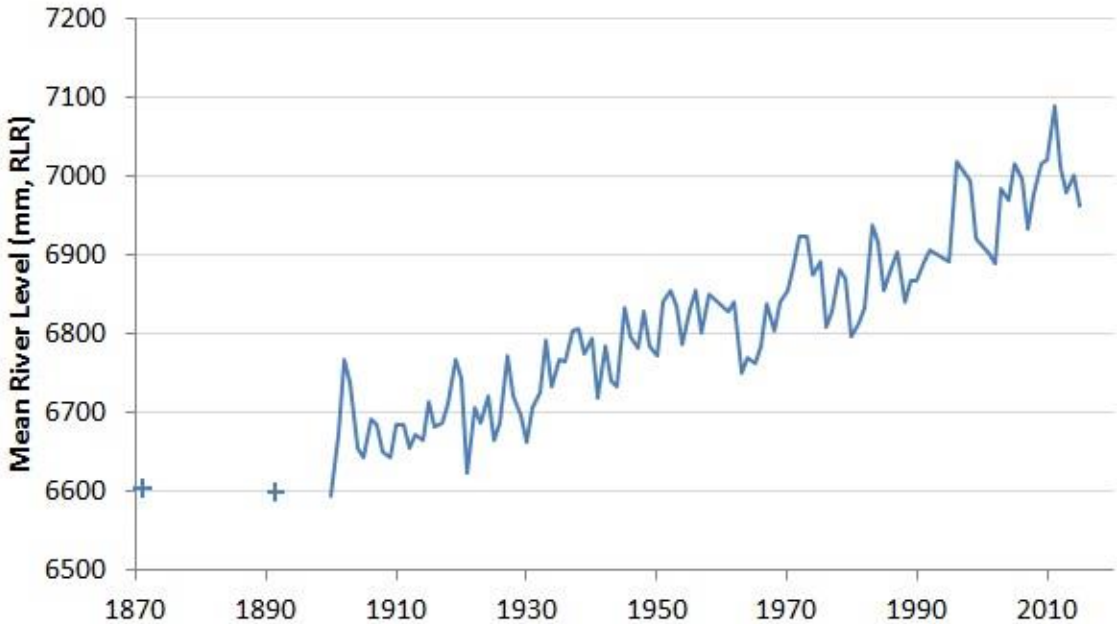

Figure 23: Extended annual MRL time series from Philadelphia

The acceleration value derived from the extended annual data is 0.0138mm/yr^2.

Analysing the long PSMSL composite time series available from Atlantic City (Million Dollar pier between 1912 and 1920, Steel pier between 1923 and 1986, and Ventnor since 1986) also shows a higher linear relative MSL trend of 4.10mm/yr from 1912 to the present (2015), but the second order component in this case is affected by a small but consistent offset shift of around -40mm in the Atlantic City time series between 1945 and 1961. The Atlantic City MSL time series has an acceleration component of 0.0132 mm/yr^2, but this should be viewed with caution given the apparent offset section of data. The data from Lewes which runs with several gaps from February 1919 to the present also shows a high relative MSL trend of 3.38 mm/yr, and a relatively higher apparent acceleration component of 0.0214 mm/yr^2, which is partly attributed to the shorter time series and the position of the data gaps. The high first order component will be more robust to these issues than the acceleration term derived from the second order component. A difference plot of Lewes and Atlantic City also highlights issues of order 50mm in one or both data sets. These differences are less apparent in a difference plot of Baltimore and Lewes, again suggesting the Atlantic City record shows some variations which are not recorded by nearby gauges and not recorded as datum shifts.

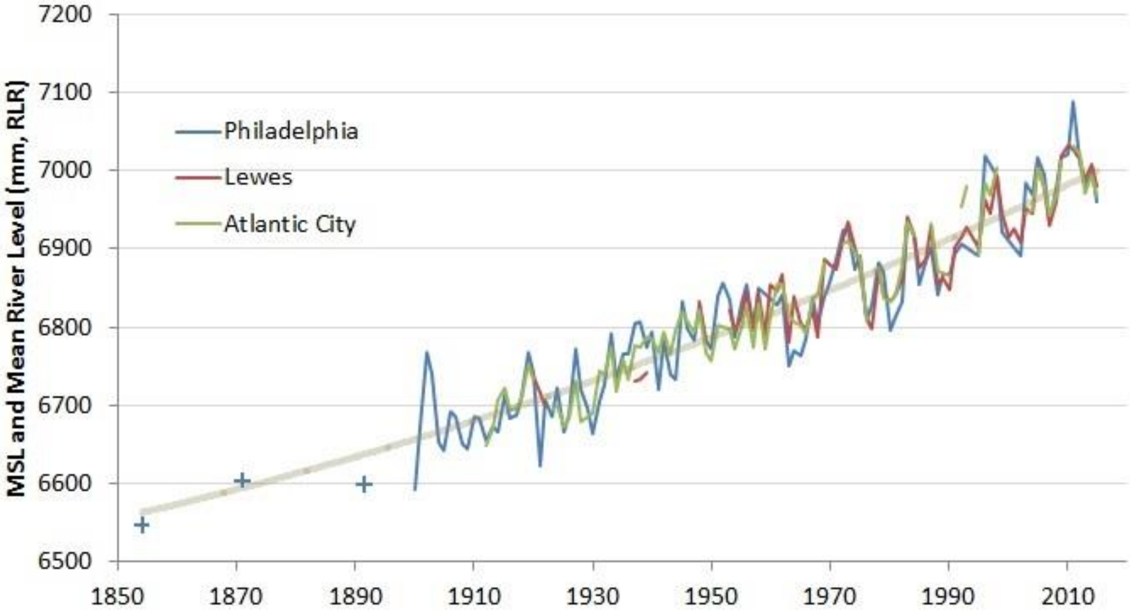

Figure 24: Extended annual MRL data for Philadelphia, with annual MSL data for Lewes and Atlantic City overlaid (adjusted for offset and linear trend in order to show similarities).

Chesapeake Bay, including Old Point Comfort, Washington D.C. and Baltimore.

There are several historically important tidal recording sites in Chesapeake Bay. One of the earliest is Old Point Comfort, at the mouth of the James river. Data was recorded on a standard tide staff from before 1844, but annual MTL data was published as measured below the “Old tidal benchmark” (set in 1852) on the lighthouse from 1853 using a self-registering tide gauge to July 1878 (Schott 1897), when the station was discontinued.

Tidal (monthly “metric”) data from Baltimore is available from the PSMSL from July 1902 to the present, and for Washington D.C. from 1931 to the present. MSL data from Baltimore from 1902 to 1927, plus data from the Washington Navy Yard from July 1891 to July 1899 and other nearby sites has also been published (Haight et al 1930). The Navy yard gauge had issues due to silting, so another gauge was set up at the foot of Seventh Street (USCGS report 1900) and data from this gauge (June 1898 to March 1901), along with another gauge at Easby Point (April 1901 to April 1902) and a further gauge at the Lighthouse Wharf (December 1924 to May 1926), which is at the present tide gauge site have also been published (Haight et al 1930). The older tidal data from Washington D. C. is referenced to the tide gauge zeroes for each site, and these are not at the same level. To connect these sections of data, then the relative elevation of the tide gauge zeroes is needed, plus any water elevation due to slope of the river at the time of the tide gauge readings.

The reference “Ordnance” bench mark at the Navy yard, Washington D. C. was 16.35 feet above Standard Sea Level (Cole 1925) pre-adjustment of 1929, and 16.23 ft above NGVD29 (from benchmark data sheets, levelled in the late 20th Century). The elevation of this BM was 20.747 feet above the Tide gauge zero at the Navy Yard (Schott 1897). This allows direct levelling connection to the later Washington D.C. data from the (noted in PSMSL), benchmark BMB1 which was 11.31 ft above standard sea level (pre-adjustment), and 11.16 ft relative to NGVD29, and 16.309 ft above the zero for the present tide gauge near the Lighthouse Wharf. The difference of differences between old and new BM elevations is of order 10mm so it can be assumed that localised relative vertical land motion, or subsidence over this period is minimal and errors are relatively small.

To offset the 1892 to 1898 Navy yard data to the later 1932 zero datum, then 16.309-11.16+16.23-20.747 ft or 0.632 ft needs to be added to the Navy yard data.

For the Seventh Street data, the required TGZ offset to the Navy yard data can be obtained from the mean difference of six months of overlapping water level data (which gives a required offset of -0.53 ft between the Navy yard and Seventh Street tide gauge zeroes), or from the mean difference of the river level to the then accepted sea level over a defined period compared with the same difference derived at the navy yard (5.103-0.26)-(4.603-0.26) which gives -0.506 ft. The above offset to the later Washington data of 0.632 ft (see below) must also be added to the TGZ difference.

The MSL to Mean River Level difference values for several Washington sites were published (Haight 1930). These allow relative elevations of the tide gauge zero levels to be derived.

Site	*analysis period*	*MRL*	*MRL-MSL*
Navy Yard	1892 to 1898	4.603	0.26
Seventh Street	1898 to 1901	5.103	0.26
Easby point	1901 to 1902	5.393	0.60
Lighthouse Wharf	1925 to 1926	4.532	0.16

The Easby Point and Lighthouse Wharf gauge datums can be similarly estimated and the time series can be similarly offset to the 1932 Washington D.C. datum. This gives a composite monthly series for Washington D.C. with 78% completeness from 1892 to 2015.

