Extended Tide Gauge Data. Hogarth 2014, Supplementary note 4: Indian Ocean (January 2016)

Complete century scale records from around the Indian Ocean have been relatively sparse in the PSMSL, and the process of deriving rates of sea level rise is complicated by cases of apparent significant decadal scale sea level divergences between data from relatively closely spaced tide gauges (Emery and Aubrey 1989, Survey of India 1950, Unnikrishnan et al 2007a, 2007b). Much of the MSL data for the late 19th and first two decades of the 20th Century are from hourly or better readings from analysis of marigrams, but some of the data between 1921 (Survey of India 1928) and the late 1950s is from high water and low water observations only. For some sites (eg Mumbai, Kidderpore) the difference between averaged hourly readings (Mean Sea Level, MSL) and mean of high and low waters (Mean Tide Level, MTL) is of the order of 10s of mm, and a change from MSL to MTL in the records can therefore have a similar effect to a datum shift of the same magnitude. Obviously this will affect linear or second order analysis of the time series and this error must be corrected to obtain more consistent results. The PSMSL has always been clear about which records are represented by MSL and MTL data where this information is available. This supplementary note examines the sea level records from around the Indian Ocean, and attempts to systematically correct and extend the existing PSMSL records using recovered historical information. These new extended time series are then used to estimate sea level acceleration over the period including at least the entire 20th century. The notes are arranged in order of tide gauge sites.

Aden

There is early automatic tide gauge data from Aden, Yemen, for a few months of 1846 (Montriou 1850), but as with the Colaba data (see section on Mumbai/Bombay) from the same source the lack of information about the vertical datum limits the usefulness of these records, despite them being tabulated, reduced to a nominal MSL and published.

Annual data from Aden for 1877 and 1879 has been published in the Great Trigonometrical Survey (GTS) records (Baird 1881). At the same site in Aden a new self-registering tide gauge was set up in 1880 and the PSMSL record starts in this year, but as with other sites around the Indian Ocean there were large gaps in the record. Accepting this data (PSMSL as at early 2013) the derived acceleration would have been -0.036mm/yr^2.

The correct early datum was used in recent work by the National Institute of Oceanography, (NIO) India (Unnikrishnan 2007a) and this series has now been corrected in the updated PSMSL records (2014 onwards, private correspondence, Woodworth 2013) to rectify the improbable resultant step in 1894. This resolves the anomalous negative acceleration value derived from the previous uncorrected data, which unfortunately has been used in several previous studies. This highlights not just the evolving nature of our understanding of regional sea level rise, but the ongoing scientific process of analysing, checking and updating the vitally important global data bases of historical data. As more old data is rediscovered or re-analysed, the ability to cross check and correct existing data and make better regional models of sea level behaviour is improved.

