Hogarth 2014: Supplementary note 1: Australian, New Zealand and Tasmanian tide gauge data

Introduction

Data from tide gauges in Australia and New Zealand give us some of the very few longer tidal time series from the Southern Hemisphere for both Western Pacific and Eastern Indian Oceans which extend into the 19th century. Extending these further or extending other regional time series to cover similar century scale time periods is important for climate and sea level studies. This document briefly summarises work on extended PSMSL (Permanent Service for Mean Sea Level) data series from Australia using published but largely overlooked data from 19th and early 20th Century documents (which has therefore been un-cited in recent studies, Watson 2012), as well as extended data using overlapping time series from nearby stations and other long published data series not as yet in the standard PSMSL dataset. These notes give details of regional information which contributed to the results in Hogarth (2014), which discusses global sea level acceleration based on a larger extended dataset.

This document focusses on data from several Australian ports where preliminary progress has been made on extending time series. These are Sydney, Port Adelaide, Newcastle NSW, and Williamstown (Melbourne). The long record from Fremantle (Perth) is also discussed. Other small amounts of early data is noted (and some is recorded in this document) from Ballina, Yamba, Port Augusta, Port Pirie, Port Darwin (Chapman 1903), Brisbane, and Port Hedland, but in these cases either gaps are too large to satisfy acceptance criteria or datum issues remain unresolved. However they may be useful as near neighbour checks to help identify outliers, datum shifts or fill gaps in the longer series. A brief comparison is also made between Port Arthur, Tasmania, using the data from Hunter (2003), Mault (1889), Hobart and other Tasmanian sites from the PSMSL, and data from the nearest Australian extended time series. The four long extended annual data series from New Zealand (Hannah 2010, 2012) are also not all in the standard PSMSL data set but are updated to 2013 and covered briefly here.

Sydney

Spada et al (2012) opted not to include the monthly PSMSL Sydney data (one data series starting 1886) in their global analysis, as the linear SLR (Sea Level Rise) trends from the two almost co-located Fort Denison gauges are statistically different over their respective full spans. However an analysis of the trends limited to the overlap period 1915 to 1993 shows they are statistically identical, and annual and monthly differences between the gauges are small (figure 3). The difference in overall trends is most likely due to the lower rate of sea level rise in the earlier 1886 to 1915 period compared to the post 1993 period at this location. An annual time series using data from both temporally overlapping gauges has been created. This has been extended further back by 13 years to 1873 using “forgotten” published data (table 8, Russell 1885). This data appears to be a first hand corrected version of that reported by Darwin (1889), transmitted via Captain Wharton, originally from Russell, and recorded in the PSMSL ancillary time series (Spencer et al 1986). The version reported by Darwin would give anomalously high MSL values at the start of the series, (which Darwin comments upon) which if accepted would lead to much higher centennial acceleration values (figure 1). The values reported directly from Russell resolve this apparent anomaly, but caution should be exercised as other contemporary notes also indicate possible issues with the gauge leading up to 1886. Russell himself seems satisfied with the accuracy of the data, was on site and was certainly aware of the gauge problems, highlighting an issue with the original gauge installed by his predecessor Smalley in 1867, which lead to the replacement of this gauge in 1872 by Russell. Russell also comments on the stability of mean sea level over previous decades.

A possible explanation of the difference in reported values (from the same gauge) may be that multiple datums were in use at this time in Sydney. The bench marks and datums used for the corrected data are the same as used in the data from 1886 onwards and these are noted by Russell. Early detailed discussions on the various Sydney benchmarks (and others) are also given in "The Surveyor" (1894-1902).

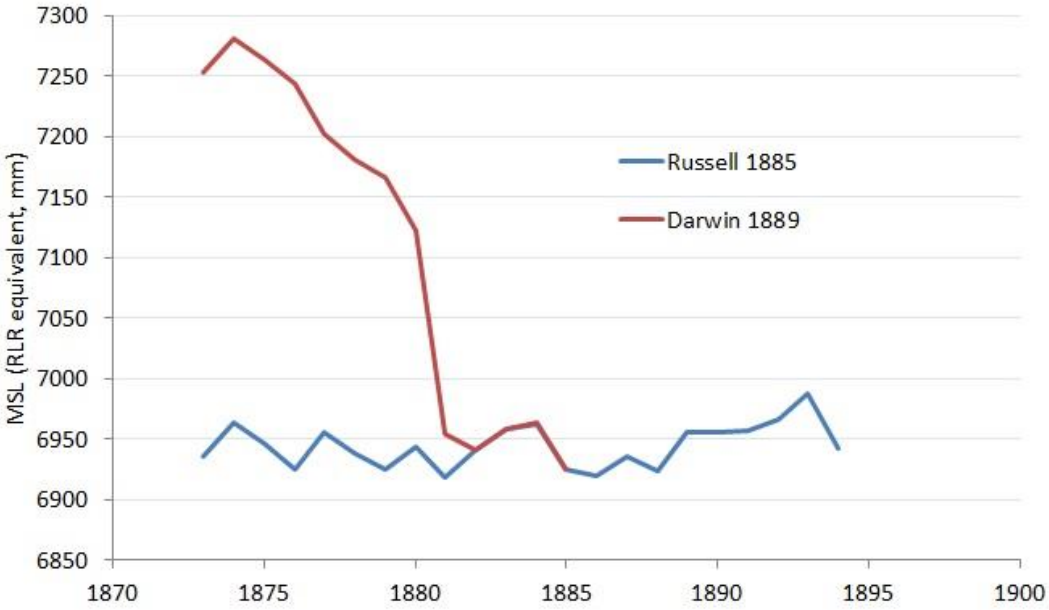

Figure 1. Chart showing Russells Data from Sydney as reported in 1885, and data in PSMSL ancillary files reported by Darwin and deposited with the Royal Society, London. Scale is RLR in mm.

In terms of corrections for SLR trends, the vertical land motion at Sydney is measured by a local CGPS (Continuous Global Positioning System) to be -0.56 ± 0.42mm/yr, (http://sideshow.jpl.nasa.gov/post/tables/GPS_Time_Series.pdf) which is consistent with -0.89 ± 0.65mm/yr from ULR5 reprocessed CGPS data, (Santamaria-Gomez 2012). A small subsidence rate or continental tilt of median -0.8mm/yr is reported from many CGPS stations on or inland from the Eastern Australian coast from the CORS (Continually Operating Reference Station) network. This is at odds with the suggested small regional uplift derived from the difference between most Australian East coast tide gauge data and current satellite altimetry data (for example Ostanciaux 2011). Some of the mm scale difference between CGPS and the altimetry derived data could be due to geocentre motion or reference frame issues (Wu 2012, Melachroinos 2013). These latter factors may affect SLR trend, but do not affect analysis of long term SLR acceleration. Whilst ground water extraction (Ng 2010) and subsidence due to mining have been suggested as affecting some gauges, eg Newcastle (Watson 2011), and this could affect acceleration estimates, direct comparison and difference plots of these gauges reveals high correlation in the latter half of the 20th Century and lower trend divergence when considering centennial timescales.

Newcastle NSW

The data from Newcastle NSW consists of several time series from successive and overlapping gauges each with their own zero points, but all of the "metric" data in the PSMSL are referred back to bench mark PM 60000 (for Newcastle V), which is the same as BM No. 1 (Modra 2013), the original harbour bench mark at the Customs house (for Newcastle II and III), and therefore can be connected and reduced to a common RLR datum. The earliest PSMSL monthly data extends back to 1925, but the series finishes in 1988. This data is used to create a longer composite time series up to 2012 using overlapping data from another nearby gauge. In addition, earlier data is also included. The PSMSL ancillary data includes one annual data point for 1900 (originally from Wright 1902), but a local newspaper article (Anon. 1951) refers to the Newcastle tide gauge installed by Russell in 1890 still working 60 years later. Further research uncovered some of this data, with a monthly time series for the years 1890 to 1902 (Russell 1893-1904, table 4), as well as a complete annual series from 1892 to 1916 (Coghlan 1914, Coghlan 1917, table 6) leaving only a nine year gap in the 122 year long record (figure 3). The early data is referred to the same zero datum 14 feet below benchmark BM No. 1. The tide gauge which Russell fitted in 1890 replaced an earlier one he installed around 1870. A third gauge was installed in 1896 after it was noticed that the float chain on the second gauge appeared to have stretched around 1895. The data for 1895 was corrected (the increase in length of chain was known) in a subsequent 1897 update, but the Coghlan data table retains the uncorrected values for 1895. As it stands, the available data from Newcastle broadly matches the Sydney data, although caution should be observed as there are significant interannual differences in the early data and subsidence is suspected close to the gauge sites (Watson 2011). Further monthly MSL data from Ballina (18th March 1897 to 1902) and Yamba (July 1900 to 1902) can be linked with later data from both locations and these extended series can be "buddy checked" against both Sydney and Newcastle.

Williamstown

The PSMSL records from Williamstown, Geelong, and Point Lonsdale were compared. These series were then used to create a more continuous composite series from late 1927 onwards, although still with some gaps, and then extended using corrected earlier data (e.g. Ellery 1879). Some gaps were partially filled with data published by the International Association for Physical Oceanography (IAPO).

The literature suggests that long records existed for Williamstown, where a gauge was operating as early as 1858 (Ellery 1879). Ellery states that he was unable to find datum information for the earliest data from the late 1850s. The LWST (Low Water Spring Tides) datum of 9.84 feet below the sill of the Williamstown Lighthouse reported by Captain Cox on the 1865 chart of Hobson's Bay was subject to an offset error caused by referencing to the zero of the gauge rather than to the Low Water mark (Stanley 1875). This LWST datum of Cox was corrected to 7.62 feet below B.M., (Stanley 1875, Ellery 1879, it should be noted that the value of 5.95 ft in Ellery should probably read 4.95ft and mean tide should therefore be 6.285 ft below B.M.). The high and low water levels would then be consistent with the reported tidal range. The responsibility for the gauge was handed over to the Melbourne Observatory under Ellery in 1874. From this time data was recorded in the observatory tidal ledger up to 1916 (e.g. Visitors report 1881). LWST was determined again in 1884 as 7.81 feet below the same benchmark. This value became adopted as State Datum and was used until 1970, although the Harbour authority continued to refer tidal levels to a zero value at 7.62 feet below the B.M. This means that 0.19 feet needs to be subtracted from any state datum referenced annual MSL values, e.g. the 1909 to 1911 averaged MSL values (Bradley 1949) using 1908, 1909, and 1910 data sent from the Melbourne Observatory, in order to reduce to the 7.62 ft datum used in the PSMSL "metric" data (Association d'Oceanographie Physique 1950). A value of 2.387 ft should be subtracted from the 1931 to 1939 monthly data (Association d'Oceanographie Physique, 1939) as this is referenced to the "new" datum of 10.00 feet below the same bench-mark. The tide gauge for the early 1930s is believed to have been affected by silting problems outside of the tide gauge well, which reduced the total tidal range reported (Bradley 1949), but this should have a lesser impact on derived monthly MSL values. Silting inside the tide gauge well was also reported in 1881 and 1894.