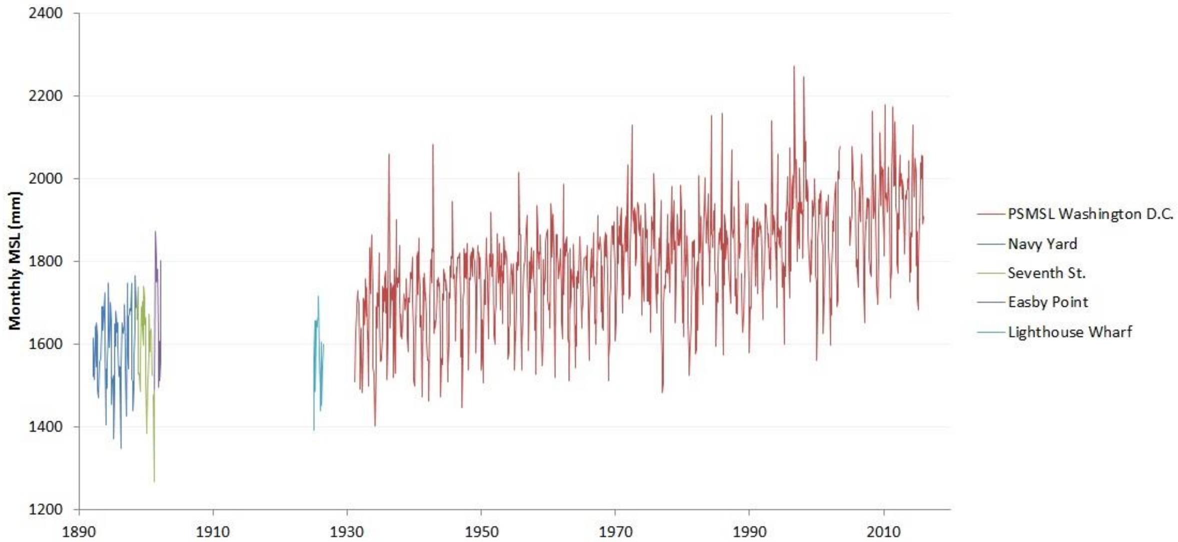

Figure 25: Composite monthly mean water level for Washington D.C. (unadjusted for seasonal variations)

At first glance there appear to be datum issues for the Easby point data (appears too high) and the Lighthouse Wharf data for 1925 (too low). However, this can be checked by comparing with the monthly MSL data from Baltimore (PSMSL metric). The average offset required to reduce the mean difference to zero over 85 years is 0.632 ft. The difference plot also shows no significant linear trend so differential land motion between these sites is assumed minimal. If this difference offset is applied to all of the early Washington data and this is compared with the Baltimore data, then it can be seen by comparison that these apparent level variations are real for the Lighthouse Wharf data for 1925, and realistic for the Easby Point data, considering the peak mean water level around 1902 that is observed at all nearby sites.

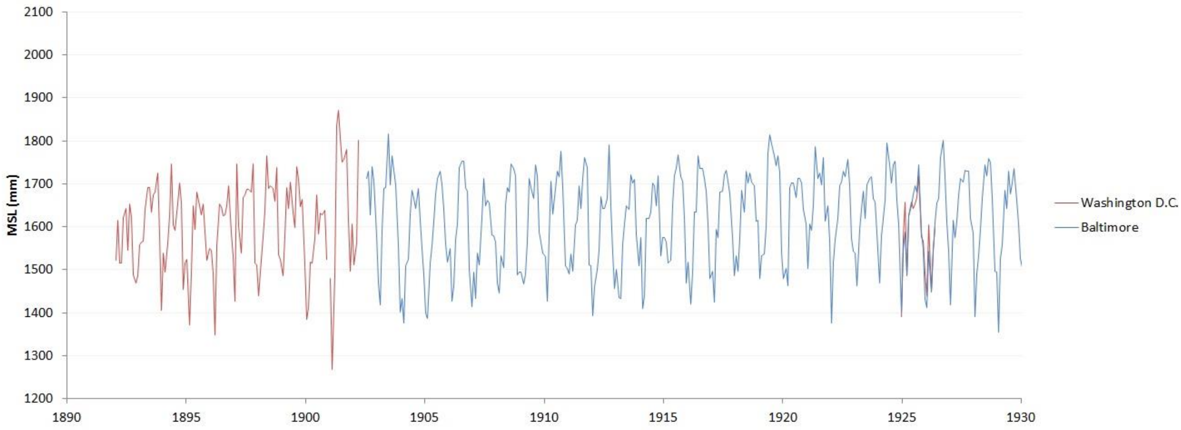

Figure 26: Composite of monthly Washington D. C. water level data and MSL from Baltimore reduced to the same datum.

The acceleration for the extended Washington time series from 1892 to 2015 is 0.0138 mm/yr^2 but there are still some gaps (78% complete).

For the existing (as at 2015) PSMSL Baltimore data from 1902 the derived MSL acceleration is 0.0024 mm/yr^2, which is not statistically significant. A composite of the Baltimore data (extended with the correctly offset Navy Yard and other Washington data from 1892 to 1902), is essentially gap free from 1892 to 2015, and has an acceleration of 0.0124 mm/yr^2. Another data "point" covering a recording period from 1858 to 1860 can be added from the published elevation of the Flagstaff BM above mean HW and LW given in the 1870 USCS report (Anon 1873), giving an MTL value 39.06 ft below the BM. This can be connected using later and NGVD29 bench mark elevations (Marshall 1910, 1914, NOS bench mark sheets) giving an elevation of -0.119 ft below NGVD29, or 3.892 ft above the Baltimore TGZ once average river level elevation is accounted for.

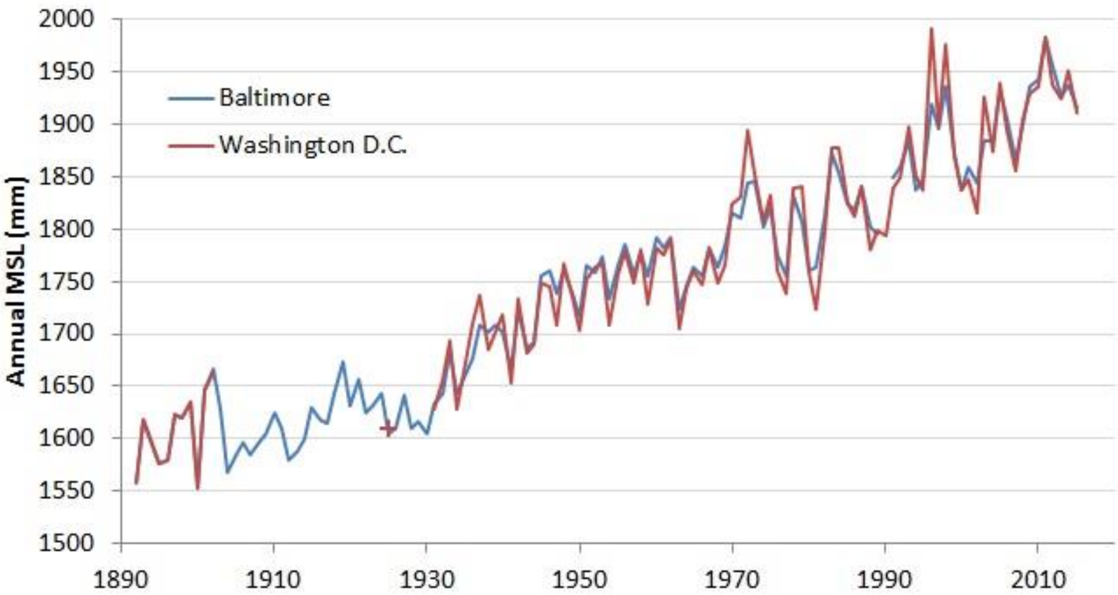

Figure 27: Composite annual MSL time series for Washington D.C. overlaid on Baltimore

At Baltimore, BM 32 (set in 1922) near the tide gauge at Fort McHenry, is 6.21 feet above the adjusted NGVD29 sea level datum (Bench mark data sheet) and 10.361 feet above the tide gauge zero (PSMSL, Holgate et al 2012, and Proudman et al 1939).

When using these older elevations, differences between absolute datum levels at sites separated by more than one or two km need to be considered carefully. The level re-adjustment correction of 1929 of the accepted sea level value in Columbia of +0.141 ft, affects the Washington D.C. elevations (average pre and post adjustment elevation differences from bench marks near the tide gauge sites gives 0.137 ft from this study, and the Navy Yard Ordnance BM is now given as 16.23 ft above NGVD29). The earlier level net adjustments of 1912 (Bowie and Avers 1914), 1903 (Hayford 1903) and 1899 (Hayford 1900) differ slightly again. At Baltimore, BM32 was set in 1922, but the earlier tidal BM1 set in 1886 had an elevation of 4.442 ft (Marshal 1912) pre-adjustment and 4.429 ft post adjustment (NGVD29). For this note it is assumed that the Washington D. C. sites would require correction for this time related adjustment, whilst any required correction at Baltimore is minimal.