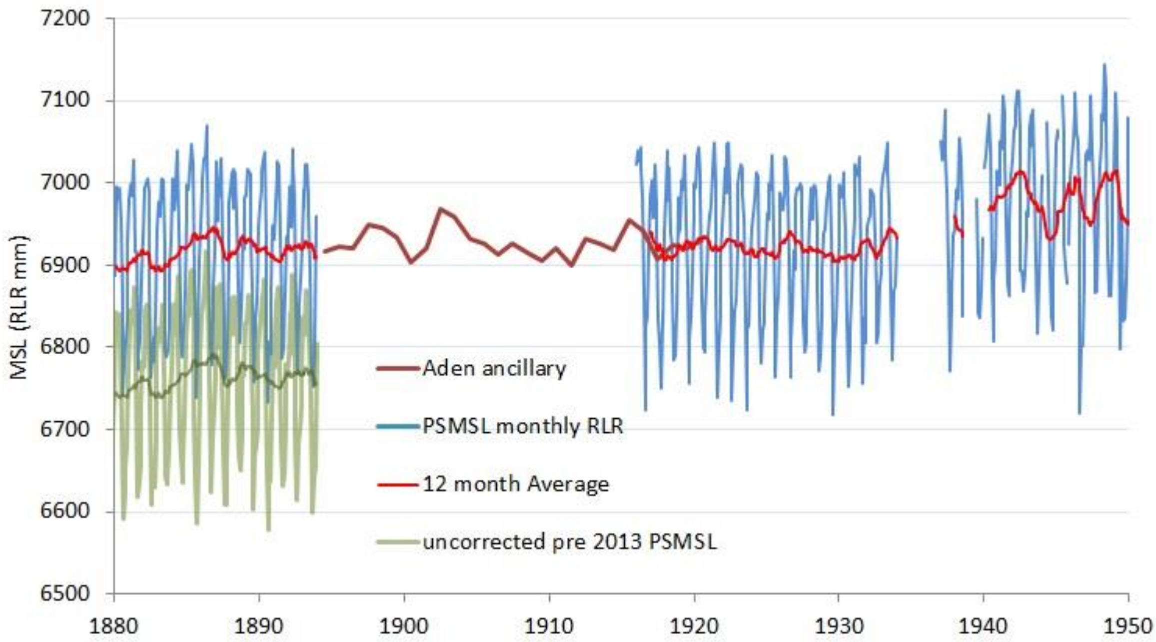

Figure 1: Corrected Aden PSMSL monthly data and the data as at 2013. The annual ancillary data highlighted a datum issue that allowed subsequent correction of the data.

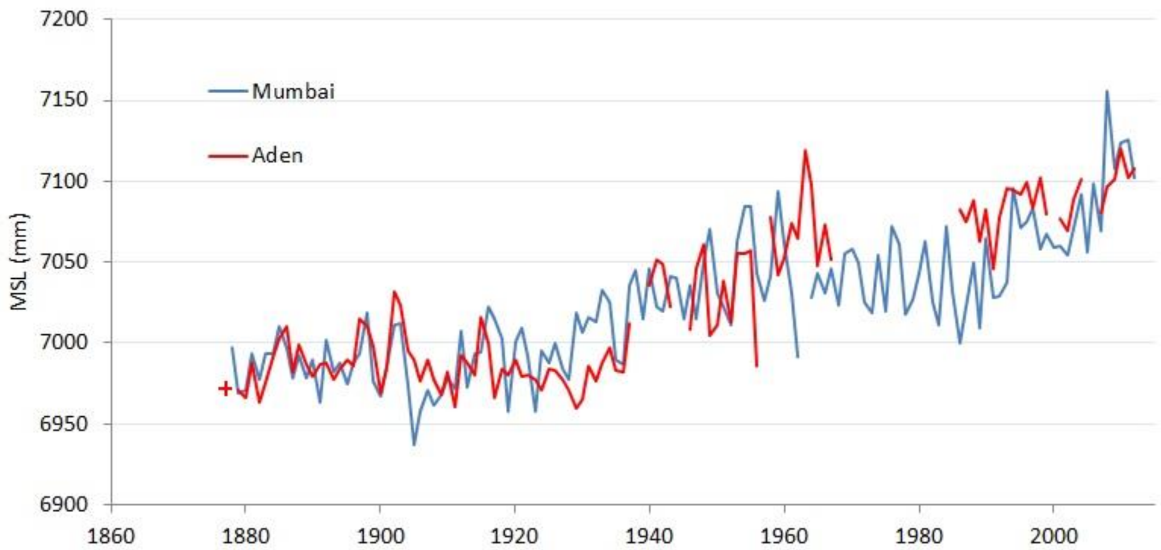

Figure 2: Extended annual data from Aden, overlaid on the corrected Mumbai data from this study, showing significantly higher correlation than prior to correction. A relative vertical land motion difference of -0.3mm/yr has been added to the Aden record.

For this study the gap in the annual time series between 1933 and 1937 was filled with "actual" tide pole readings derived from the difference between predicted and actual values from the Indian tide table given in the annual Geodetic Reports of the Survey of India for the years 1934 to 1938. The difference between MSL and MTL at Aden is estimated to be small from the overlapping data between 1957 and 1960 (IAOP 1958) The new corrected and extended annual series, essentially complete from 1880 up to 1969, with a gap up to the 1990s (figure 2), gives an acceleration value of 0.0114mm/yr^2.

Karachi

Early data is available for Karachi for 18th May to 17th October 1855 at Manora, referenced to the Tide Gauge Bench Mark (TGBM) which is 9.287 ft or 2831 mm above MSL, (Tennant 1856, Walker 1863). Further data is available from December 1857 to March 1858 referenced to 4.75 ft on the Harbour Works Datum (BM1), (Parkes 1868, pg 695), as well as data from March to August 1865, and 1867.