Although much of the early 1874 to 1916 data has yet to be digitised, we do have an annual MSL (Mean Sea Level) value for 1864, average low water values for various dates, complete monthly MSL values from July 1894 to December 1895 and some annual and longer period averaged values (Bradley 1949, Mackenzie 1939) which are referenced to known benchmarks. These values help to constrain trend values for the overall time series. Although Bradley questioned the reliability of the early data due to large differences in MSL, a comparison with Sydney, Port Adelaide and Newcastle shows that these differences most likely reflect real decadal variations in MSL. The extended series also show that previous comments (Mackenzie 1939) about periods between the 1870s and 1930s having similar averaged MSL values "within 0.01 of a foot" are also consistent with the recorded MSL values for these periods in the region.

Port Adelaide

For Port Adelaide the PSMSL monthly RLR data from the outer harbour (completed around 1907) reaches back to 1940. It is offset by an arbitrary 5616mm from the post 1971 LAT (Lowest Astronomical Tide) datum of the PSMSL metric "outer harbour" data. This metric data is partially derived from (and includes some corrections for) the "outer harbour II" metric series which is referenced to the older LWST (Low Water Spring Tides) datum (270mm below LAT at this location). The PSMSL metric data from the inner harbour also has an updated version with the (somewhat gappy) data from 1933 onwards referenced to LAT. The earlier monthly automatic tide gauge data from 1882 to 1891 is referred to a different datum, described in the original reference (Chapman and Inglis 1896) as that selected by Lieut. Goalen in his survey of 1875. This datum was stated as differing by "about 3 inches" from the Surveyor Generals City survey datum. A datum defined by Goalen was used in early hydrographic charts (eg chart of the river 1884). His report of 1875 refers to a low water datum 15 feet 8 inches below the deck surface above the tide gauge at the far end of the Semaphore Jetty (Proceedings of the Parliament of South Australia, 1875). This benchmark was destroyed when the jetty was damaged by storms in the 1930s. The inner harbour II metric data is simply the pre LAT adjusted 1933 onwards inner harbour data referred to the same original LW datum as the original outer harbour data. From 1921 onwards the tide gauge zero was described as 12.73 feet below a permanent "iron rail" benchmark DMH (Department of Marine and Harbors) BM1 (113.53 feet R.L.) at the Glanville Docks (Admiralty 1922) which still exists. Prior to 1921 (eg in the 1920 Admiralty tide tables) the datum was 13.5 feet below the deck of the government wharf (possibly on North Parade) for the inner harbour, and approximated to LWST. This same 13.5 ft government wharf datum was mentioned in Lieut. Goalens survey report of 1875 as equivalent to the Semaphore LW datum. In an article in "Surveyor" of 1894 relative elevations of various datums for Port Adelaide are again given, including the one 13.5 ft below the government wharf. In this article, however, the mean tide level of 10 years of inner harbour data is stated to be 4.79 ft above the Admiralty chart datum established by Goalen in 1867-1868. This was also stated to be the Marine Board datum. The average MSL over the same 10 years from the *same* tide gauge tabulated in Chapman and Inglis, referenced to the 1875 Goalen Datum is 4.179 ft. This datum discrepancy of 0.611 ft requires investigation.

The 1882 to 1891 monthly time series (Chapman and Inglis 1894) can be extended continuously to 1902 adding an additional published, but often overlooked, complete 11 years of monthly data (Chapman and Inglis 1902). The same 1875 datum is used. The Inner Harbour datum was also stated to be the same as the Semaphore datum in a report from a committee including Chapman and Inglis (Bragg et al 1892) contemporary with publication of the monthly results. This current work (Hogarth 2014) has also recovered published monthly HHW (Higher High Water) and LLW (Lower Low Water) tide gauge records (Proceedings of the Parliament of South Australia, 1902) from the year 1900 (figure 8). These records give a mean HTL (Half Tide Level) of 4.847 ft referenced to the MLLWST (Mean Lower Low Water Spring Tides). This allows the two sets of monthly series from 1900 to be compared. The monthly data from Chapman and Inglis (1902) averaged over the year 1900 gives 4.231 ft. The difference of 0.616 ft is almost identical to the 0.611 ft difference derived above. It would therefore appear that the original harbour datum was MLLWST at the inner harbour, and this would be different from an equivalent low water datum at the Semaphore.

The Admiralty tide tables also provide evidence of different datums being used. For each year from at least as far back as 1891 to 1902 they list an approximate MSL value of 4.7 ft above chart datum at the Semaphore and the Inner Harbour. Between 1903 and 1920 the MSL height above datum for Port Adelaide is listed as 4.2 ft. In the 1969 tide tables the MSL at both the Inner and Outer Harbours is listed as 4.9ft, referenced to a datum 0.6 ft below local LAT at the Inner Harbour (not the later Australian LAT) from one years observations in 1939, and 1 ft below local LAT from 1 years observations in 1945 at the Outer Harbour. Between 1939 and 1945 the difference in MSL from the annual records is only around 5 to 8mm, the larger difference between LAT at the two locations is down to the different tidal range. It would appear that sometime around 1903 the datum was changed. The authority referred to in the tide tables for the years either side of this change is Chapman. The Semaphore and Inner harbour elevations were frequently tied together by levelling in the 19th Century, going as far back as 1856. The main tidal planes are also compared in the 1902 Proceedings, the measured tidal range was known to be greater in the Inner Harbour than at the Semaphore by around 3 to 4 inches.

The datum issue across the 1902 to 1933 gap is therefore resolved using the 1892 to 1902 data, as well as levelling information from benchmarks from the tide stations, and other historic documentation. This allows a preliminary correction for the different datums, and a connection between the original mean tide level (1882 datum) and MSL values referred to the modern LAT. This is estimated by least squares to be 186mm. We can then sanity check the datum shift result against old and new bench mark elevations. Lt. Goalens survey of 1875 used a datum (Lowest Low Water datum) 15 feet 8 inches below the top of the deck of the Semaphore jetty, and modern measurements of the elevation of a newer survey mark on the deck of the jetty of 15.87 ft to LAT, would give a difference of 62mm between these “bench-marks”. This is 22mm short of the 84 mm difference (270 -186mm) estimated from the tidal data, an error of less than 1 inch – the resolution of the original imperial datum measurement, whilst the "three inches" or approximately 76mm, falls somewhere between 62 and 84mm. This datum offset should remain preliminary until the benchmark data can be further verified, although it appears virtually identical to the offset used by the DMH to connect the early and later data as reported by Wynne et al (1984).

This result highlights issues with a previous study using the old inner harbour data (Culver 1970). This study is known to have datum errors, and the derived SLR of 2.4mm/yr for Port Adelaide between 1882 and 1968 from Culver is therefore most likely an overestimate. As this anomalously high long term relative SLR rate was partly attributed to an assumed extension of the subsidence in the Northern Plain to the area near the tide gauges (Belperio 1993), this interpretation must be re-evaluated. The value derived from DMH of 1.5mm/yr (and 1.41mm/yr from this study) is more consistent with long term regional SLR over this timescale.

Other documented monthly and annual data is available for Port Adelaide from the Semaphore (Annual Proceedings of the Parliament of South Australia, 1886-1915), this requires cautious evaluation as it is tabulated as high and low waters referenced to the nominal shallowest point in the channel in the river (figure 2).

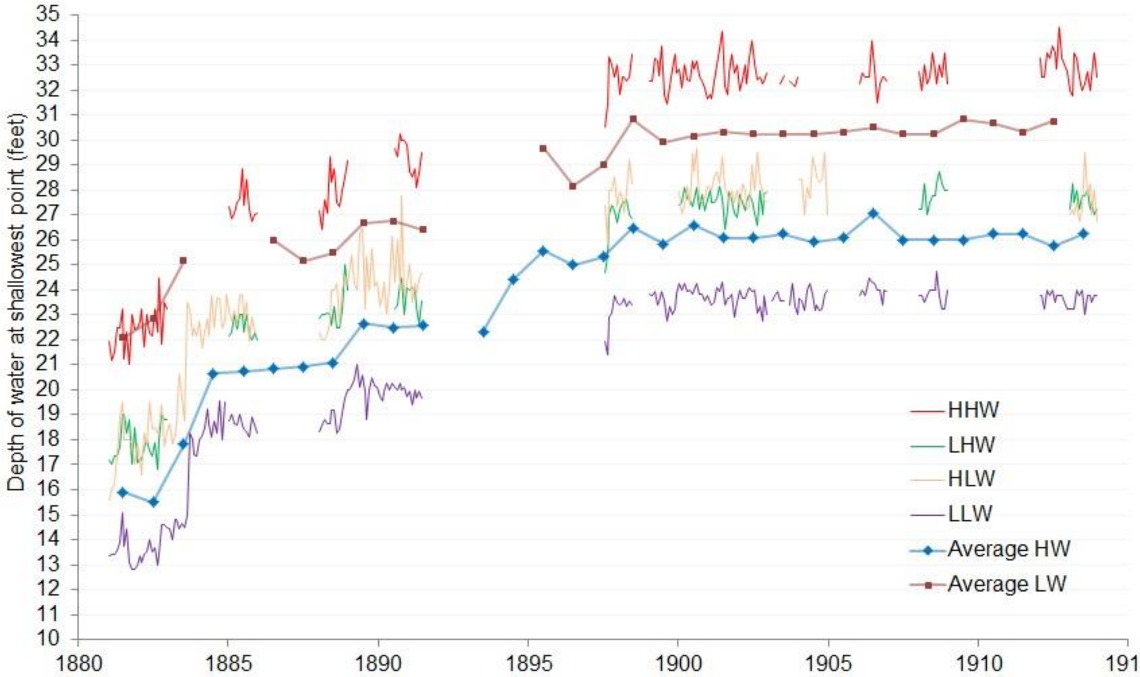

Figure 2: Monthly and annual channel depths reported by the Semaphore tide station 1881 to 1914

The readings from the tide gauge were offset by this depth (relative to Low Water Spring Tides datum) in the Marine Board annual reports. This was for navigation and keel clearance purposes, and as the channel was dredged deeper several times during the observation period to accommodate ever larger vessels, knowledge of the steps in assumed channel depth (and the times that these depths were changed for recording purposes) relative to low water is also required in order to correctly reduce these observations to a consistent datum (eg "The Register" 1910). The precision of monthly averages is given to the nearest imperial inch (25.4mm), although combining HHW, HLW, LHW, and LLW and using annual averaging will increase this precision by a factor of around three or four. The previous data from 1882 to 1902 from the inner harbour bridges the main period of dredging activity from start to finish and allows cross checking and reduction of this data to a common datum. This allows monthly and annual Half Tide Level data from 1881 and from 1902 to 1914 to be added to the Port Adelaide time series. It is fortuitous that these years were outside the main channel deepening operations. Similar old data is available for Port Augusta and Port Pirie. Other changes associated with the Inner Harbour involved using the more permanent “iron rail” benchmark at the Glanville Docks from 1921 (Anon 1922) which still exists (TGZ is 12.73 feet below this BM, originally referred to as DMH BM1), and the official Australia wide datum changes from local LW (Low Water) to AHD (Australian Height Datum, approximate MSL) in 1971 and then LAT in 2001. The offset metric PSMSL values for 1933 to 1940 appear to give anomalously low values which are not apparent in the data for the inner harbour from DMH (Wynne et al 1984). These low values, if included, would increase the overall sea level acceleration values. In this study the DMH observations are used. The final acceleration value is still slightly outside the error limits of the global average (0.01 ± 0.008 mm/yr^2), and this is consistent with possible contribution from groundwater extraction in recent decades.