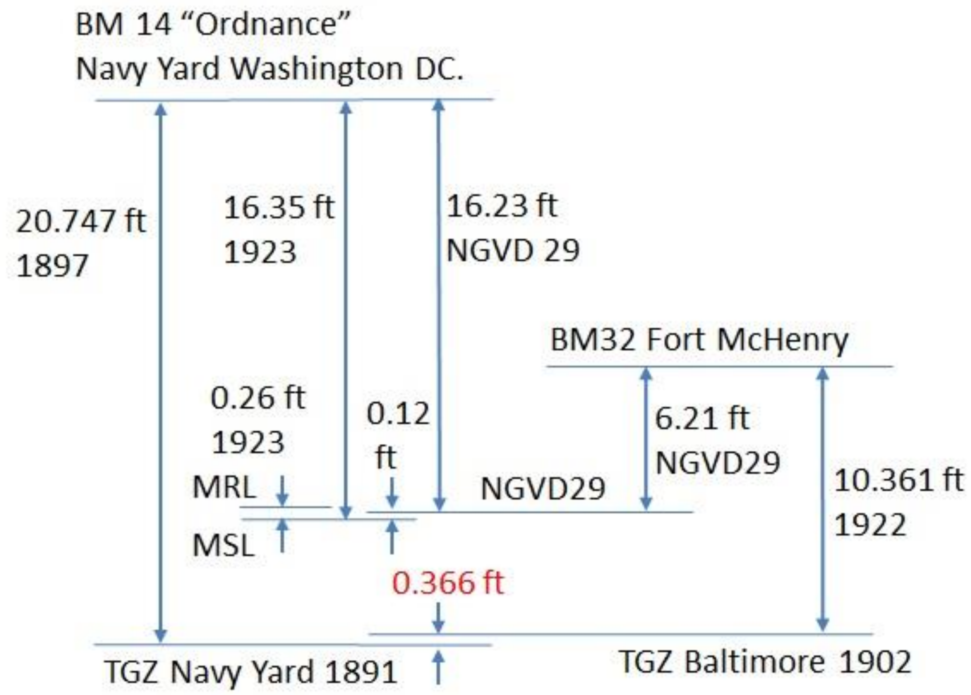

Figure 28: Stick diagram showing datum relationship between Baltimore and Washington tide gauge zeros.

The modern and old BM elevation information also allows a new geodetic connection to be estimated between the gauge zero at Baltimore and the tidal BM at Old Point Comfort. Attempts in 1884 at connecting the mean tide level at Old Point Comfort to Washington resulted in large accumulated errors of as much as 0.66 metres (Schott 1897) by the end of the levelling runs at Washington. This was quickly realised, but the various level net adjustments up to 1912 still used the 1884 MTL elevation at Old Point Comfort derived from the early tide data (Bowie and Avers 1914), and unsurprisingly, these also show differences (of 0.34 ft) to the more modern elevations to NGVD29, due to relative SLR since the 1850s.

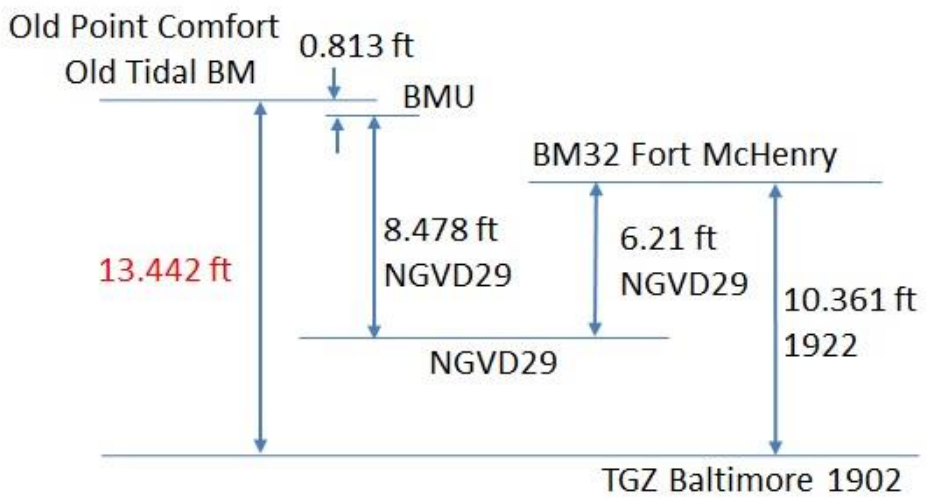

Figure 29: Stick diagram showing datum relationship between Baltimore tide gauge zero and Old Point Comfort tidal bench mark.

The Old Point Comfort data, is published as elevations below the bench mark, so subtracting the MTL values below "Old tidal BM" from 13.442 ft gives the MTL relative to the Baltimore TGZ, assuming the NGVD29 elevations are correct. This gives a further extension to the local time series back to 1853. Two further published monthly values are shown for reference, but not used in the trend calculation. It can be seen that the early data from Point Comfort shows large variance even relative to other data from the same period (eg Boston). The cause of this may be freshets in the constricted narrows near the tide gauge site, or may be due to the wharf site being unstable or prone to interference by heavy vessel traffic as reported in 1875. Nevertheless the mean water level over this period is referred directly to a stable benchmark, and the mean is around 20mm from the average Washington Navy Yard value from 1858 to 1860. The derived acceleration for the entire composite is 0.0166 mm/yr^2, which is still within the 95% confidence level of the global mean value derived from all extended records.

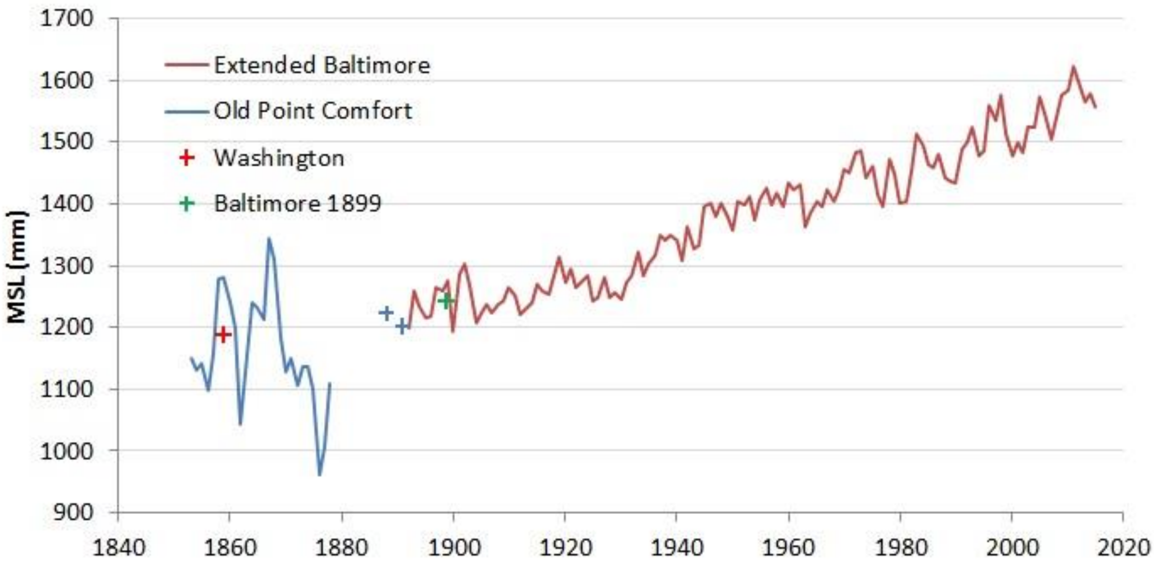

Figure 30: Annual extended MSL composite of Washington D.C. and Baltimore, showing estimated MSL at Old Point Comfort reduced to the same datum.

There has been discussion on anomalous subsidence at Hampton Roads based on the evidence of the Sewell's Point tide gauge (1928 to present) and groundwater level measurements. In this case the gauge appears to be inside the cone of depression affected by the high levels of water extraction (Egglestone and Pope 2013). An updated difference plot of either the Washington D.C. annual MSL time series or the Baltimore time series and the Sewell's Point time series confirms that it is subsiding by an extra 1.4 mm/yr averaged over an 85 year period compared with nearby tide gauge sites (see also Boon 2010) which already appear to be subject to an underlying smaller regional subsidence. There is also a visible second order component in the difference plot which suggests the additional local subsidence component shows acceleration or increased rate of relative sea level rise above the regional scale sea level rise over this period.

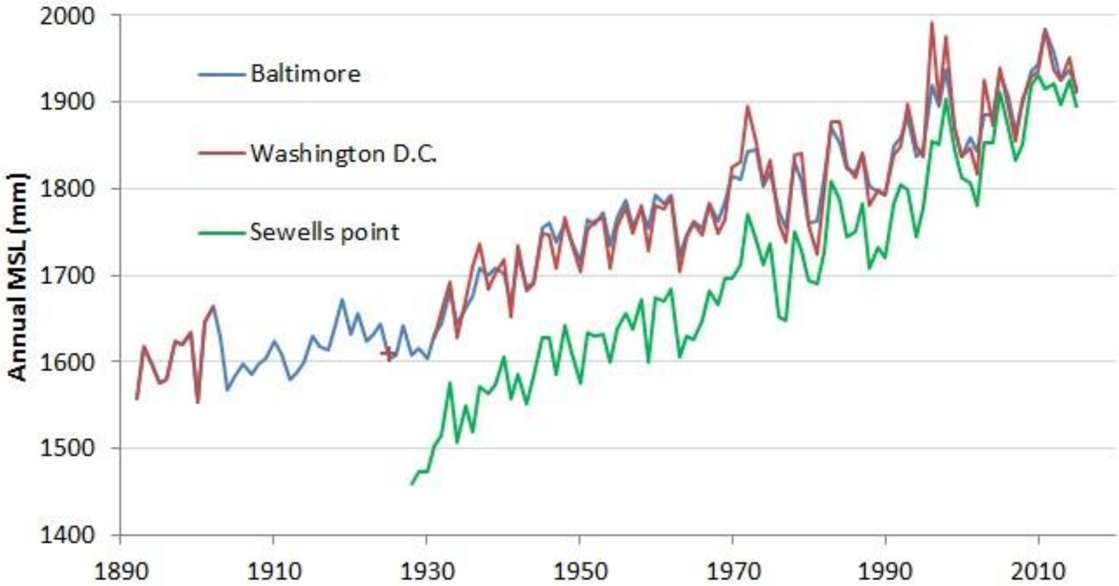

Figure 31: Higher rate of relative sea level rise seen at Sewell's Point, Hampton Roads (4.58 mm/yr) compared with the nearby Baltimore and Washington data (2.97 mm/yr).