The PSMSL tide gauge record for Karachi (1916 onwards) contains large gaps. In contrast to the original uncorrected record from Aden, the unadjusted acceleration trend for Karachi is high at 0.052mm/yr^2. For this study the essentially complete ancillary annual time series for Karachi (1868 to 1920) was added to the annual PSMSL record and offset to RLR (Spencer et al 1988), extending the time series back by 48 years. Data from 1922 to 1936 has been derived from the Indian tide table "predicted" values and the difference between predicted and actual values (from tide pole readings of HW and LW) given in the annual Geodetic Reports of the Survey of India. This data was also included in the analysis. The monthly and annual data from 1937 to 1947 available from the PSMSL is also from HW and LW readings. The PSMSL record then has a gap from 1948 to 1957.

Data from 1957 to 1965 was supplied to the PSMSL by the Pakistan Meteorological Service, and is believed to be MSL values from hourly readings, (although the datum information is not clear) and that from 1966-85 was supplied by from National Institute of Oceanography, but with recorded bench mark and datum information. The average difference between MSL and MTL has not yet been derived. It appears that the 1957 to 1965 data is offset by approximately 50mm when compared with the corrected Mumbai data, or other nearby sites like Kandla. As more than one nearby record shows consistent differences to the Karachi record over this period, and the Karachi datum is not explicitly stated, it is assumed here that there is likely to be an unrecorded datum shift during this period. Before comparing with the time series from Kandla, the Kandla data must be corrected for the difference between MTL and MSL, which is significant for this site. The step of +160mm from Kandla MTL to MSL occurred in 1957 and appears clearly in the PSMSL chart of the data. This mean difference of 160mm is derived from the overlapping monthly records of MSL and MTL published in the IAPO reports between 1957 and 1961. The standard tide tables for these years for Karachi may also be relevant in that the MSL value above datum is 5.2 ft in the tables published up to 1953, but a 0.2 ft step to 5.4 ft is introduced from 1954 onwards, in addition the value for Chart Datum below Mean Low Water Springs steps from 2ft to 1.5 ft between 1950 and 1951 (Admiralty tide tables covering these years). The NIO supplied PSMSL data (1966 onwards) has been updated with corrections derived from the daily UHSLC data and also from recent research published by NIO (Rabbani). There are differences between the data reported by NIO (Pakistan) and the PSMSL for the years 1983, and 1986 to 1989, although these have a small effect on overall acceleration or deceleration of sea level rise.

The gap between 1994 and 2007 can be filled with satellite altimeter data and also double checked against overlapping data from the nearby tide gauge site at Okha. This shows that the post 2007 PSMSL RLR data, which is from a different site in Karachi (opposite Manora), appears to be offset by an average of approximately +80 mm compared with the satellite or the Okha MSL record if these are adjusted to match the mean level of the Karachi data up to 1994.