Subsidence due to water extraction has certainly been observed in Northern parts of Adelaide. This subsidence may extend far enough to influence the Port Adelaide tide gauges (Belperio 1993, King 2008), although the situation and geology, and actual aquifer recharge rates near the port area are complex (Lamontagne 2005). Third order re-levelling in 1969 gave estimates of around -1.8mm/yr relative land motion in the Port Adelaide area (Culver 1970) based on the differentials between an 1880 survey of the old EWS (Engineering and Water Supply) department benchmarks and the 1969 elevations. More accurate repeat levelling work in the 1980s and 1990s has confirmed and refined the estimates of relative subsidence in the North Plain area where industrial scale water extraction is ongoing, but as yet no information has been found about further studies at the tide gauge sites. The earliest EWS cast iron benchmarks, set after 1872, were marked with height in feet above EWS low water datum of the time. Some of these still exist. A brief examination of three of these could be interpreted as settling in the vicinity of Glenelg relative to Central Adelaide at a rate around 1mm/yr, although the stability of the benchmarks over this period should be considered (Filmer et al 2007), and individual variations were noted in the report by Culver, which used 42 benchmarks in total.

Bench Mark		**EWS (ft) 1872/1879**	**LAT (ft) 1999/*2005**	**Difference mm**
BM10	Near E. and S. Terraces	170.76	169.71	318.6
BM9	Victoria Square	153.70	152.84	260.8
BM29	Glenelg	17.25	*16.81	134.8

Table 1: Original and modern elevations of three old EWS benchmarks in Adelaide, from which relative vertical motion can be estimated assuming original levelling errors are low. BM29 appears to have moved downwards relative to BM9 by approx. (261-135mm)/120 years =1mm/yr

It is also possible that there is slight upwards tectonic motion or tilting up towards the Adelaide foothills, including the locality chosen as the “stable” reference point of the re-levelling work near the Hope Valley reservoir. To determine whether the tide gauge is subsiding, or the foothills are rising, we need absolute geocentric estimates of movement from CGPS (Continuous Global Positioning System) over several years. The CGPS station near Elizabeth in Adelaide is around 20km from the tide gauges, but closer to the centre of the cone of depression in the water table, and gives a land subsidence rate of -1.266 ± 0.2 mm/yr over approximately 11 years, starting 1999. The reprocessed

ULR5 solution gives -0.95 ± 0.29 mm/yr over the same period (Santa Maria Gomez et al 2012). The CORS CGPS sites in central Adelaide and at Port Stanvac give vertical motion of 0.6mm/yr (4.5 years record) and -0.1 mm/yr (four years record) respectively, but these time periods are short, so these rates should be regarded as indicative only. However, whilst an analysis of differences in tide gauge data between the outer Harbour and either Port Victor or Port Lincoln between 1965 and 1995 do reveal interannual variations, no significant secular trends are apparent that could be attributed to longer term relative differences in land motion. At Port Stanvac, which is considerably closer to the Adelaide tide gauges, but where only 20 years of overlapping data are available, the differential values do suggest a difference in relative SLR (most likely due to relative land subsidence) of around 1mm/yr at the Outer Harbour. Comparing with Port Pirie, where 50 years of overlapping data are available, the trend difference is around +3mm/yr, which is consistent with the tectonic uplift and tilting towards Port Augusta at the head of the bay reported in geological studies of the area. As yet there are not enough long term records from CGPS stations that could help fully clarify the situation, and we must rely on the tide gauge, benchmark and levelling information. These suggest a long term (centennial) SLR of around 1.5mm/yr at Port Adelaide, in line with global estimates, and an acceleration value slightly higher than the global average, any small difference possibly due to localised subsidence in recent decades.

Fremantle

The long record from Fremantle on the West Coast of Australia was also used in the overall global analysis. There is significant and variable recorded subsidence in nearby urban areas over past decades due to ground water extraction (Belperio 1993) as measured using bench marks and levelling. The rate of extraction and water table measurements correlate with subsidence rates as measured directly by CGPS (Featherstone 2012), and the long (14 yr) GPS record (TIGA ULR5) gives -2.99 ± 0.39 mm/yr although this station is not co-located with the gauge. Whilst increased subsidence at the tide gauge would have the effect of increasing the rate of Relative Sea Level rise, the Fremantle gauge is slightly outside the probable radius of influence of subsidence, and is situated on bedrock. Feng (2004) also links the multidecadal variations in the Fremantle tide gauge data to phases of the SOI, and this would help explain the relatively low average rate of sea level rise in the second half of the 20th Century at this location. The recent decade has seen acceleration in SLR to values much higher than the global average, which is probably linked to a change in phase of SOI. If this is the case, then this excess rise is a regional effect which is temporary at multi-decadal timescales. The ongoing water extraction rate is certainly implicated in the higher relative rise at the Hillary gauge (Burgette 2013), much closer to the GPS station.

Summary of results

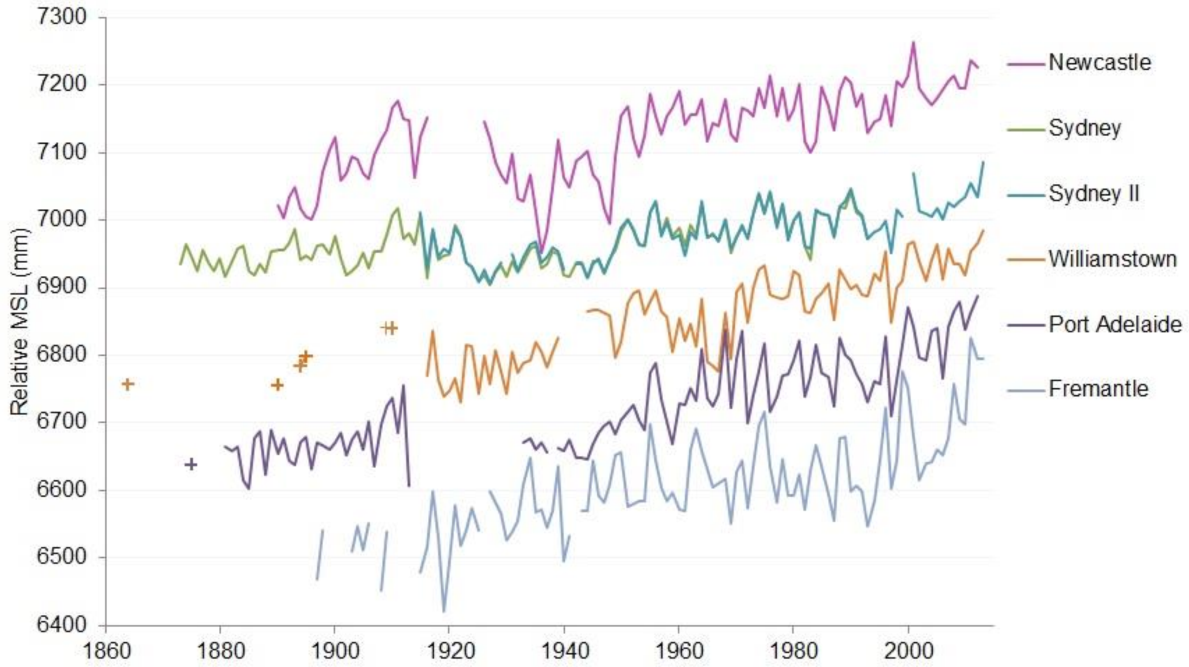

Figure 3: Annual MSL time series from five Australian ports showing extended data at four locations. Time series have been offset for clarity.

Other regional data: New Zealand

PSMSL data with the corrections, extensions and updates as suggested by Hannah (2010, 2012) from the four longest tide gauge series in New Zealand was also used, these were further updated as far as possible to 2013 (figure 4), and checked against results of Cole (2011). The work of Hannah in terms of data recovery is comprehensive, and only very sparse additional documentary evidence leading to one or two years of time series extension has been found to date. Recent attempts have been made to correct the trends with vertical land motion from altimetry and CGPS (Fadil et al 2013, Tenzer et al 2014), however in figure 3 no vertical land motion corrections are applied. The early data 1891 to 1893 from Wellington is not used in deriving acceleration for this station as the datum information is unclear.

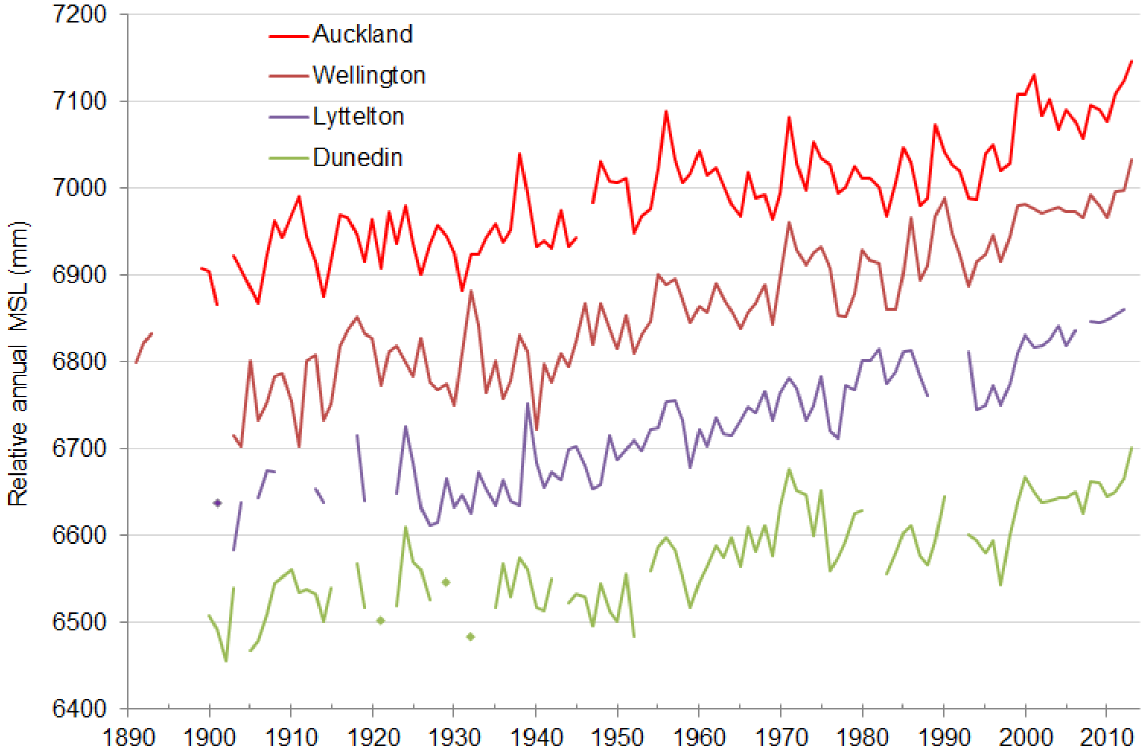

Figure 4: MSL data from four centennial scale records in New Zealand (after Hannah 2012). Vertical offsets have been added for clarity.