Difference plots of nearby tide gauge time series are highly sensitive to small secular differences in RSL trend, as any inter-annual, decadal and long term variations tend to be common mode (due to common regional or even global scale drivers) and therefore cancel, leaving local differences. In this case there is a local decadal term increase in rate of subsidence at Sewell's Point.

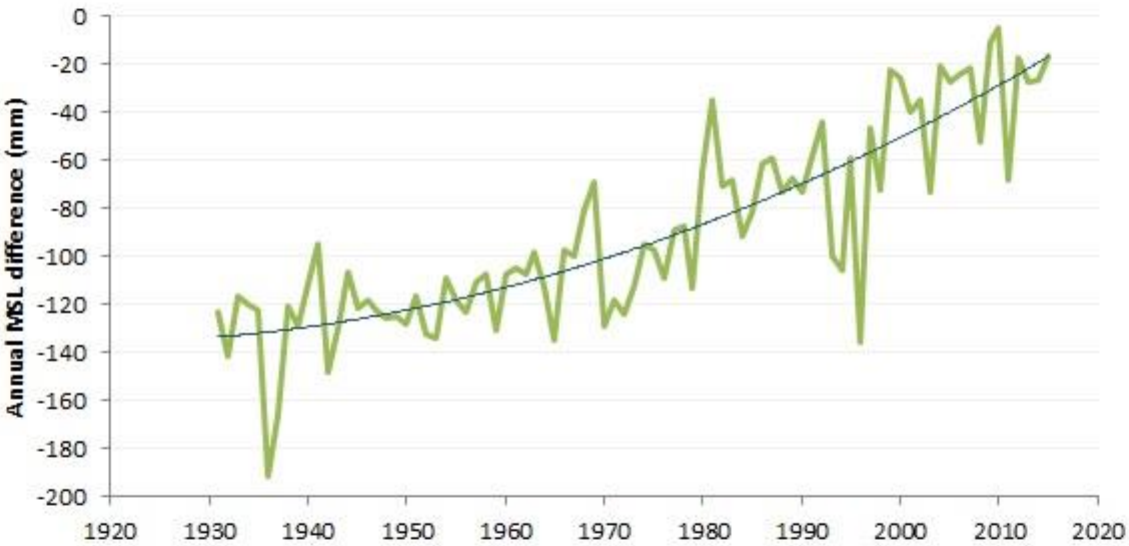

Figure 32: Difference plot of Washington D.C. and Sewell's Point annual sea level time series generated as part of routine buddy checking process for this work. The difference is unusual in showing a significant second order (acceleration) component in addition to the background acceleration at each site being discussed (Hogarth 2014).This has been attributed to localised high rates of groundwater removal near Sewell's Point.

Florida: Key West, Cedar Keys and Fernandina

Key West

For Key West, monthly MSL data is available from the PSMSL from 1913. A comprehensive data recovery and bench mark connection effort was carried out by Maul and Martin (1993), giving a composite annual time series (with some large gaps) running from 1846, which with the recent annual data available from the PSMSL can be extended to the present (2015). The acceleration of sea level rise derived from this extended time series (74% complete) is 0.0102 mm/yr^2.

Fernandina

At Fernandina a tide gauge was set up in 1855 at Fort Clinch (a bench mark elevation above MLW is given as well as the contemporary maximum rise and fall of 7.35 ft) and observations were taken up to the Civil War (USCS annual reports). One year of data from 1860 to 1861 was analysed in the British Association for the Advancement of Science report for 1877, and a Mean Sea Level (A_0 value) of 6.4451 ft was given, but unfortunately without an elevation reference. The gauge was operated up until around April 1861 (Coast Survey report for 1861). The station and data were presumed destroyed during the Civil War in the early 1860s. Further tide gauges and bench marks were set up in 1876-77, then at Fort Clinch in 1889, and yet again in 1890 (annual USE reports). A further gauge was set up at Railroad wharf in January 1898, with a parallel gauge set up at the Iron Pier from 1901 (Bacon 1902). The PSMSL monthly record starts in June 1897, but there is a large gap from July 1924 to November 1938. By subtracting the average seasonal component and using all available data the acceleration derived from the un-extended monthly time series is 0.0150 mm/yr^2. The data gap can be partially filled (and smaller ones in the 1990s) by creating a composite time series using data from nearby Mayport which is available from May 1928. The data can be offset and any linear VLM difference component adjusted for using the long overlap period in the time series between 1938 and 2000. A few months of additional data (seasonally compensated) from Fort Clinch from 1889 and 1890 (USE reports) can be added by estimating the required gauge zero and low water datum difference. This is derived from a comparison of over a year of monthly data from the same gauge between 1900 and 1901 and the PSMSL metric data over the same period. The derived acceleration of the time series would then be 0.0148 mm/yr^2. An additional year (1892) of carefully recorded data from the St. Augustine tide gauge used in the geodetic connection across Florida could be added by connecting the BMA elevation above the TGZ at St. Augustine as recorded in 1892 (Hayford 1900), through the 1903 level net adjustments (Marshall 1912) to BMC (as BMA was later lost), and then through BMC (which still exists) using the modern NGVD29 elevations to BM34 set in 1923 and recorded in the PSMSL RLR diagram for Fernandina. This additional point would increase the derived acceleration slightly to 0.0152 mm/yr^2.

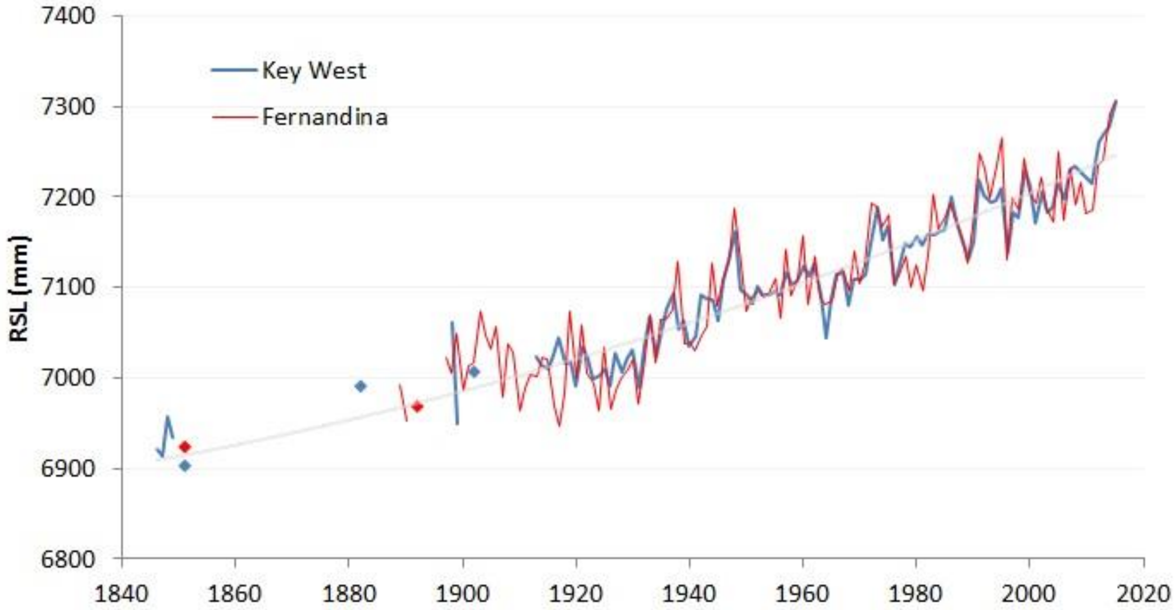

Figure 33: Extended annual time series for Fernandina from this study overlaid with series from Key West from Maul and Martin (1993), showing the strong correlation between the independently extended data. This gives some confidence in the various bench mark connections.

Charleston

The PSMSL record for Charleston starts in 1922 and runs to the present (2015). Early data was recorded in 1851 (Bache 1853) as HW and LW values, and a mean range and benchmark elevation above MLW is given. The same benchmark elevation and another bench mark on the bottom Custom-house step are referred to along with the elevation above MHW and MLW value (7.2 and 12.3 ft respectively) in the 1870 USCS report (Anon 1873). The MTL value is therefore 9.75 ft below the BM. Fortunately this second benchmark (USE 1, near Tidal 2) still exists. This allows connection from the TGZ and bench mark Tidal 13 at Charleston directly through the NGVD29 elevations (bench mark data sheets) for Tidal 13 and Tidal 2 to the correctly offset MTL value for 1851 (13.189-8.26+9.31-9.75=4.489 ft or 1368 mm). Adding this data point would result in an acceleration of 0.0082 mm/yr^2 although with a large gap. Further data from Fort Sumter at Charleston was recorded from when the US Engineers set up a gauge in 1883. The gauge survived an earthquake of 1886, but was destroyed by a storm of 1893 (USE annual reports), and a new gauge was then installed in collaboration with the USCGS. This data is referred to in the USE reports but only a few years of tidal range have been published. The Fort Sumter gauge was again destroyed in a storm in November 25th 1900, the plane of mean low water was stated to be 0.27 feet too low at this gauge compared with the Custom House gauge (Allen 1901).