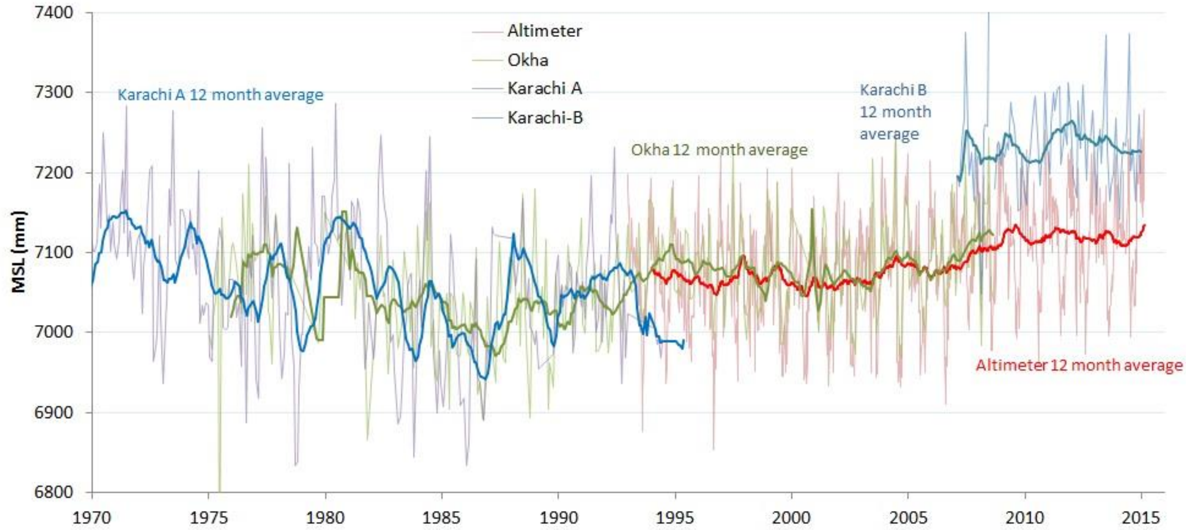

Figure 3: Zoomed in section of Karachi A from the tide gauge at Manora and Karachi B from the radar gauge at the harbour opposite Manora (blue) referenced to the harbour datum. Using buddy checks from overlapping data from Okha (green) and Satellite Altimeter data (red) it appears there is a 70 to 80 mm datum shift at Karachi between 1995 and 2007.

The modern Keamari Radar gauge TGZ reference is stated as 4392mm below the "Old Tide Gauge Bench Mark" BMA on Manora Island (Gloss station information for Karachi), whereas the datum for the 1937 onwards Manora data is 4309 mm below what appears to be the same benchmark. The Karachi Port Trust in Pakistan have kindly confirmed that BMA (originally 4309 mm above TGZ and Chart Datum) was disturbed in 1992 (Woodworth 2015, personal communication), and moved to a new site at a different elevation of 4392 mm above TGZ. However, it is also confirmed that the Chart Datum did not change and the old value of 4309 mm is still used. This datum was transferred across the river to the new site in 1993, using tide poles at each side of the river with recordings taken over two days. It is still slightly uncertain if the difference in elevations of -83 mm is a factor in the apparent step change in recorded tide levels. The UHSLC notes suggest an apparent offset of around +200mm between the Karachi "A" data series from 1985 to 1994 and the post 2007 Karachi "B" series (figure 3). However by comparing with data from other nearby tide gauge sites it is estimated that around 100mm of this difference is due to an inter-annual regional relative rise in sea level over this period.

For this work, based on the difference between the Keamari tide gauge data and the altimeter and Okha data an offset of -83 mm is applied to the Karachi PSMSL (as at 2013) RLR data from 2007 onwards. This estimated correction is consistent with nearby data from several different sources, but this then leaves doubt about the bench mark elevations and tide gauge zeroes. Certainly since the new gauge was established, the standard of levelling work and tidal data quality is high.

There may be a tentative clue to this site related issue in tide gauge measurements taken for an EIA (Environmental Impact Assessment) survey associated with the construction of the new Deep Water Harbour for the Karachi Port Trust (Haskoning 2011). These consisted of a few days of hourly readings of Neap and Spring tides recorded in January and February 2007. As the new Radar gauge was first operating in February 2007, there is some overlap of data at hourly resolution. Both gauges are stated as referenced to the Port Trust Datum (CD) but there is a consistent offset of just over 70mm between the data sets. As this is quite close to the difference in elevations when BMA was reset in 1992, and also close to the difference estimated from other regional tide gauge and monthly averaged altimeter data from the nearest 1 degree resolution cell, it would be interesting to find out if the EIA survey gauge was levelled to another GTS (Great Trigonometrical Survey) benchmark elsewhere in the harbour. At the moment, the correction must remain preliminary.