Other regional data: Tasmania

Recorded tide data from Tasmania goes back to at least 1822 (Brisbane 1825), but early records were simply times and heights of high water, without benchmark information. The modern tide data at Port Arthur in Tasmania has been connected to old data that does have a benchmark from 1840 (Shortt 1889, Hunter et al 2003) which resulted in a positive SLR trend estimate of order 1mm/yr since 1840. It is noted that this trend derived from the reconstructed time series is more consistent with the extended time series shown in figure 3 than with the alternative hypothesis of a static or falling sea level over this period. If acceleration of SLR during the 20th Century has indeed occurred then we would expect a linear trend since 1840 defined by sparse end point data to be somewhat less than linear trends derived from a nearby series running from the late 19th Century. This can be investigated by examining the Port Arthur and Hobart data and comparing with extended Australian tide gauge data from nearest locations with long records (Williamstown and Port Adelaide). In this case absolute trends are important in order to derive and compare the relative rates of sea level rise, so the time series have been corrected where possible with relative vertical land motion estimates from CGPS (figure 5).

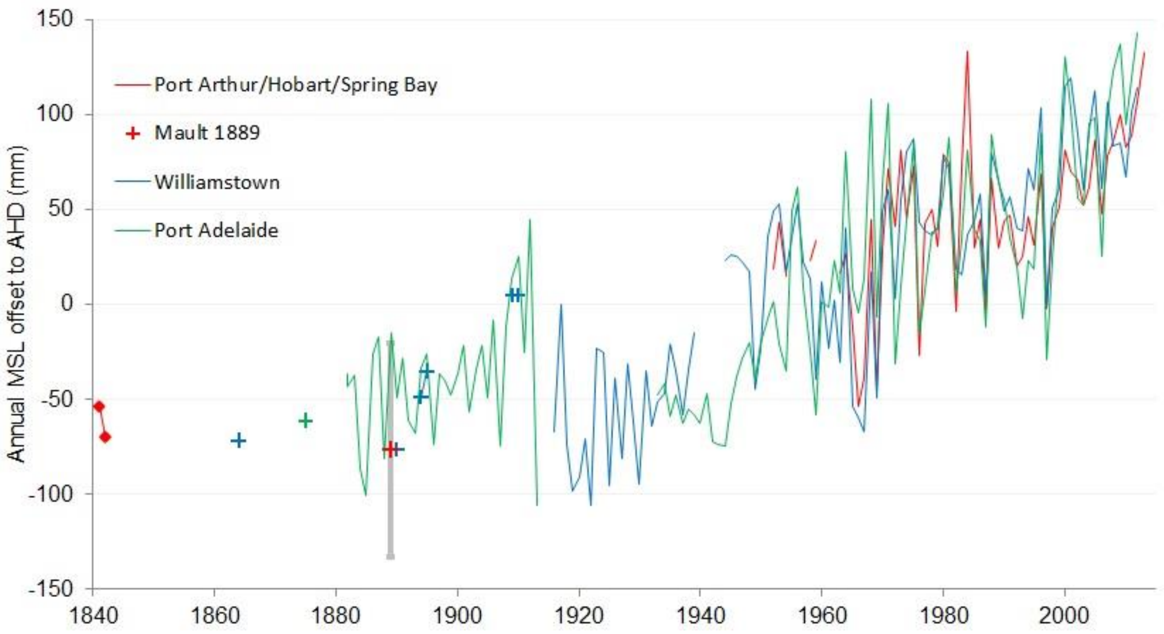

Figure 5: Annual tide gauge time series from Port Arthur, Tasmania (composite using data from Hunter 2003, Mault 1889, PSMSL data from Hobart and Spring Bay), extended Williamstown data, and extended Port Adelaide data. All data has been corrected for vertical land motion relative to the Hobart CGPS vertical motion trend value using nearby CGPS stations (NASA series). Estimated vertical offsets from least squares analysis of data from 1980 onwards, are applied to each overall series to align vertical datums approximately to AHD (Australian Height Datum), Tasmania, 1983.

Confidence in the approach and datum offset estimates can be further increased by comparing the extended time series with other time series where datums and bench-marks have remained relatively consistent over the measurement period, as in Sydney (figure 6). The results in this case appear to further validate the Port Arthur reconstruction as well as the extended data. Hunter (2008) additionally refers to MSL data from Hobart (Mault 1889), which has a known benchmark elevation. This allows reduction of this reported mean MSL value (from February 4th to March 6th 1889) to -120mm relative to the modern AHD (Tasmania). As February is the month with the lowest MSL in the annual cycle at Hobart, it is reasonable to attempt to correct this 1889 value for seasonal bias using an averaged seasonal cycle derived from stacked data of monthly variations from annual averages (figure 7) using the entire length of the available record from Hobart after outliers are removed. This adds an estimated correction of +43mm. This adjusted result is consistent with the other data sets (figure 5 & 6). Comparing figures 5 and 6 the decadal scale similarities between these regional time series are noteworthy. The MSL peak centred around 1910 and the lower values or dip centred around 1930 in the Sydney data appear to be independently corroborated by data from the other regional tide gauges, and therefore representative of region wide changes in sea level. It is interesting to compare this with Northern Hemisphere tide gauge data.

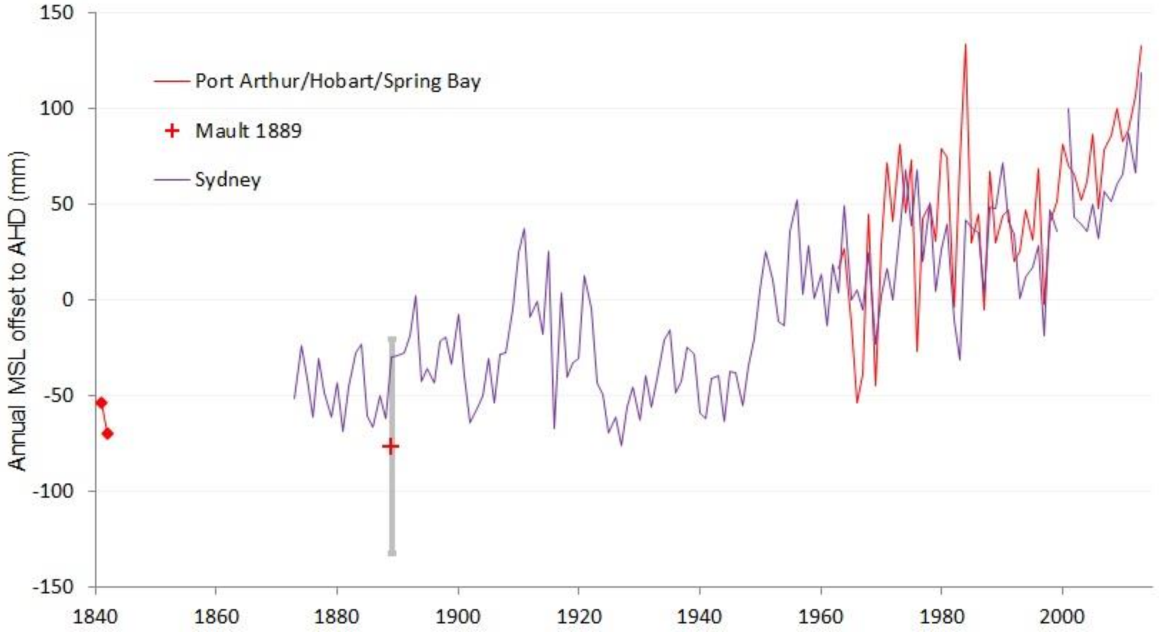

Figure 6: Port Arthurand Hobart composite series compared with Sydney extended data. The similarities with figure 4 give confidence in the datum connections in these data sets.

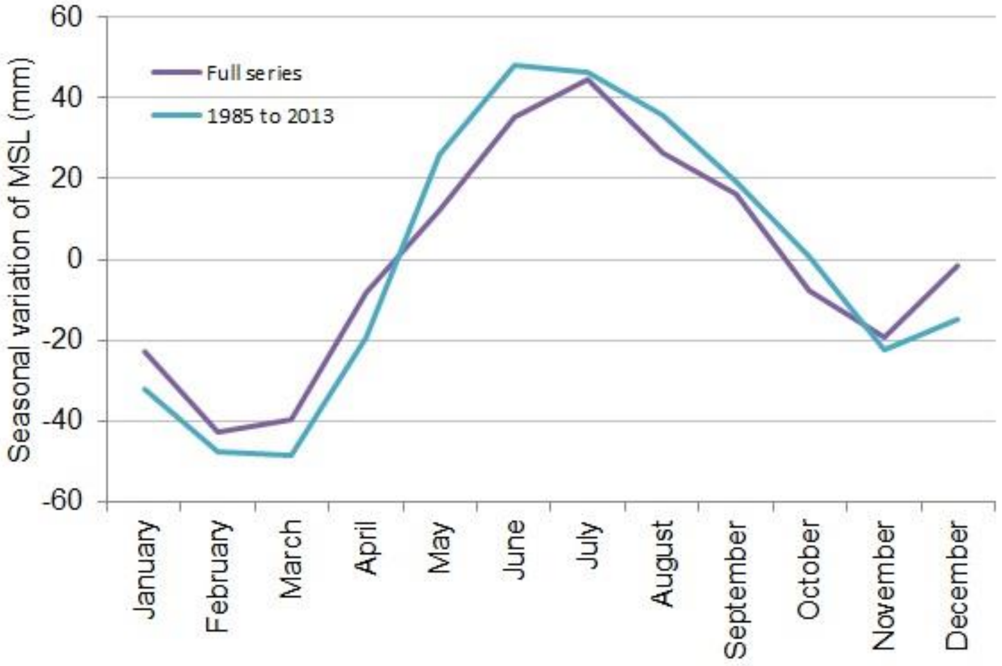

Figure 7: Seasonal variation in MSL averaged over arbitrary periods for Hobart referenced to mean annual value.

Acceleration values for the extended data series is shown in table 2. It is not suggested that a quadratic fit is a suitable or appropriate model for sea level acceleration (especially when gaps exist in the records), but it allows a convenient comparison with previous results.