If the extended time series for Charleston is offset and a linear trend offset is added so as to minimise long term differences with Fernandina, then a composite series can be created which runs from 1851. The acceleration derived from this composite series up to 2015 is 0.0134 mm/yr^2.

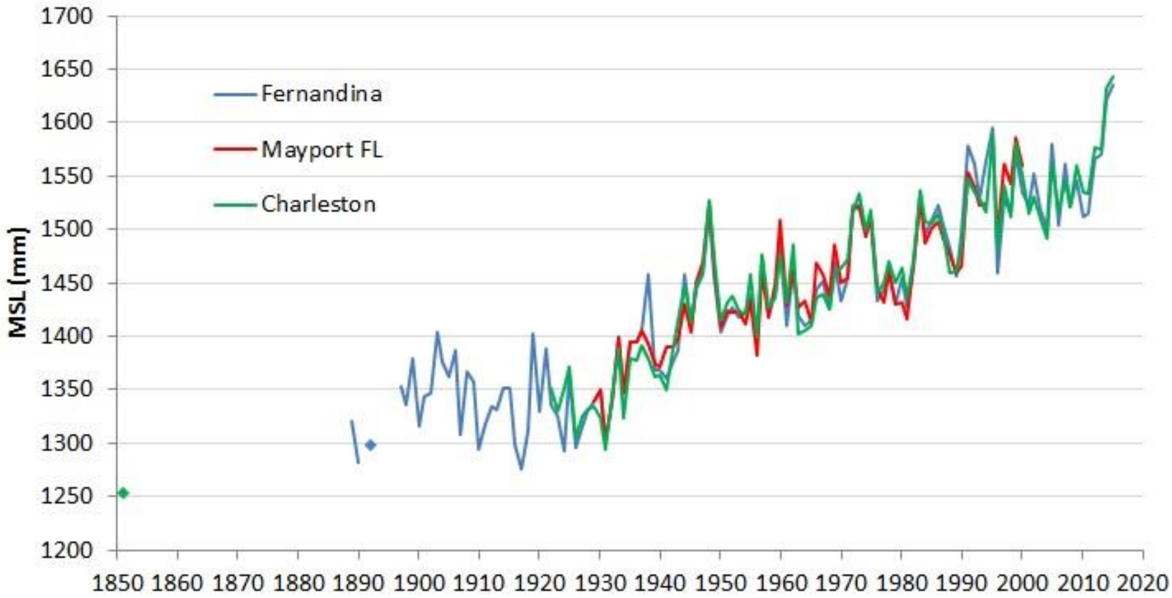

Figure 34: Extended annual MSL record for Fernandina, with Mayport and Charleston (extended) overlaid to show similarities (and differences). As individual time series are extended to century scale or more, the derived acceleration values tend to converge.

Cedar Keys

Early tidal observations were taken in 1850 for a week (Gerdes 1852) and later with a box gauge at Cedar keys January 10th to March 16th 1852 (Bache 1857) and mean tidal HW above MLW of 2.5 ft is given. A gauge was re-installed in 1858 (Pourtales 1859), and removed in 1860 (Pourtales 1861). After the Civil war another box gauge was set up at Cedar Keys in 1872 (pg 724 USE report).

The PSMSL record from Cedar Key is in two sections, April 1914 to December 1925 and October 1938 to the present (2015). These can be connected using the bench mark information (datum below BM11 for the later data is 3051 mm and earlier data is 3481 mm) so offset required is 430mm. The NOAA tide data repository has the same data but the two sections are already reduced to the same datum. There is a year of additional monthly MSL data from 1892 (Hayford 1900) derived from hourly readings referenced to BMY (TGZ given as 5723.3 mm below BMY) and this can be connected using the difference in elevations of BMY and BM8 given in the precise levelling (Rappleye 1934) reports giving a required offset of 744 mm to match the 1938 TGZ datum.

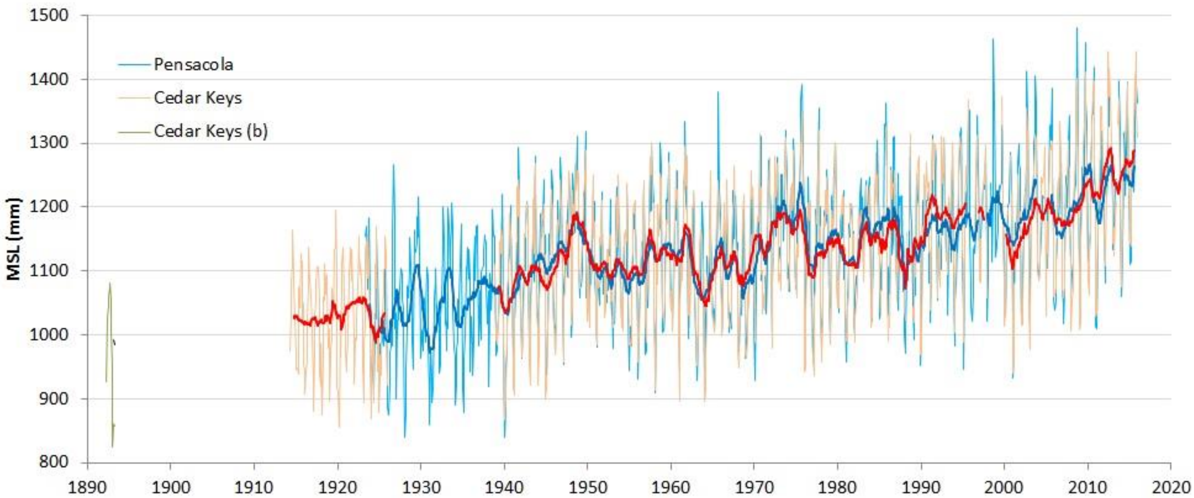

Figure 35: Monthly MSL time series and 12 month rolling averages for Cedar Keys and Pensacola adjusted to match datums. In this case Pensacola has a trend of 0.2 mm/yr added derived from

minimising differences. This allows a composite to be created filling the gap in the Cedar Keys time series between 1926 and 1938.

The large gap from 1926 to 1938 is filled with appropriately offset data from Pensacola, as the difference plot shows that the two series match well in the overlap period. The match in the overlap at the start and end of the gap is at mm scale for 12 month averaged values.

The unadjusted deceleration derived from the Pensacola time series available in the PSMSL for 1923 to 2015 is -0.0012 mm/yr^2 which is not significant. The acceleration for the extended composite from 1914 to 2015 is 0.0028 mm/yr^2, and whilst this acceleration has altered sign it is also not significant, it is probable that further extension of the time series to pre-1900 with any additional recovered data would show the acceleration converging on the values derived from time series from nearby gauges, as implied in figure 36.

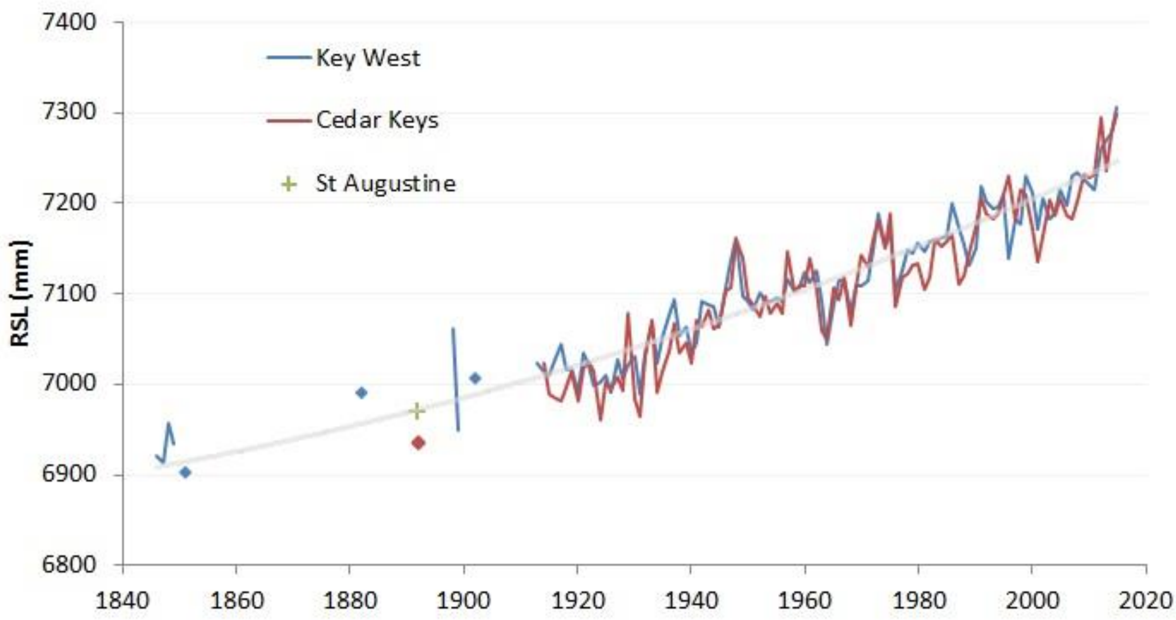

Figure 36: Overlaid extended annual time series of relative sea level for Key West and Cedar Keys, with the single years data from St Augustine after datum levels have been connected using relative bench mark elevations.

Details of tide gauges and Bench Marks for many other sites (but only for brief time periods) are given in a report on the Everglades (1914). These will prove useful if other tide gauge records become available. Bench mark information is also given for several levelling campaigns in the late 19th and early 20th Centuries (e.g. Marshall 1912).