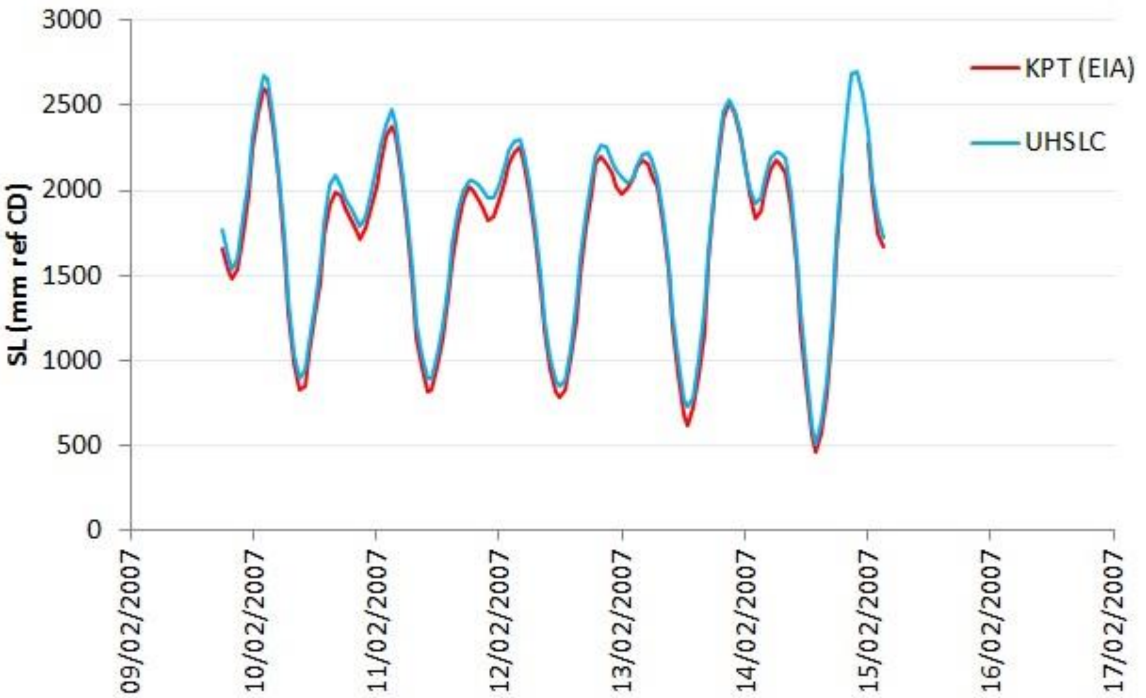

Figure 4: Hourly data from Karachi, blue is the UHSLC high resolution data from the same gauge as the PSMSL monthly values, red is the KPT EIA report data referenced to the same datum but recorded by an independent tide gauge.