Conclusion

The extended Australian data series show some common large scale multi-decadal features which are not readily apparent in the un-extended data. The data also shows differences between individual time series and high annual and inter-annual variability which would clearly affect trend analysis using shorter time series. These long term patterns are also evident in the four long time series from New Zealand (figure 4). As can be seen from table 2 there is also evidence of convergent acceleration values of order 0.012mm/yr^2 using all regional time series of centennial scale or longer. This is consistent with larger scale or global estimates of acceleration of order 0.01mm/yr2 reported in a recent global study (Hogarth 2014) using extended data series and previous results from mainly Northern Hemisphere tide gauges using long time series extending into the 19th Century.

Acknowledgements:

Bench mark data in Adelaide area extracted in early 2014 from http://maps.sa.gov.au/plb/

CGPS: CORS station data (2014) from http://192.104.43.25/status/solutions/analysis.html

CGPS: from NASA JPL http://sideshow.jpl.nasa.gov/post/tables/GPS_Time_Series.pdf

CGPS at tide gauge sites (ULR5) http://www.sonel.org/-GPS-.html

Monthly and Annual RLR and Metric MSL data from http://www.psmsl.org/

Other links:

Map of Port Adelaide River 1884
http://digital.slv.vic.gov.au/view/action/nmets.do?DOCCHOICE=450935.xml&dvs=1405432876110

Map of Hobson’s Bay River 1865 showing LWST datum (Captain Cox 1864)
http://digital.slv.vic.gov.au/dtl_publish/simpleimages/14/999503.html

Tide station	mm/yr^2	Sources
SYDNEY, FORT DENISON	0.0130	Russell 1885 and composite of both PSMSL Sydney series
WILLIAMSTOWN	0.0141	Ellery 1880 and metric PSMSL data, (buddy checked)
FREMANTLE	0.0072	As original PSMSL some gaps filled with UHSLC hourly data
DUNEDIN	0.0128	Composite with Dunedin II, Hannah and updated to 2013
AUCKLAND	0.0099	Hannah and updated to 2013
WELLINGTON HARBOUR	0.0142	Hannah and updated to 2013 (1891 to 1893 not used)
PORT ADELAIDE	0.0216	Chapman and Inglis 1902 and Proc Parliament SA 1888 – 1915
NEWCASTLE	0.0125	Russell 1893 to 1904 and Coghlan 1914 and 1917
LYTTELTON	0.0181	Hannah 2012 and updated to 2012
PORT ARTHUR/HOBART	0.0118	Hunter 2003, Mault 1889, updated using nearby PSMSL data

Table 2 showing preliminary results of quadratic fits to 9 Australian and New Zealand time series greater than 100yrs length with 70% completeness. The additional estimate for Port Arthur is also shown although based on sparse available data.

Year	Sydney		Port Adelaide		Newcastle		Williamstown
	mm		mm		mm		mm
1864							406.9
1865							
1866							
1867							
1868							
1869							
1870							
1871							
1872							
1873	6935.46						
1874	6963.40						
1875	6945.62		6788.53				
1876	6925.30						
1877	6955.78						
1878	6938.00						
1879	6925.30						
1880	6943.08						
1881	6917.68						
1882	6940.54		6810.67				
1883	6958.32		6816.26				
1884	6962.13		6767.76				
1885	6925.00		6753.92				
1886	6919.00		6829.09				
1887	6935.00		6838.17				
1888	6923.00		6774.09				
1889	6955.00		6840.59				
1890	6956.00		6806.67		6871.20		406.3
1891	6957.00		6828.26		6853.42		
1892	6966.00		6795.85		6871.20		
1893	6987.00		6789.09		6899.14		
1894	6942.00		6823.61		6868.66		434.5
1895	6948.00		6831.31		6944.86		448.3
1896	6941.00		6784.09		6850.88		
1897	6962.00		6821.63		6871.20		
1898	6964.00		6818.25		6922.00		
1899	6950.00		6811.32		6955.02		
1900	6976.00		6822.49		6972.80		
1901	6944.00		6838.06		6909.30		
1902	6919.00		6803.65		6919.46		

Year	Sydney		Port Adelaide		Newcastle		Williamstown
	mm		mm		mm		mm
1903	6925.00		6844.87		6944.86		
1904	6933.00		6857.57		6939.78		
1905	6952.00		6825.82		6919.46		
1906	6929.00		6856.94		6911.84		
1907	6954.00		6800.42		6947.40		
1908	6955.00		6853.76		6970.26		
1909	6978.00		6889.32		6982.96		490.7
1910	7007.00		6902.02		7015.98		490.7
1911	7019.00		6851.22		7026.14		
1912	6973.00		6911.97		7000.74		
1913	6981.00		6776.61		6998.20		
1914	6964.00				6914.38		
1915	7007.00				6972.80		
1916	6914.00				7003.28		419.4
1917	6985.00						486.8
1918	6941.00						413.4
1919	6948.00						388.7
1920	6950.00						396.8
1921	6993.00						417.1
1922	6976.00						381.8
1923	6937.00						464.8
1924	6931.00						463.0
1925	6911.00						392.8
1926	6919.00				6996.00		449.5
1927	6904.00				6972.00		407.0
1928	6924.00				6937.00		457.3
1929	6934.00				6918.00		427.0
1930	6917.00				6906.00		394.0
1931	6940.00				6948.00		454.3
1932	6923.00				6883.00		425.1
1933	6938.00		6820.50		6879.00		438.3
1934	6958.00		6827.00		6917.00		442.6
1935	6963.00		6810.42		6861.00		469.2
1936	6930.00		6721.33		6801.00		455.3
1937	6936.00		6806.92		6834.00		432.2
1938	6954.00				6899.00		455.8
1939	6950.00				6970.00		475.6
1940	6919.00				6914.00		
1941	6916.00				6899.00		
1942	6937.00				6939.00		
1943	6938.00		6837.42		6945.00		
1944	6914.00		6863.08		6953.00		514.7
1945	6940.00		6820.00		6917.00		517.8
1946	6939.00		6835.00		6907.00		516.9
1947	6922.00		6845.00		6868.00		514.1
1948	6943.00		6853.00		6845.00		508.8
1949	6957.00		6834.00		6945.00		447.5
1950	6982.00		6854.00		7005.00		469.3
1951	7002.00		6867.00		7018.00		528.3
1952	6987.00		6876.00		6971.00		541.6
1953	6965.00		6854.00		6944.00		545.6
1954	6963.00		6840.00		6976.00		510.3
1955	7012.00		6925.00		7037.00		529.1
1956	7028.00		6938.00		7005.00		546.4
1957	6979.00		6885.00		6978.00		515.6
1958	7004.00		6852.00		7005.00		506.7
1959	6976.00		6819.00		7016.00		454.4
1960	6989.00		6879.00		7042.00		505.5
1961	6962.00		6876.00		6992.00		471.2
1962	6994.00		6901.00		7006.00		496.2
1963	6979.00		6884.00		7007.00		463.5
1964	7024.00		6959.00		7030.00		534.4

Year	Sydney		Port Adelaide		Newcastle		Williamstown
	mm		mm		mm		mm
1965	6975.00		6887.00		6967.00		440.8
1966	6980.00		6875.00		6994.00		435.3
1967	6969.00		6893.00		6990.00		427.4
1968	6999.00		6988.00		7030.00		512.3
1969	6951.00		6873.00		6978.00		446.0
1970	6976.00		6944.00		6967.00		544.7
1971	6990.00		6987.00		7016.00		556.3
1972	6974.00		6850.00		7013.00		498.3
1973	7010.00		6891.00		7005.00		551.3
1974	7041.00		6926.00		7046.00		576.3
1975	7012.00		6967.00		7016.00		583.2
1976	7041.00		6867.00		7065.00		539.3
1977	6993.00		6890.00		7004.00		535.2
1978	7024.00		6921.00		7046.00		533.3
1979	6977.00		6923.00		6998.00		537.9
1980	6999.00		6942.00		7014.00		574.8
1981	7012.00		6972.00		7051.00		568.8
1982	6962.00		6890.00		6967.00		516.1
1983	6941.00		6919.00		6951.00		512.8
1984	7014.00		6966.00		6967.00		534.2
1985	7010.00		6925.00		7047.00		541.7
1986	7007.00		6919.00		7019.00		556.3
1987	6975.00		6874.00		6983.00		502.1
1988	7020.00		6976.00		7042.00		578.2
1989	7019.00		6951.00		7063.00		563.7
1990	7043.00		6942.00		7053.00		547.8
1991	7012.00		6922.00		7018.00		555.2
1992	7005.00		6908.00		7038.00		539.0
1993	6972.00		6880.00		6980.00		537.6
1994	6983.00		6911.00		6996.00		570.7
1995	6988.00		6907.00		7001.00		560.0
1996	6999.00		6979.00		7035.00		603.3
1997	6952.00		6860.00		6989.00		497.8
1998	7017.00		6913.00		7057.00		550.8
1999	7006.00		6966.00		7048.00		561.1
2000			7021.00		7064.00		614.7
2001	7070.00		6993.00		7114.00		619.3
2002	7013.00		6947.00		7045.00		590.3
2003	7009.00		6943.00		7031.00		561.1
2004	7005.00		6987.00		7020.00		592.6
2005	7019.00		6990.00		7031.00		613.4
2006	7001.00		6917.00		7043.00		562.0
2007	7026.00		6993.00		7057.00		607.9
2008	7020.00		7016.00		7065.00		585.1
2009	7029.00		7030.00		7045.00		586.3
2010	7034.00		6988.00		7046.00		568.8
2011	7056.00		7013.00		7086.00		603.1
2012	7035.00		7037.00		7076.00		615.9
2013	7087.00						634.3

Table 3: Extended data sets for four Australian ports, historical composite data is adjusted by offsetting to arbitrary station PSMSL RLR datum where available, or retained as metric values (Williamstown) where RLR factor is unavailable. Data in colour is extended or composite data outside of the PSMSL annual time series.