Galveston Texas

At Galveston, the MSL record from the PSMSL runs from May 1908 when the gauge was set up (USCGS report for 1908) at Pier 21 on 20th Street. However there is earlier published annual MSL data from 1904 (Bowie 1936) from Fort Point allowing the series to be extended without gaps. Extending the time series by these additional few years changes the derived MSL acceleration from 0.0018 to 0.008 mm/yr^2. Earlier tide data was recorded at the Government Wharf at the foot of 18th Street from March 17th 1887 (Zinn 1888) with some gaps up to 1898, until interrupted by operations associated with the war with Spain in 1899 and a major storm in 1900 which destroyed many of the local tide gauges (Hartrick 1901). Tidal data was also recorded intermittently at other sites, and some has been published in the US Engineers reports and elsewhere (Stiles 1918) along with contemporary revised relative benchmark elevations (Hartrick 1901). The Galveston MLW datum (which became the Gulf of Mexico mean low tide datum) was also set using measurements recorded from an even earlier tide gauge at Brick Wharf for a year from 1872 to 1873 (Zinn 1888). This levelling connection was double checked during the later recording period (1889). Average HW and LW values from May 1887 to Dec 1888, and then averaged values through to Dec 1890 have been published (Langfitt, 1889, 1891) referenced to the then accepted 1873 MLW datum of 6.879 ft below BM18, (the water table on the Hendley Building), or 10.796 ft below BM19 on the same building (Langfitt 1891). MLW on the actual tide staff read 3.2 ft (Zinn 1888). From this information annual Mean Tide Levels (or average data from most of a year) can be derived from data for 1877 also from Brick Wharf (Ripley 1877), Government wharf for 1888, 1889, 1890, 1891, and a two year mean from June 1895 to June 1897. Some of the data is also given graphically in the references. Several average LW values are also tabulated from 1873 to 1897, but unfortunately not all have published matching HW values so are of limited use here (Oppikofer 1898). Likewise tidal data from tide staff observations taken from March 1851 to January 1st 1853, with mean MHW-MLW of 1.1 ft and bench mark (copper plate) at Doswells Wharf given as 1.24 ft above MLW (Bache 1854, 1857), were not used, as information has not been found (by this author) to allow more recent connection to the old bench mark elevation. The USE report for 1873 mentions that this original USCS BM was washed away.

The datum of the current TGZ for the PSMSL metric data from 1908 can be connected to the Government wharf TGZ, or more correctly the City MLW datum, using old and new differential elevations of the tidal bench marks, as some of the older marks still survive. The connection for this note will use the NGVD29 adjusted datum and recent and older elevation information to link BM35 (PSMSL) to Tidal BM 19. This gives an elevation difference of 9.37-4.84+8.48-10.796 = 2.214 ft (City MLW datum above 1908 TGZ). Although older levelling connections generally can be less precise than modern ones, and bench marks can also move over time, in this case the distances are short and the bench marks are described as stable.

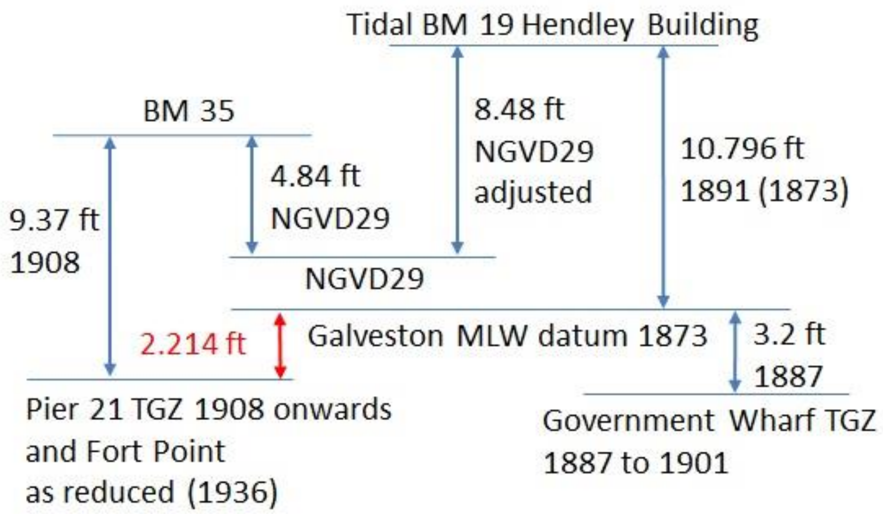

Figure 37: Stick diagram showing relationship of modern benchmark elevations to the Galveston MLW datum of 1872-73.

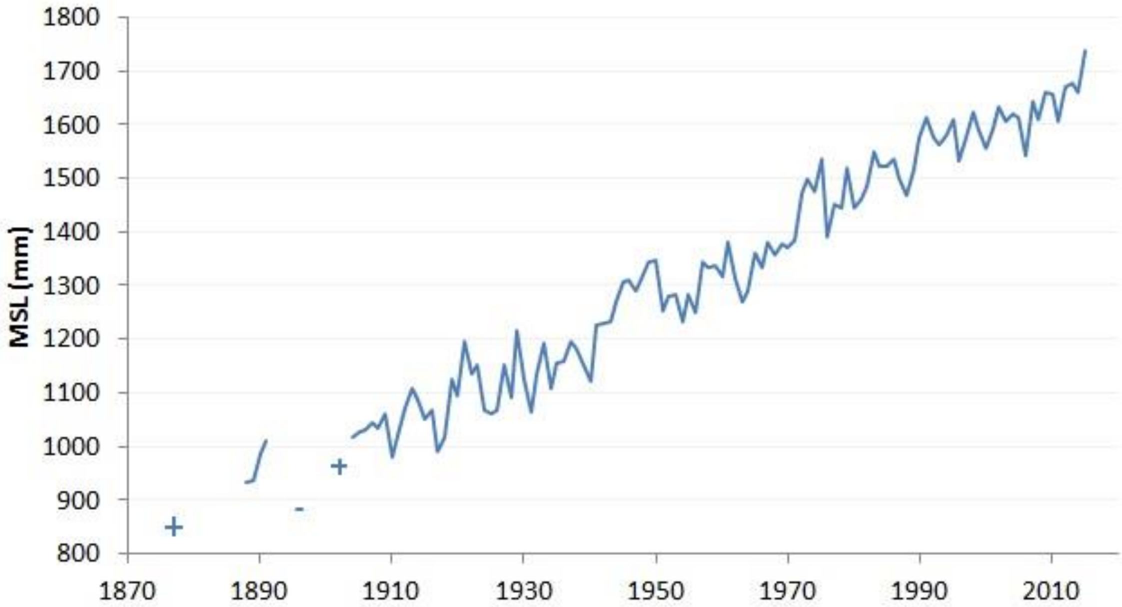

Figure 38: Extended annual time series from Galveston using additional published data from Fort Point, Government Wharf and Brick Wharf.

The addition of these extra annual points gives the extended time series an acceleration of 0.0116 mm/yr^2. Although there are gaps, this is convergent with independently derived global century scale results and other results from the Eastern seaboard of the U.S (Hogarth 2014). The linear component of century scale SLR is 6.2 mm/yr, which indicates an excess vertical land motion or subsidence of over -4mm/yr at this site. Comparison with continuous century scale data from other tide gauge sites suggests that this vertical land motion is long term and relatively constant, appearing to pre-date industrial scale oil extraction, which suggests a tectonic or compaction related driver (Turner 1991, Wolstencroft et al 2014, Yu et al 2014), similar to the process believed to be ongoing on the Mississippi Delta.

Mississippi and Biloxi.

A large amount of historical water level data exists for various stages of the Mississippi and the river delta. The records for Carrollton, for example, go back to 1849, and can be connected to other nearby water level gauges in New Orleans using available bench mark information to create a relatively complete composite times series running up to the present. As the distance inland from the gulf increases, so the large river level variations increasingly dominate the relatively weak tidal component. Data from the various outlets or passes on the delta, assumed to represent relative Gulf ocean level, is also available, but whilst the early data is referenced to fixed local datums, over the past century relative subsidence of land (Penland and Ramsey 1990) and bench marks on the delta compared to marks on more "stable" ground (notably Biloxi was used as a reference) has been so great that when wider net level adjustments started being made to refer to the regional "Gulf" sea level, the bench mark and water level records required frequent datum adjustments, and similarly the NGVD29 and NAVD88 derived regional datum has successive epochs where vertical adjustment steps have been made. Some of these local shifts at individual gauges were not recorded, and this makes it challenging to create long term composite records where local subsidence can be isolated from the SLR signal. This is compounded as many gauges were only read manually once per day in the past.

Summary: Comparing extended time series

Plotting the annual mean sea level for the sites discussed and comparing visually, it can be seen that all of the extended time series follow a similar long term (century scale) pattern. Clearly the relative rate of sea level rise differs at different locations, but the deviation from the global average over these extended periods appears to be largely due to vertical land motion.