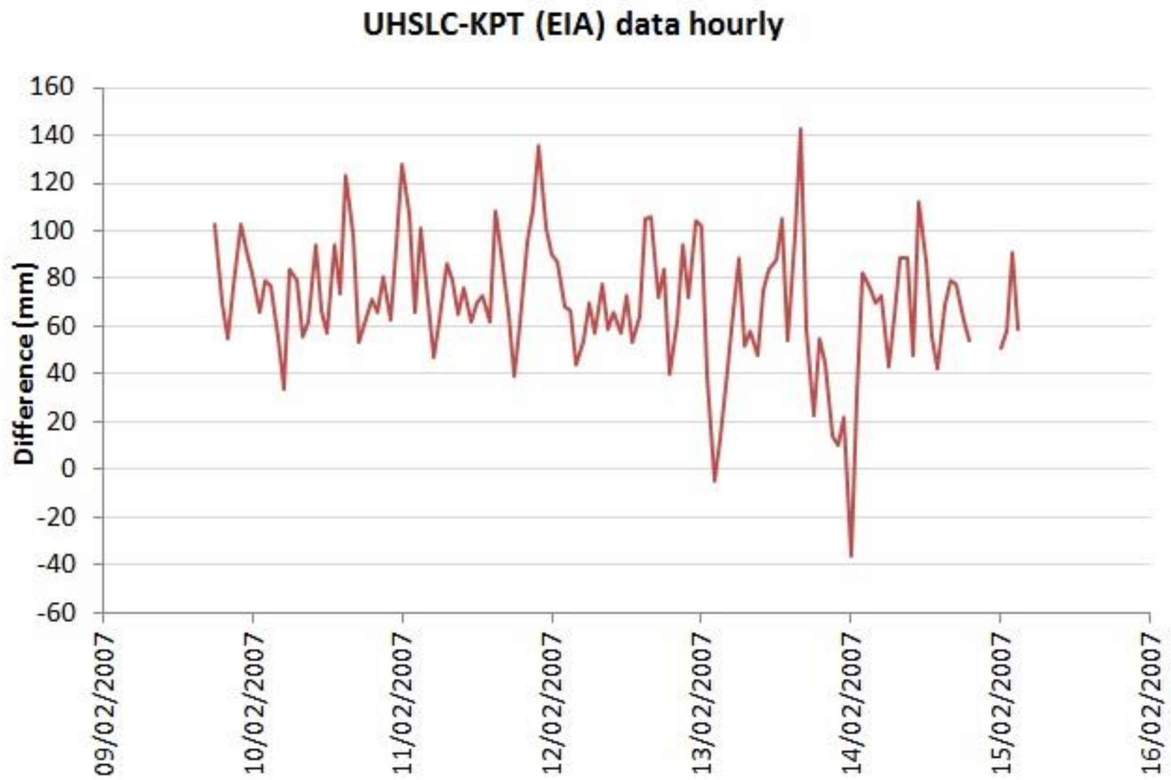

Figure 5: Difference plot of the hourly data plotted in figure 4. The mean difference is around 73mm.

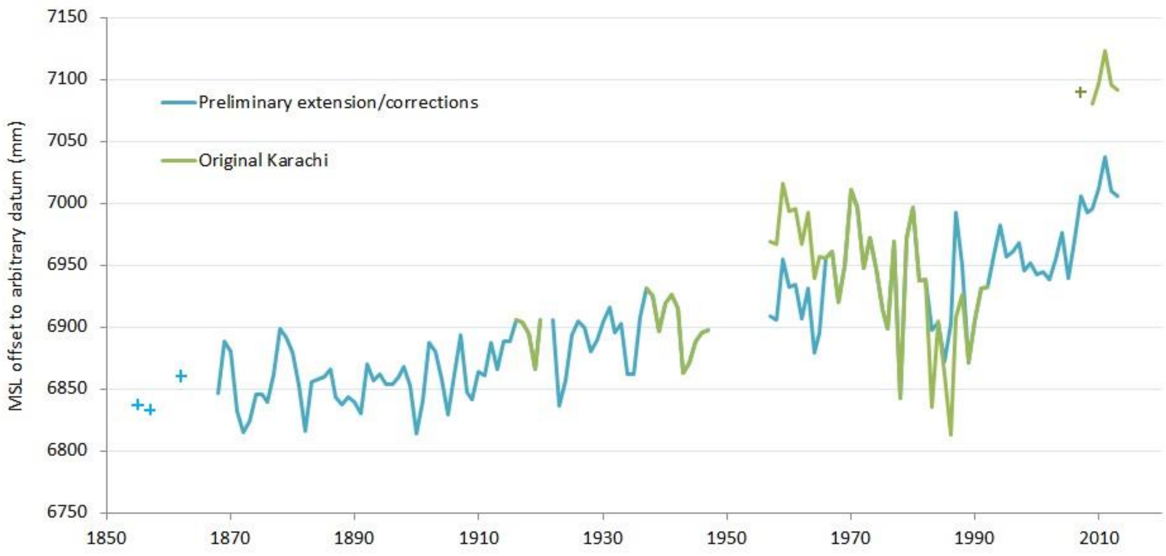

Figure 6: The original Karachi annual data (PSMSL) overlaid on the corrected and extended data from Karachi, including the ancillary data also available from the PSMSL

The extended series with this initial correction now shows a much reduced acceleration value of 0.0026 mm/yr^2. If this new series is buddy checked against the corrected long time series of Mumbai from this study, the long term correlation shows a remarkable improvement (figure 7). If the uncorrected Karachi data is compared with Mumbai, this again highlights the 1957 to 1965 Karachi data as offset relatively high, possibly due to an unrecorded datum shift under the different reporting authority during this period. The effect of adding the estimated -0.2 ft (61mm) correction (figure 6) would be to change the overall full series acceleration value to 0.007 mm/yr^2 . However until the 1957 datum information can be verified, the correction for these years should again remain preliminary. However, the correlation with the independently corrected time series from Mumbai adds additional weight in favour of the estimated corrections for Karachi being reasonable (figure 7).