Year	feet	inches	feet	mm	mm RLR	Year	feet	inches	feet	mm	mm RLR
1890.042	2	4.2	2.350	716.3	6749.3	**1895.042**	2	11.1	2.925	891.5	6924.5
1890.125	2	8.3	2.692	820.4	6853.4	**1895.125**	3	1.1	3.092	942.3	6975.3
1890.208	2	11	2.917	889.0	6922.0	**1895.208**	2	11.1	2.925	891.5	6924.5
1890.292						**1895.292**	2	10.4	2.867	873.8	6906.8
1890.375						**1895.375**	2	11.9	2.992	911.9	6944.9
1890.458						**1895.458**	3	0.8	3.067	934.7	6967.7
1890.542						**1895.542**	2	10.4	2.867	873.8	6906.8
1890.625						**1895.625**	2	8.2	2.683	817.9	6850.9
1890.708						**1895.708**	2	10.4	2.867	873.8	6906.8
1890.792						**1895.792**	3	0.1	3.008	916.9	6949.9
1890.875						**1895.875**	3	1.5	3.125	952.5	6985.5
1890.958						**1895.958**	3	4.4	3.367	1026.2	7059.2
1891.042	2	7.6	2.633	802.6	6835.6	**1896.042**	2	9.4	2.783	848.4	6881.4
1891.125	2	7.3	2.608	795.0	6828.0	**1896.125**	2	7.3	2.608	795.0	6828.0
1891.208	2	8.8	2.733	833.1	6866.1	**1896.208**	2	10.4	2.867	873.8	6906.8
1891.292	2	7.7	2.642	805.2	6838.2	**1896.292**					
1891.375	2	5.8	2.483	756.9	6789.9	**1896.375**					
1891.458	3	2.1	3.175	967.7	7000.7	**1896.458**					
1891.542	2	10.6	2.883	878.8	6911.8	**1896.542**					
1891.625	2	7.7	2.642	805.2	6838.2	**1896.625**					
1891.708	2	8.3	2.692	820.4	6853.4	**1896.708**					
1891.792	2	5.6	2.467	751.8	6784.8	**1896.792**					
1891.875	2	6.2	2.517	767.1	6800.1	**1896.875**					
1891.958	2	9.5	2.792	850.9	6883.9	**1896.958**					
1892.042						**1897.042**	2	11.6	2.967	904.2	6937.2
1892.125						**1897.125**	2	6.7	2.558	779.8	6812.8
1892.208						**1897.208**	2	10.9	2.908	886.5	6919.5
1892.292	3	2.8	3.233	985.5	7018.5	**1897.292**	2	10.4	2.867	873.8	6906.8
1892.375	2	9.2	2.767	843.3	6876.3	**1897.375**	2	8.6	2.717	828.0	6861.0
1892.458	3	0.1	3.008	916.9	6949.9	**1897.458**	2	6.7	2.558	779.8	6812.8
1892.542	2	7.4	2.617	797.6	6830.6	**1897.542**	2	10.7	2.892	881.4	6914.4
1892.625	2	8.3	2.692	820.4	6853.4	**1897.625**	2	8.8	2.733	833.1	6866.1
1892.708	2	8.6	2.717	828.0	6861.0	**1897.708**	2	7.7	2.642	805.2	6838.2
1892.792	2	7.5	2.625	800.1	6833.1	**1897.792**	2	8.3	2.692	820.4	6853.4
1892.875	2	9.2	2.767	843.3	6876.3	**1897.875**	2	9	2.750	838.2	6871.2
1892.958	2	11.2	2.933	894.1	6927.1	**1897.958**	2	8.8	2.733	833.1	6866.1
1893.042	3	0	3.000	914.4	6947.4	**1898.042**					
1893.125	3	0.4	3.033	924.6	6957.6	**1898.125**					
1893.208	3	0.4	3.033	924.6	6957.6	**1898.208**	2	10.7	2.892	881.4	6914.4
1893.292	3	0.7	3.058	932.2	6965.2	**1898.292**	2	11.7	2.975	906.8	6939.8
1893.375	3	0	3.000	914.4	6947.4	**1898.375**	3	3.7	3.308	1008.4	7041.4
1893.458	2	10.5	2.875	876.3	6909.3	**1898.458**	3	0.1	3.008	916.9	6949.9
1893.542	2	10.2	2.850	868.7	6901.7	**1898.542**	2	11.8	2.983	909.3	6942.3
1893.625	2	7.7	2.642	805.2	6838.2	**1898.625**	2	6.9	2.575	784.9	6817.9
1893.708	2	6.8	2.567	782.3	6815.3	**1898.708**	2	11.3	2.942	896.6	6929.6
1893.792	2	7.2	2.600	792.5	6825.5	**1898.792**	2	9.9	2.825	861.1	6894.1
1893.875	2	7.8	2.650	807.7	6840.7	**1898.875**	3	0.8	3.067	934.7	6967.7
1893.958	2	9.1	2.758	840.7	6873.7	**1898.958**	2	10.3	2.858	871.2	6904.2
1894.042	2	6.5	2.542	774.7	6807.7	**1899.042**	3	1	3.083	939.8	6972.8
1894.125	2	7	2.583	787.4	6820.4	**1899.125**	2	8.3	2.692	820.4	6853.4
1894.208	2	11.2	2.933	894.1	6927.1	**1899.208**	2	10.4	2.867	873.8	6906.8
1894.292	2	7.8	2.650	807.7	6840.7	**1899.292**	3	3.3	3.275	998.2	7031.2
1894.375	3	0.6	3.050	929.6	6962.6	**1899.375**	3	2.9	3.242	988.1	7021.1
1894.458	2	11	2.917	889.0	6922.0	**1899.458**	3	1.1	3.092	942.3	6975.3
1894.542	2	10.3	2.858	871.2	6904.2	**1899.542**	2	11.9	2.992	911.9	6944.9
1894.625	2	8.6	2.717	828.0	6861.0	**1899.625**	3	2.1	3.175	967.7	7000.7
1894.708	2	6.7	2.558	779.8	6812.8	**1899.708**	2	9.8	2.817	858.5	6891.5
1894.792	2	6.2	2.517	767.1	6800.1	**1899.792**	2	11.8	2.983	909.3	6942.3
1894.875	2	10.9	2.908	886.5	6919.5	**1899.875**	3	0	3.000	914.4	6947.4
1894.958	2	7.6	2.633	802.6	6835.6	**1899.958**	3	0.5	3.042	927.1	6960.1

Table 4: Monthly MSL data from Newcastle NSW, in the original feet and inches, decimal feet, mm and RLR converted values using zero datum 14 feet below benchmark BM1 at the Customs House. Continued overleaf.

Year	feet	inches	feet	mm	mm RLR
1900.042	2	10	2.833	863.6	6896.6
1900.125	2	10.6	2.883	878.8	6911.8
1900.208					
1900.292					
1900.375					
1900.458					
1900.542					
1900.625					
1900.708					
1900.792					
1900.875					
1900.958	2	10.2	2.850	868.7	6901.7
1901.042	2	11.9	2.992	911.9	6944.9
1901.125	2	9.6	2.800	853.4	6886.4
1901.208	2	9.8	2.817	858.5	6891.5
1901.292	3	2	3.167	965.2	6998.2
1901.375	2	11.5	2.958	901.7	6934.7
1901.458	3	2.3	3.192	972.8	7005.8
1901.542	2	11	2.917	889.0	6922.0
1901.625	2	8.3	2.692	820.4	6853.4
1901.708	2	8.2	2.683	817.9	6850.9
1901.792	2	9.6	2.800	853.4	6886.4
1901.875	2	7.1	2.592	789.9	6822.9
1901.958	2	11	2.917	889.0	6922.0
1902.042	3	0.5	3.042	927.1	6960.1
1902.125	2	11.9	2.992	911.9	6944.9
1902.208	3	0.1	3.008	916.9	6949.9
1902.292	3	0.5	3.042	927.1	6960.1
1902.375	2	10.7	2.892	881.4	6914.4
1902.458	2	10.7	2.892	881.4	6914.4
1902.542	2	10.6	2.883	878.8	6911.8
1902.625	2	8.6	2.717	828.0	6861.0
1902.708	2	11.3	2.942	896.6	6929.6
1902.792	2	9.7	2.808	856.0	6889.0
1902.875	2	8.5	2.708	825.5	6858.5
1902.958	2	11.1	2.925	891.5	6924.5

Table 4 continued: Monthly MSL data from Newcastle NSW (Russell 1893-1904) in the original feet and inches, as well as decimal feet, mm and RLR converted values using zero datum 14 feet below benchmark BM1 at the Customs House

Year	feet	inches	feet	mm
1900.042	-	-	-	-
1900.125	-	-	-	-
1900.208	-	-	-	-
1900.292	-	-	-	-
1900.375	-	-	-	-
1900.458	-	-	-	-
1900.542	2	5.0	2.417	736.6
1900.625	2	3.3	2.275	693.4
1900.708	1	11.9	1.992	607.1
1900.792	1	10.6	1.883	574.0
1900.875	1	6.2	1.517	462.3
1900.958	1	10.9	1.908	581.7
1901.042	2	0.4	2.033	619.8
1901.125	1	10.8	1.900	579.1
1901.208	2	0.3	2.025	617.2
1901.292	2	2.8	2.233	680.7
1901.375	2	3.1	2.258	688.3
1901.458	2	5.4	2.450	746.8
1901.542	2	3.6	2.300	701.0
1901.625	1	11.7	1.975	602.0
1901.708	1	8.6	1.717	523.2
1901.792	1	11.4	1.950	594.4
1901.875	1	6.1	1.508	459.7
1901.958	2	1.5	2.125	647.7
1902.042	2	2.6	2.217	675.6
1902.125	2	3.4	2.283	696.0
1902.208	2	0.4	2.033	619.8
1902.292	2	5.4	2.450	746.8
1902.375	2	2.9	2.242	683.3
1902.458	1	9.8	1.817	553.7
1902.542	1	8.4	1.700	518.2
1902.625	1	10.0	1.833	558.8
1902.708	1	11.1	1.925	586.7
1902.792	1	8.7	1.725	525.8
1902.875	1	7.4	1.617	492.8
1902.958	1	9.7	1.808	551.2

Table 5: Monthly MSL data from Yamba NSW, (Russell 1901-1904). Gauge installed June 1900

Year	feet	inches	feet	mm	mm RLR
1890	2	9.0	2.750	838.2	6871.2
1891	2	8.3	2.692	820.4	6853.4
1892	2	9.5	2.792	850.9	6883.9
1893	2	10.1	2.842	866.1	6899.1
1894	2	8.9	2.742	835.7	6868.7
1895	2	*11.9/8.4	*2.982/2.700	823.0	6856.0
1896	2	8.2	2.683	817.9	6850.9
1897	2	9.0	2.750	838.2	6871.2
1898	2	11.0	2.917	889.0	6922.0
1899	3	0.3	3.025	922.0	6955.0
1900	3	1.0	3.083	939.8	6972.8
1901	2	10.5	2.875	876.3	6909.3
1902	2	10.9	2.908	886.5	6919.5
1903	2	11.9	2.992	911.9	6944.9
1904	2	11.7	2.975	906.8	6939.8
1905	2	10.9	2.908	886.5	6919.5
1906	2	10.6	2.883	878.8	6911.8
1907	3	0.0	3.000	914.4	6947.4
1908	3	0.9	3.075	937.3	6970.3
1909	3	1.4	3.117	950.0	6983.0
1910	3	2.7	3.225	983.0	7016.0
1911	3	3.1	3.258	993.1	7026.1
1912	3	2.1	3.175	967.7	7000.7
1913	3	2.0	3.167	965.2	6998.2
1914	2	10.7	2.892	881.4	6914.4
1915	3	1.0	3.083	939.8	6972.8
1916	3	2.2	3.183	970.3	7003.3

** Data in red as in original 1895 observations and reported in Coghlan, values in black are corrected for gauge stretched chain (Russell 1897). Data from newer gauge used from 1896 onwards in both sources.*

Table 6: Annual MSL data from Newcastle NSW (from Coghlan 1913, 1917)