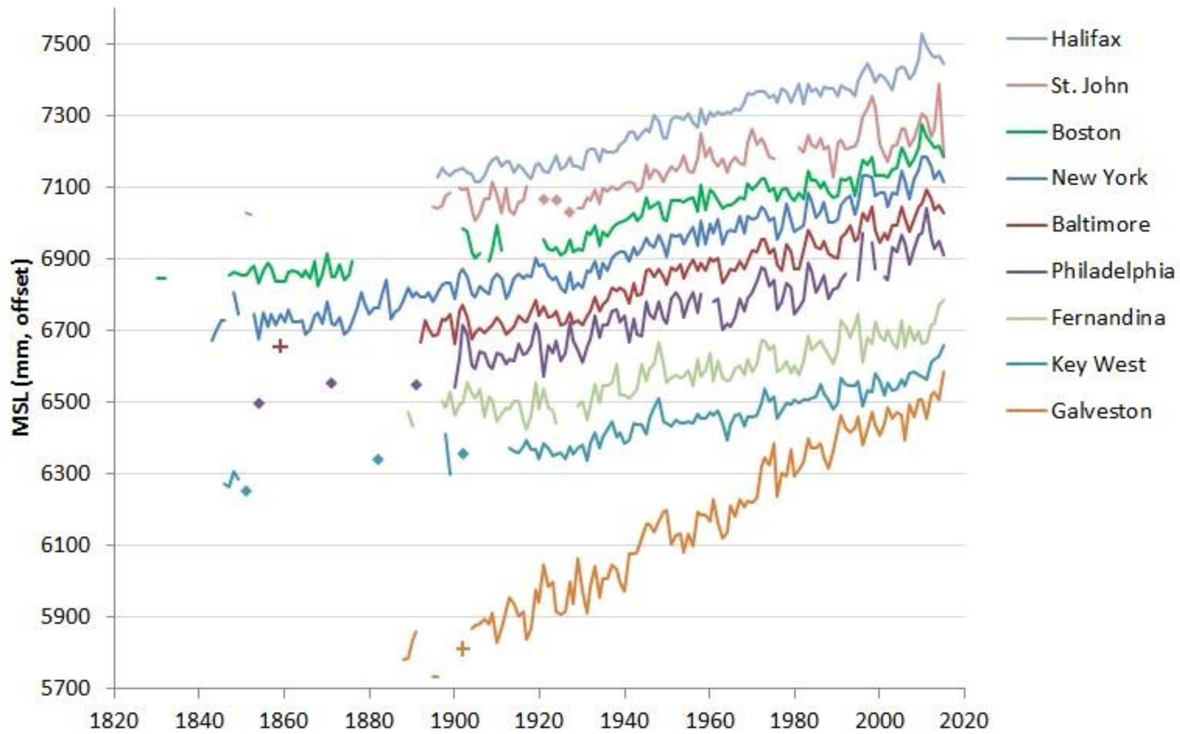

Figure 39: The extended sea level annual time series (offset for clarity) showing the effect of long term differences in vertical land motion at different sites.

If the effect of vertical land motion is minimised by subtracting a VLM estimate derived either from direct CGPS measurements or from simply normalising all SLR rates to a uniform value, then the similarities in long term variations from the mean SLR become very apparent for every site.

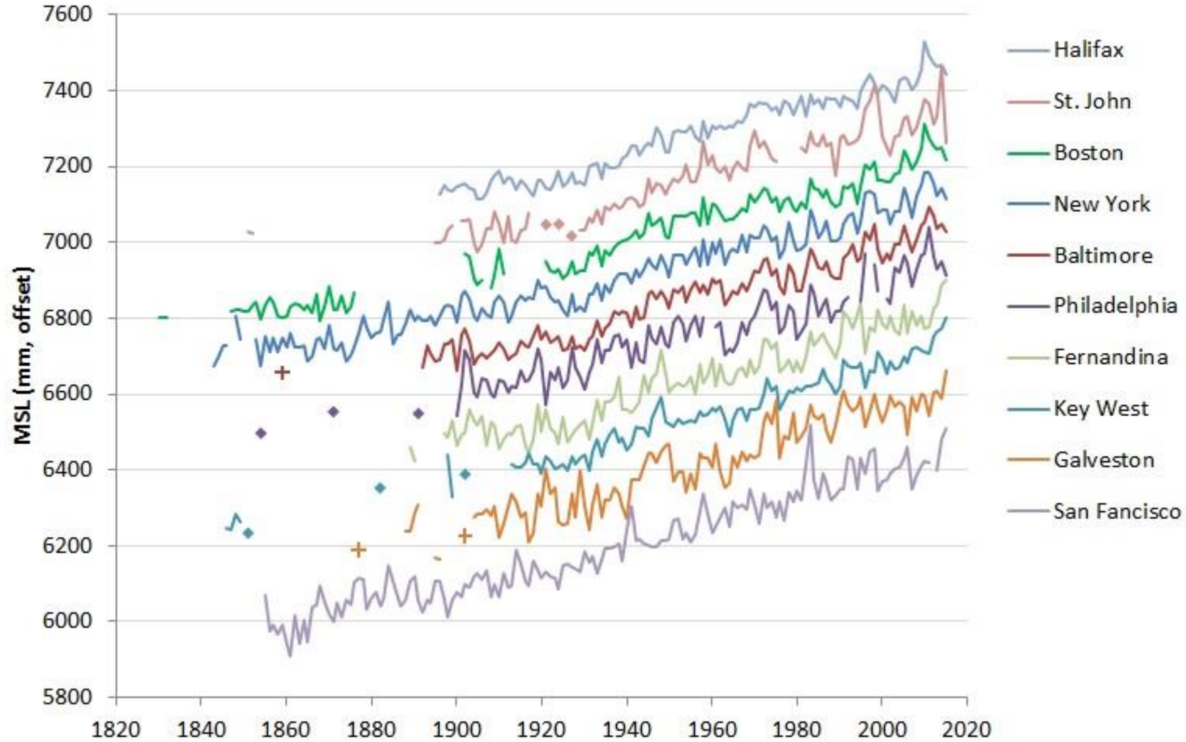

Figure 40: The same time series with vertical land motion adjusted with a linear scale factor to allow comparison of long term non-linear and inter-annual variations. The extended data series all show convergent acceleration values compared with the wide variance exhibited by the acceleration derived from the un-extended series. San Francisco is also shown as representative of the West Coast time series.

The inter-annual variations have common components at neighbouring sites, but decadal scale components are common over longer distances. Over time scales of a century or more the similarity with RSL variations as distant as the Western coast of the North American Continent (as represented by the time series from San Francisco) is also clear. If a quadratic curve is fitted to the data series in order to estimate the lowest order non-linear component of SLR, then the similarity can be quantified. This is not to say that a quadratic curve is a good model for SLR over the 20th Century, but a second order fit is a simple measure of increasing rate of SLR. The effect of missing data samples is reduced as the amplitude of the inter-annual variations tends to be similar throughout any given time series, such that the biasing effect of a single sparse sample coinciding with a peak or trough is progressively reduced as the time series is extended. It is very clear over these longer time periods that a second order fit is a better model than a linear fit, and the convergence of the extracted acceleration estimates at these sites is remarkable (table 1). The extended West Coast series, show similar mean acceleration values (table 2). The convergence of SLR acceleration values towards a value of order 0.01 mm/yr2 from all sites where significant extensions of annual time series beyond century time scales are possible provides a more consistent picture with higher confidence than previous US coast studies which have mainly used the previously available un-extended data series (for example Houston and Dean 2011). These preliminary results give context to and update the results from such shorter term studies and reconcile them with global analyses using longer time series (e.g. Church and White 2011). Similar convergence is apparent in all other regions of the world where extended data is available, suggesting this SLR acceleration value over century scale and longer is global.

Table 1: East Coast

Tide Gauge Site	Start Year	% Complete	Acceleration (mm/yr^2)
Halifax	1851	74%	**0.0096**
St. John	1895	89%	**0.0058**
Boston	1824	78%	**0.0145**
Providence*	1853	57%	**0.0144**
New York	1843	88%	**0.0131**
Baltimore	1859	79%	**0.0147**
Philadelphia	1854	70%	**0.0118**
Fernandina	1889	92%	**0.0159**
Key West	1846	74%	**0.0101**
Galveston	1877	71%	**0.0116**

**Providence R.I. was not used in the global study (Hogarth 2014) due to <70% completeness*

Table 2: West Coast results (from supplementary note 3)

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 3: Annual MSL values (mm) Red is extended, Blue is re-estimated datum connection

Year	Halifax	St. John	Boston	New York	Baltimore	Philadelphia	Fernandina	Key West	Galveston
1820									
1821									
1822									
1823									
1824			6805						
1825									
1826									
1827									
1828									
1829									
1830			6846						
1831			6846						
1832			6846						
1833									
1834									
1835									
1836									
1837									
1838									
1839									
1840									
1841									
1842									
1843				6674					
1844				6700					
1845				6729					
1846				6729				6921	
1847			6856					6914	
1848			6861	6805				6957	
1849			6859	6745				6935	
1850			6853						
1851	6628		6854					6903	
1852	6624		6871						
1853			6878	6745					
1854			6831	6674		6547			
1855			6869	6751					
1856			6891	6711					
1857			6876	6747				6793	
1858			6838	6713					
1859			6835	6747	1186				
1860			6838	6723					
1861			6862	6760					
1862			6868	6722					
1863			6864	6722					
1864			6852	6727					
1865			6865	6687					
1866			6846	6700					
1867			6893	6743					