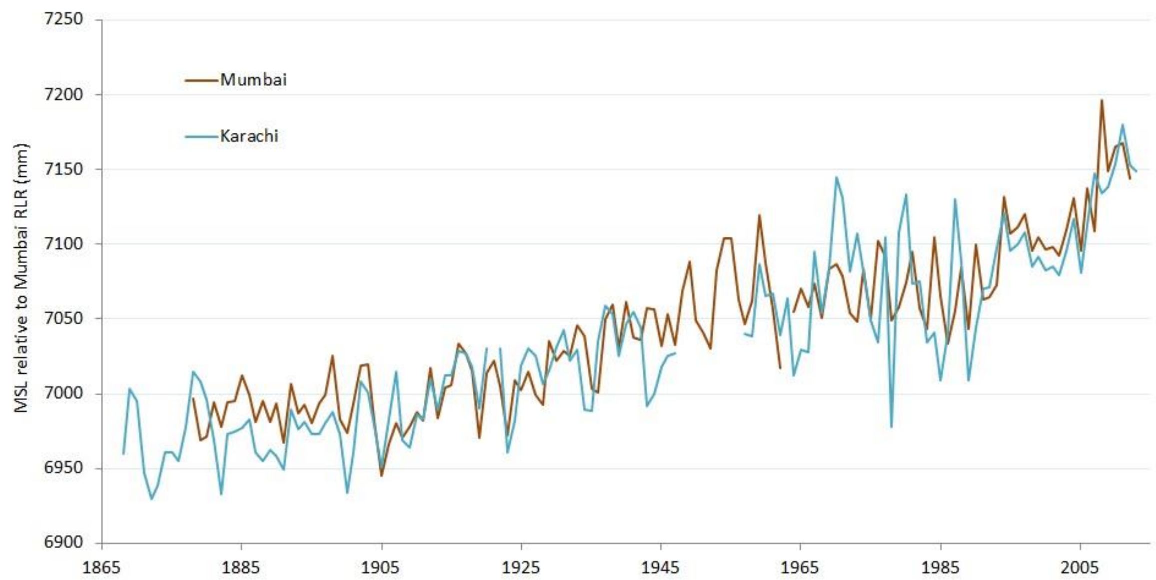

Figure 7: The new corrected data from Karachi overlaid on the record from Mumbai (both from this study) showing high correlation and convergent sea level acceleration values when using the extended series.

Mumbai (previously Bombay)

There are published references to extreme high waters for Bombay (Mumbai) from as early as 1791 (Goldingham 1827), as well as a value for the mean rise of the tide at the head of the dock. A table of systematically recorded high waters from 1832 was published (Noton, 1842), though these are un-reduced values only. A continuous series of daily higher high water, (HHW), lower high water (LHW), higher low water (HLW) and Lower low water (LLW) tide staff readings from May 1835 to the end of 1840 has also been published (Ross 1844) which was also recorded at the head of the Government dock. This appears to be referenced to a datum 1 foot below Lowest Low Water Springs from examination of the record itself.

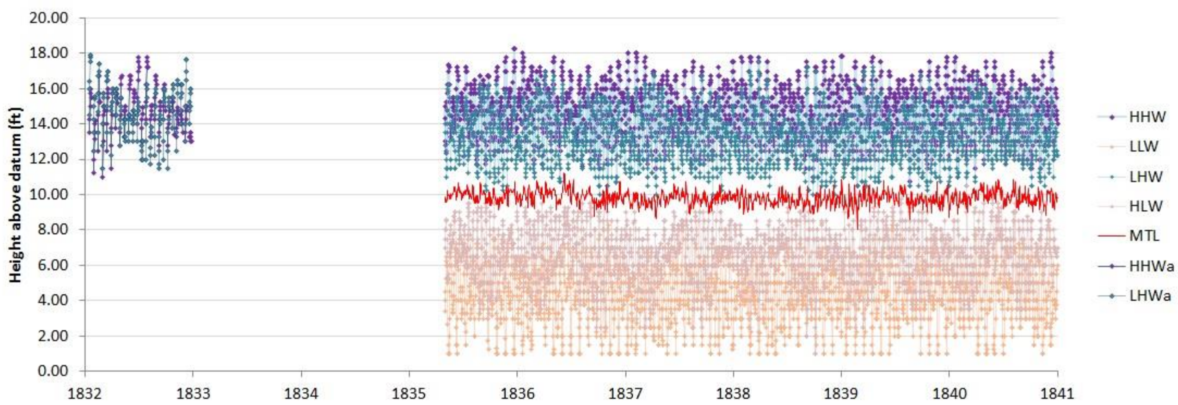

Figure 8: Tidal data from Noton and Ross, with MTL derived from mean of HHW, LWW, HLW and LHW.