Year	feet	inches	LW ft	feet	inches	HW ft	HTL ft	HTL mm
1900.042	0	0	**0.000**	9	8	**9.667**	4.833	1473.2
1900.125	0	3	**0.250**	8	6	**8.500**	4.375	1333.5
1900.208	0	3	**0.250**	10	6	**10.500**	5.375	1638.3
1900.292	0	1	**0.083**	10	6	**10.500**	5.292	1612.9
1900.375	0	0	**0.000**	9	3	**9.250**	4.625	1409.7
1900.458	0	4	**0.333**	9	10	**9.833**	5.083	1549.4
1900.542	0	4	**0.333**	9	9	**9.750**	5.042	1536.7
1900.625	0	4	**0.333**	10	6	**10.500**	5.417	1651.0
1900.708	0	8	**0.667**	9	0	**9.000**	4.833	1473.2
1900.792	0	8	**0.667**	8	10	**8.833**	4.750	1447.8
1900.875	0	3	**0.250**	8	4	**8.333**	4.292	1308.1
1900.958	0	0	**0.000**	8	6	**8.500**	4.250	1295.4

Table 7: Monthly HHW and LLW observations for Port Adelaide in 1900, (from Proceedings of the Parliament of South Australia, 1902)

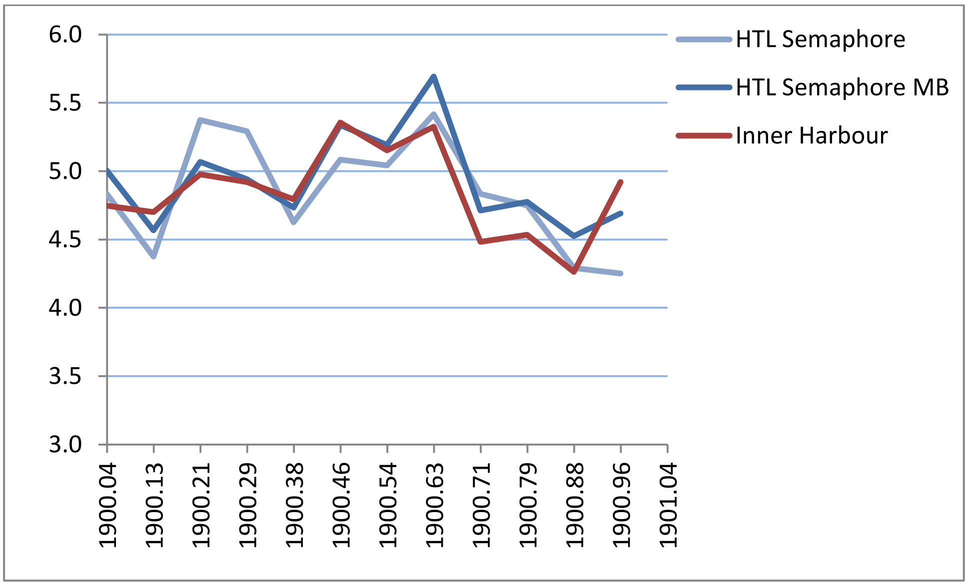

Figure 8: Offset corrected MSL and HTL values for Port Adelaide from sources in text

Year	feet	mm	Year	feet	mm	Year	feet	mm	Year	feet	mm	Year	feet	mm
1882.042	4.209	1283	**1887.042**	4.918	1499	**1892.042**	3.743	1141	**1897.042**	3.928	1197	**1902.042**	4.821	1469
1882.125	3.704	1129	**1887.125**	3.780	1152	**1892.125**	4.824	1470	**1897.125**	4.010	1222	**1902.125**	4.399	1341
1882.208	3.983	1214	**1887.208**	4.357	1328	**1892.208**	4.196	1279	**1897.208**	4.427	1349	**1902.208**	4.361	1329
1882.292	4.344	1324	**1887.292**	4.114	1254	**1892.292**	4.144	1263	**1897.292**	4.463	1360	**1902.292**	4.130	1259
1882.375	4.774	1455	**1887.375**	4.331	1320	**1892.375**	4.351	1326	**1897.375**	4.137	1261	**1902.375**	4.157	1267
1882.458	4.314	1315	**1887.458**	4.672	1424	**1892.458**	4.334	1321	**1897.458**	4.364	1330	**1902.458**	4.506	1373
1882.542	4.636	1413	**1887.542**	4.852	1479	**1892.542**	3.934	1199	**1897.542**	4.556	1389	**1902.542**	3.974	1211
1882.625	4.072	1241	**1887.625**	3.793	1156	**1892.625**	4.157	1267	**1897.625**	4.520	1378	**1902.625**	3.660	1116
1882.708	4.413	1345	**1887.708**	4.482	1366	**1892.708**	4.098	1249	**1897.708**	4.236	1291	**1902.708**	4.087	1246
1882.792	3.957	1206	**1887.792**	4.163	1269	**1892.792**	3.649	1112	**1897.792**	4.218	1286	**1902.792**	3.877	1182
1882.875	3.953	1205	**1887.875**	4.072	1241	**1892.875**	4.183	1275	**1897.875**	4.120	1256	**1902.875**	3.970	1210
1882.958	3.953	1205	**1887.958**	3.862	1177	**1892.958**	4.115	1254	**1897.958**	3.764	1147	**1902.958**	4.093	1248
1883.042	3.780	1152	**1888.042**	4.131	1259	**1893.042**	3.875	1181	**1898.042**	4.448	1356			
1883.125	4.055	1236	**1888.125**	4.081	1244	**1893.125**	3.708	1130	**1898.125**	4.031	1229			
1883.208	4.094	1248	**1888.208**	3.967	1209	**1893.208**	3.748	1142	**1898.208**	4.114	1254			
1883.292	4.357	1328	**1888.292**	3.917	1194	**1893.292**	4.367	1331	**1898.292**	4.375	1334			
1883.375	4.629	1411	**1888.375**	4.150	1265	**1893.375**	4.595	1401	**1898.375**	4.155	1266			
1883.458	4.718	1438	**1888.458**	4.560	1390	**1893.458**	4.365	1330	**1898.458**	4.425	1349			
1883.542	4.281	1305	**1888.542**	4.783	1458	**1893.542**	4.000	1219	**1898.542**	4.749	1447			
1883.625	4.452	1357	**1888.625**	4.124	1257	**1893.625**	4.223	1287	**1898.625**	4.082	1244			
1883.708	3.694	1126	**1888.708**	3.911	1192	**1893.708**	4.667	1423	**1898.708**	4.252	1296			
1883.792	3.940	1201	**1888.792**	3.658	1115	**1893.792**	4.194	1278	**1898.792**	4.079	1243			
1883.875	4.052	1235	**1888.875**	3.839	1170	**1893.875**	3.684	1123	**1898.875**	4.016	1224			
1883.958	4.478	1365	**1888.958**	3.750	1143	**1893.958**	4.036	1230	**1898.958**	3.884	1184			
1884.042	4.226	1288	**1889.042**	4.203	1281	**1894.042**	4.245	1294	**1899.042**	4.280	1305			
1884.125	3.668	1118	**1889.125**	3.757	1145	**1894.125**	3.633	1107	**1899.125**	4.058	1237			
1884.208	3.425	1044	**1889.208**	4.081	1244	**1894.208**	3.931	1198	**1899.208**	4.380	1335			
1884.292	4.104	1251	**1889.292**	4.042	1232	**1894.292**	4.285	1306	**1899.292**	4.707	1435			
1884.375	4.209	1283	**1889.375**	4.268	1301	**1894.375**	4.43	1350	**1899.375**	4.760	1451			
1884.458	4.948	1508	**1889.458**	5.112	1558	**1894.458**	4.828	1472	**1899.458**	4.480	1366			
1884.542	3.927	1197	**1889.542**	4.193	1278	**1894.542**	4.944	1507	**1899.542**	3.932	1198			
1884.625	4.281	1305	**1889.625**	4.557	1389	**1894.625**	4.228	1289	**1899.625**	3.955	1205			
1884.708	3.957	1206	**1889.708**	4.380	1335	**1894.708**	4.128	1258	**1899.708**	3.780	1152			
1884.792	3.947	1203	**1889.792**	4.390	1338	**1894.792**	4.234	1291	**1899.792**	3.857	1176			
1884.875	3.471	1058	**1889.875**	4.114	1254	**1894.875**	4.159	1268	**1899.875**	4.180	1274			
1884.958	4.459	1359	**1889.958**	4.393	1339	**1894.958**	3.776	1151	**1899.958**	3.968	1209			
1885.042	3.930	1198	**1890.042**	3.717	1133	**1895.042**	3.875	1181	**1900.042**	4.130	1259			
1885.125	3.871	1180	**1890.125**	3.661	1116	**1895.125**	4.278	1304	**1900.125**	4.085	1245			
1885.208	3.999	1219	**1890.208**	3.855	1175	**1895.208**	4.002	1220	**1900.208**	4.361	1329			
1885.292	3.757	1145	**1890.292**	4.052	1235	**1895.292**	4.211	1284	**1900.292**	4.304	1312			
1885.375	4.101	1250	**1890.375**	4.117	1255	**1895.375**	4.148	1264	**1900.375**	4.178	1273			
1885.458	4.482	1366	**1890.458**	4.928	1502	**1895.458**	4.417	1346	**1900.458**	4.739	1444			
1885.542	4.075	1242	**1890.542**	4.226	1288	**1895.542**	4.749	1447	**1900.542**	4.536	1383			
1885.625	4.560	1390	**1890.625**	4.193	1278	**1895.625**	4.829	1472	**1900.625**	4.709	1435			
1885.708	3.825	1166	**1890.708**	4.413	1345	**1895.708**	4.452	1357	**1900.708**	3.867	1179			
1885.792	3.698	1127	**1890.792**	4.573	1394	**1895.792**	4.045	1233	**1900.792**	3.917	1194			
1885.875	3.602	1098	**1890.875**	4.308	1313	**1895.875**	3.695	1126	**1900.875**	3.647	1112			
1885.958	4.177	1273	**1890.958**	4.111	1253	**1895.958**	4.423	1348	**1900.958**	4.304	1312			
1886.042	4.800	1463	**1891.042**	4.416	1346	**1896.042**	3.971	1210	**1901.042**	3.926	1197			
1886.125	4.301	1311	**1891.125**	3.875	1181	**1896.125**	3.859	1176	**1901.125**	3.788	1155			
1886.208	3.832	1168	**1891.208**	4.272	1302	**1896.208**	4.436	1352	**1901.208**	4.213	1284			
1886.292	4.163	1269	**1891.292**	4.229	1289	**1896.292**	4.571	1393	**1901.292**	4.354	1327			
1886.375	4.386	1337	**1891.375**	4.147	1264	**1896.375**	4.532	1381	**1901.375**	4.749	1447			
1886.458	4.177	1273	**1891.458**	4.482	1366	**1896.458**	4.452	1357	**1901.458**	5.055	1541			
1886.542	4.016	1224	**1891.542**	4.770	1454	**1896.542**	4.517	1377	**1901.542**	4.296	1309			
1886.625	4.541	1384	**1891.625**	4.334	1321	**1896.625**	3.881	1183	**1901.625**	3.947	1203			
1886.708	4.285	1306	**1891.708**	4.042	1232	**1896.708**	3.893	1187	**1901.708**	4.357	1328			
1886.792	4.291	1308	**1891.792**	3.875	1181	**1896.792**	3.762	1147	**1901.792**	4.318	1316			
1886.875	4.232	1290	**1891.875**	3.917	1194	**1896.875**	3.427	1045	**1901.875**	4.240	1292			
1886.958	4.012	1223	**1891.958**	4.646	1416	**1896.958**	3.964	1208	**1901.958**	4.147	1264			

Table 8: Original monthly mean sea level data from Port Adelaide Inner Harbour, 1882 to 1902. (Chapman and Inglis 1902), with metric values added. The 1882 to 1892 values are identical to those in the PSMSL "metric" dataset for the Inner Harbour. The datum is referred to as one selected by Goalen in 1875, about "3 inches" different from the City Survey datum.