Year	Halifax	St. John	Boston	New York	Baltimore	Philadelphia	Fernandina	Key West	Galveston
1868			6823	6749					
1869			6860	6719					
1870			6914	6782					
1871			6849	6719		6604			
1872			6848	6717					
1873			6885	6735					
1874			6842	6687					
1875			6856	6704					
1876			6892	6725					
1877				6760					849
1878				6805					
1879				6775					
1880				6748					
1881				6761					
1882				6763				6991	
1883				6798					
1884				6842					
1885				6733					
1886				6756					
1887				6758					
1888				6783					934
1889				6821			1321		936
1890				6795			1282		987
1891				6806		6599			1011
1892				6792	1198				
1893				6794	1258				
1894				6806	1235				
1895		6864		6782	1215				883
1896	6727	6862		6807	1219				883
1897	6752	6871		6829	1264		1352		
1898	6740	6895		6835	1260		1335	7062	
1899	6733	6906		6832	1274		1380	6950	
1900	6747			6791	1193	6593	1316		
1901	6750	6915		6859	1286	6673	1343		
1902	6755	6914	6983	6871	1304	6767	1347	7007	962
1903	6741	6918	6974	6851	1268	6739	1405		
1904	6738	6855	6917	6804	1208	6654	1376		1018
1905	6715	6828	6902	6792	1225	6643	1363		1027
1906	6715	6847	6914	6826	1237	6692	1387		1030
1907	6730	6888		6810	1225	6685	1308		1045
1908	6762	6888	6891	6802	1237	6651	1368		1033
1909	6775	6934	6923	6842	1244	6644	1358		1061
1910	6786	6899	6992	6860	1265	6685	1294		981
1911	6757	6849	6925	6844	1250	6684	1318		1021
1912	6773	6915		6790	1220	6655	1334		1070
1913	6769	6855		6806	1228	6672	1332	7023	1106
1914	6739	6844		6844	1239	6665	1352	7014	1088
1915	6762	6877		6859	1270	6714	1351	7011	1052
1916	6750	6881	6946	6847	1258	6683	1299	7025	1067

Year	Halifax	St. John	Boston	New York	Baltimore	Philadelphia	Fernandina	Key West	Galveston
1917	6738	6920		6856	1254	6688	1277	7045	991
1918	6724			6852	1283	6711	1312	7016	1017
1919	6763			6902	1313	6768	1403	7017	1126
1920	6765			6880	1272	6742	1331	6991	1094
1921	6743	6886	6955	6884	1296	6623	1389	7034	1196
1922	6740		6929	6853	1265	6707	1336	7022	1134
1923	6765		6924	6843	1272	6686	1325	6999	1151
1924	6790	6884	6932	6849	1284	6722	1294	7003	1066
1925	6748		6909	6821	1244	6666	1362	7010	1059
1926	6760		6919	6806	1249	6687	1295	6992	1067
1927	6782	6850	6952	6864	1282	6773	1315	7027	1150
1928	6756		6921	6816	1249	6721	1329	7007	1090
1929	6760	6861	6928	6831	1257	6696	1340	7022	1216
1930	6751	6861	6925	6820	1245	6663	1351	7031	1125
1931	6801	6892	6975	6865	1273	6706	1302	6989	1064
1932	6804	6882	6967	6862	1284	6726	1339	7034	1136
1933	6807	6914	6993	6892	1323	6793	1400	7067	1191
1934	6769	6875	6936	6847	1284	6733	1348	7023	1107
1935	6807	6917	6976	6889	1302	6766	1395	7052	1156
1936	6797	6910	6963	6867	1316	6765	1396	7076	1158
1937	6796	6923	6986	6901	1348	6804	1406	7094	1196
1938	6800	6913	6998	6917	1341	6807	1458	7053	1183
1939	6819	6916	7002	6918	1348	6774	1368	7064	1150
1940	6829	6932	7005	6918	1342	6793	1369	7034	1122
1941	6854	6936	7013	6894	1307	6719	1361	7046	1226
1942	6853	6929	7027	6931	1362	6784	1376	7092	1228
1943	6830	6910	7008	6910	1327	6740	1388	7088	1232
1944	6849	6918	7020	6927	1332	6733	1457	7086	1271
1945	6864	6983	7072	6958	1395	6832	1410	7063	1308
1946	6853	6944	7039	6942	1401	6797	1443	7107	1310
1947	6902	6968	7048	6931	1379	6783	1458	7137	1290
1948	6882	6961	7058	6968	1401	6829	1518	7162	1320
1949	6837	6936	7009	6936	1379	6783	1455	7097	1343
1950	6836	6956	7006	6907	1357	6771	1404	7091	1347
1951	6890	6976	7063	6966	1405	6840	1420	7082	1253
1952	6896	6967	7062	6964	1398	6856	1427	7102	1279
1953	6891	6984	7061	6966	1413	6835	1418	7091	1284
1954	6890	7010	7060	6943	1374	6788	1422	7091	1232
1955	6907	6966	7066	6965	1406	6832	1440	7095	1284
1956	6880	6962	7069	6987	1426	6855	1395	7092	1248
1957	6866	7000	7032	6936	1397	6801	1472	7117	1343
1958	6920	7067	7108	7007	1417	6851	1421	7103	1335
1959	6876	7006	7037	6941	1395		1441	7107	1337
1960	6909	7028	7091	6999	1433		1487	7124	1317
1961	6898	6995	7086	6972	1423	6828	1411	7112	1380
1962	6908	6980	7064	7009	1432	6841	1465	7126	1312
1963	6900	6999	7042	6941	1363	6751	1419	7091	1271
1964	6908	6959	7048	6976	1386	6770	1410	7045	1288
1965	6905	6988	7048	6982	1403	6763	1415	7087	1360

Year	Halifax	St. John	Boston	New York	Baltimore	Philadelphia	Fernandina	Key West	Galveston
1966	6918	7006	7059	6974	1395	6785	1444	7114	1333
1967	6915	6988	7073	7021	1422	6838	1451	7117	1379
1968	6934	6982	7066	6973	1403	6805	1426	7081	1358
1969	6964	7044	7110	7018	1424	6840	1471	7108	1377
1970	6958	7084	7091	7012	1455	6856	1434	7108	1371
1971	6968	7040	7105	7013	1451	6887	1455	7114	1384
1972	6965	7054	7125	7043	1484	6924	1523	7149	1471
1973	6966	7038	7123	7036	1486	6924	1520	7188	1498
1974	6949	7006	7087	7004	1443	6874	1497	7153	1475
1975	6958	6999	7099	7014	1460	6891	1509	7167	1537
1976	6936		7061	6956	1415	6809	1433	7104	1389
1977	6974		7092	6983	1395	6828	1444	7126	1451
1978	6965		7098	7052	1472	6883	1464	7149	1444
1979	6934	7026	7069	7004	1448	6870	1431	7145	1518
1980	6958		7062	6977	1400	6796	1455	7156	1443
1981	6986	7029	7083	6984	1403	6814	1427	7147	1462
1982	6931	7015	7067	6995	1453	6834	1466	7158	1484
1983	6989	7066	7144	7084	1512	6937	1533	7158	1549
1984	6966	7040	7120	7061	1494	6917	1495	7161	1523
1985	6976	7028	7117	7013	1464	6855	1509	7164	1521
1986	6954	7056	7096	7033	1459	6884	1523	7199	1535
1987	6980	7027	7114	7058	1481	6903	1504	7174	1497
1988	6977	7036	7082	7003	1443	6841	1483	7155	1467
1989	6976	6946	7069	7001	1436	6867	1456	7131	1514
1990	6955	7043	7077	7011	1433	6868	1497	7150	1575
1991	6985	7051	7123	7049	1489	6892	1578	7219	1613
1992	6976	7027	7117	7067	1500	6907	1561	7202	1577
1993	6972	7030	7129	7077	1524		1530	7195	1564
1994	6953	7036	7077	7025	1478		1565	7196	1578
1995	6996	7053	7120	7052	1487	6892	1595	7209	1608
1996	7024	7116	7176	7130	1559	7019	1460	7140	1531
1997	7043	7138	7164	7133	1536		1529	7183	1576
1998	7019	7175	7183	7128	1577	6993	1515	7178	1623
1999	6994	7145	7133	7076	1512	6922	1572	7231	1589
2000	7014	7039	7134	7085	1477		1535	7211	1556
2001	7005	7009	7130	7084	1500	6901	1523	7172	1593
2002	6993	6989	7129	7047	1484	6890	1553	7206	1634
2003	6969	7036	7151	7083	1525	6984	1518	7182	1607
2004	7028	7040	7152	7080	1525	6969	1502	7188	1621
2005	7035	7084	7211	7143	1573	7016	1580	7215	1612
2006	7032	7084	7194	7119	1546	6995	1504	7198	1543
2007	7001	7034	7159	7065	1506	6934	1561	7231	1643
2008	7018	7057	7179	7122	1539	6978	1522	7234	1609
2009	7056	7097	7211	7149	1576	7016	1546	7226	1659
2010	7128	7126	7277	7185	1583	7021	1512	7220	1657
2011	7094	7114	7239	7182	1623	7089	1516	7215	1606
2012	7070	7060	7221	7156	1597	7010	1566	7260	1671
2013	7063	7080	7212	7123	1566	6979	1571	7270	1678
2014	7067	7209	7213	7143	1578	7001	1622	7278	1659

Year	Halifax	St. John	Boston	New York	Baltimore	Philadelphia	Fernandina	Key West	Galveston
2015	7044	7008	7183	7113	1556	6961	1636	7307	1737

Table 4: Summary of results from extended time series

	Halifax	St. John	Boston	New York	Baltimore	Philadelphia	Fernandina	Key West	Galveston
Completeness	74	89	78	88	80	70	95	66	71
SLR (mm/yr)*	2.94	2.07	2.08	2.58	2.92	2.92	2.16	2.09	6.20
Acceleration (mm/yr^2)	0.0096	0.0057	0.0145	0.0131	0.0147	0.0118	0.0159	0.0101	0.0116

**SLR in this table is unadjusted for vertical land motion*

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An increasing number of historical documents are being digitised and are now becoming available on-line. For archive research work of this nature these sources have become invaluable.

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