Year	ft	inches	MSL (ft)	MSL (mm)	RLR (mm)
1873	2	5.90	2.492	759.5	6935.5
1874	2	7.00	2.583	787.4	6963.4
1875	2	6.30	2.525	769.6	6945.6
1876	2	5.50	2.458	749.3	6925.3
1877	2	6.70	2.558	779.8	6955.8
1878	2	6.00	2.500	762.0	6938.0
1879	2	5.50	2.458	749.3	6925.3
1880	2	6.20	2.517	767.1	6943.1
1881	2	5.20	2.433	741.7	6917.7
1882	2	6.10	2.508	764.5	6940.5
1883	2	6.80	2.567	782.3	6958.3
1884	2	6.95	2.579	786.1	6962.1

Table 9. Sydney annual MSL, from Russell 1885

References and sources:

(1951) Ancient Tide Gauge, *Newcastle Morning Herald and Miners Advocate* 4th Jan, 3

(1910), The Register, Monday 14 February (OLWST 30ft and 23ft depths)

(1902) Proceedings of the Parliament of South Australia**,** Volume 2

(1886-1915) Marine Board Report, *Proceedings of the Parliament of South Australia*, (Annual), Volume 3

(1902) The Harbour of Port Adelaide, *Proceedings of the Parliament of South Australia*, Volume 2, report B

(1894) The Surveyor, The Institution of Surveyors, Australia. Volumes 7-8, 40-45

(1922) Notice to Mariners 31 (1187), Admiralty, London

Belperio, A. P. (1993). Land subsidence and sea level rise in the Port Adelaide estuary: implications for monitoring the greenhouse effect. *Australian Journal of Earth Sciences*, *40*(4), 359-368.

Bradley, J. E. (1949). Tides of Hobson's Bay. *Proc. Roy. Soc. Victoria, new series*, *61*(1), 3-122.

Bragg, W. H., Inglis, A., Lyle, T.R., Chapman, R. W., (1892) The Tides of the Coast of South Australia, Report of Committee No 2, AAAS, 230-231.

Brisbane, T. (1825). Table of the rise of the tide at Hobart Town, Van Diemens Land, in April and May 1822 and January 1823. *The Edinburgh Journal of Science*. Vol 3, (5) Art. 19. Pp 100-107. Blackwood, Edinburgh.

Bryant, E. A., Roy P. S., and Thom B. G. (1988) Australia: An Unstable Platform for Tide-Gauge Measurements of Changing Sea Levels: A Discussion, *The Journal of Geology*. 96 (5), 635-640

Burgette, R. J., Watson, C. S., Church, J. A., White, N. J., Tregoning, P., & Coleman, R. (2013). Characterizing and minimizing the effects of noise in tide gauge time series: relative and geocentric sea level rise around Australia. *Geophysical Journal International*.

Chapman, R. W., & Inglis, A. (1894). The Tides of Port Adelaide. *Report of the Australasian association for the advancement of science*. 5, 277-279

Chapman, R. W., & Inglis, A. (1896). The Tides of South Australia,
Proceedings of the Royal Geographical Society of Australasia: South Australian Branch, 9th Session, 93-102

Chapman, R. W., & Inglis, A. (1902). Australian Tides, *Proceedings of the Royal Geographical Society of Australasia: South Australian Branch*. 16th session, 3-18

Chapman, R. W. (1903). Tides at Port Darwin. *Nature*, *68*, 295.

Coghlan, T. A. (1914). Table 47-Tides-Newcastle-1892-1912, *New South Wales Statistical Register for 1912*. Commonwealth Bureau of Census and Statistics. New South Wales Office, 146

Coghlan, T. A. (1917). Table 47-Tides-Newcastle-1906-1916, *New South Wales Statistical Register for 1916*. Commonwealth Bureau of Census and Statistics. New South Wales Office, 480

Cole, T. N. (2011). An acceleration in New Zealand's sea level record? (Thesis, Master of Science). University of Otago. Retrieved from http://hdl.handle.net/10523/628

Cooper, J. A. G., & Pilkey, O. H. (Eds.). (2012). *Pitfalls of Shoreline Stabilization: Selected Case Studies* (Vol. 3). Springer.

Culver, R. (1970). *Final Summary Report on Beach Erosion Studies*. University of Adelaide, Dept. of Civil Eng. A report commissioned by the Seaside Councils Committee and the State Government of Sth. Aust.

Darwin, G. H. (1889) Second series of Results of the Harmonic Analysis of Tidal Data, *Proceedings of the Royal Society,* 556-611

Easton, A. K. (1970). *The tides of the continent of Australia* (No. 37). Horace Lamb Centre for Oceanographical Research, Flinders University of South Australia.

Ellery, R. L. J. (1879). The Tidal Datum of Hobson's Bay. *Transactions and Proceedings of the Royal Society of Victoria*, *16*, 146-148.

Fadil, A., Denys, P., Tenzer, R., Grenfell, H. R., & Willis, P. (2013). New Zealand 20th century sea level rise: Resolving the vertical land motion using space geodetic and geological data. *Journal of Geophysical Research: Oceans*, *118*(11), 6076-6091.

Featherstone, W. E., Filmer, M. S., Penna, N. T., Morgan, L. M., & Schenk, A. (2012). Anthropogenic land subsidence in the Perth Basin: Challenges for its retrospective geodetic detection. *Journal of the Royal Society of Western Australia*, *95*(1), 53-62.

Filmer, M.S. and Sandford, G. (2007). An investigation into the displacement of Permanent Survey Marks in the Hillcrest area resulting from reactive soils. Journal of Spatial Science. 52 (1): pp. 183-192.

Gehrels, W. R., Callard, S. L., Moss, P. T., Marshall, W. A., Blaauw, M., Hunter, J., ... & Garnett, M. H. (2012). Nineteenth and twentieth century sea-level changes in Tasmania and New Zealand. *Earth and Planetary Science Letters*, *315*, 94-102.

Hannah J., Bell, R. G., (2012) Regional sea level trends in New Zealand, Journal of Geophysical Research, 117, C01004, doi:10.1029/2011JC007591

Holbrook, N. J., Goodwin, I. D., McGregor, S., Molina, E., & Power, S. B. (2011). ENSO to multi-decadal time scale changes in East Australian Current transports and Fort Denison sea level: Oceanic Rossby waves as the connecting mechanism. *Deep Sea Research Part II: Topical Studies in Oceanography*, *58*(5), 547-558.

Hunter, J., Coleman, R., & Pugh, D. (2003). The sea level at Port Arthur, Tasmania, from 1841 to the present. *Geophysical Research Letters*, *30*(7).

Hunter, J. R. (2008). *Historical and Projected Sea-Level Extremes for Hobart and Burnie, Tasmania*. Department of Primary Industries and Water.

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

Association d'Oceanographie Physique (1950). Monthly and Annual Mean Heights of Sea-level 1937 to 1946, and unpublished data for earlier years. *Publication Scientifique No. 10*. 16 & 68.

King, R., (2008) Port Adelaide seawater & stormwater flood risk treatment. Conference Papers: IPWEA National Conference on Climate Change 'Responding to Sea Level Rise' Coffs Harbour, NSW 3 - 5 August 2008

Lamontagne, S., Le Gal La Salle, C., Simmons, C., James-Smith, J., Harrington, N., Love, A., Smith, A., Hancock, G. and H. Fallowfield. (2005) *“Estimation of groundwater and groundwater N discharge to the Adelaide Coastal Waters Study area”.* ACWS Technical Report No. 4 prepared for the Adelaide Coastal Waters Study Steering Committee by the Flinders Centre for Coastal and Catchment Environments.

Mault, A. (1889). On some tide observations at Hobart during February and March, 1889. In *Papers & Proceedings of the Royal Society of Tasmania* (pp. 8-12).

Mackenzie, A. D. (1939). Coastal Erosion in Victoria. *Journal of Institute of Engineering. Australia*. 11, 229-236.

Modra, B. (2013) *Tide Gauge Histories*. Metadata for National and NSW Tide Gauges. Report MHL2179 October 2013, Manly Hydraulics Lab. NSW.

Russell, H. C. (1885) Anniversary Address, *J. & Proc. Roy. Soc. New South Wales,* 19*,* 1-27

Russell, H. C. (1898) Meteorology of New South Wales. Results of Rain, River, and Evaporation Observations Made in New South Wales xxx-xxxii

Russell, H. C. (1904) Meteorology of New South Wales. Results of Rain, River, and Evaporation Observations Made in New South Wales

Shortt, J. (1889). Notes on the possible oscillation of levels of land and sea in Tasmania during recent years. In *Papers & Proceedings of the Royal Society of Tasmania* (pp. 18-20).

Spada G, Gallassi G, (2012). New estimates of secular sea level rise from tide gauge data and GIA modelling *Geophys. J. Int.* 191**,** 1067–1094, doi: 10.1111/j.1365-246X.2012.05663.x

Stanley, H. J., (1875). The Silting up of Hobsons Bay. *The Argus*, Melbourne, 29th April 1875, 6-7.

Tenzer, R., & Gladkikh, V. (2014). Analysis of the Sea Level Change in New Zealand. In *Earth on the Edge: Science for a Sustainable Planet* (pp. 135-139). Springer Berlin Heidelberg.

Watson, P. J. (2011). Is there evidence yet of acceleration in mean sea level rise around mainland Australia?. Journal of Coastal Research, 27(2), 368-377.

Watson, P. J., Commins, R., Janssen, V., McElroy, S., Batman, G., & Connors, D. (2012). Augmenting the utility of NSW longest tide gauge records with continuous GNSS technology.

Wright, T. (1909). Harmonic Tidal Constants for Certain Chinese and New Zealand Ports. *Proceedings of the Royal Society of London. Series A*, *83*(560), 127-130.

Wright, T. (1902). Harmonic Tidal Constants for Certain Australian and Chinese Ports. *Proceedings of the Royal Society of London* Series A. 71:91–96

Wynne, A. A., Fotheringham, D. G., Freeman, R., Moulds, B., Penney, S. W., Petrusevics, P., Tucker, R., Ellis, D. P. (1984) *Adelaide Coast Protection Strategy Review 1984* Report prepared for The Coast Protection Board South Australia