The zero of the gauge is not recorded, but is likely to be close to the level of the sill of part of the old Bombay docks (and within a few inches of the later Apollo Bandar tide gauge zero). It also appears to be identical or very close to the datum used by Noton, judging from the equivalent high water values. For this work the published data from Ross was transcribed to digital format, then quality checked for outliers and obvious typographical errors, and monthly averages of the high and low waters were calculated referenced to the tide gauge zero (figure 9). The monthly variations appear qualitatively similar to the later data from 1878 onwards recorded in the PSMSL data.

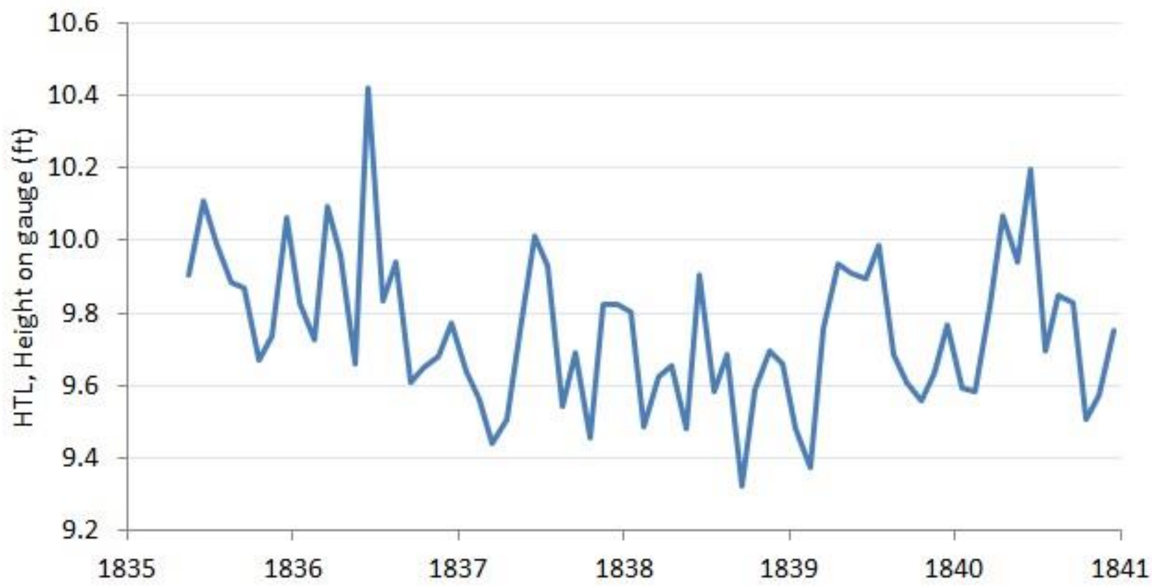

Figure 9: Monthly MSL values for Bombay derived from all daily high and low water readings from Ross, referenced to the original datum.

In 1845 a self-recording tide gauge was set up at the Colaba Observatory near Bombay, and published data is available for 1846 (Orlebar 1849) to 1861. The half hourly data for 1846 was digitised for this work. Subsequent detailed records from Colaba for years 1847 to 1861 have also been separately published (e.g. Montriou 1850) but have not yet been digitised. These records from the Colaba Observatory from 1846 onwards were not originally connected to the later Town Hall Datum (THD, 100 feet below a bench mark on the Town Hall steps) which only emerged as a standard vertical reference point for surveying work in Bombay from the 1870s (Tulloch 1869, 1873). They were reduced to a nominal MSL datum. The recorded HHW (highest high water) and HLW (highest low water) plus other details of the Colaba tidal series has been summarised in later work on drainage of the town (Latham 1890), although the data and datum connections were not obtained from the GTS (Wood 1891) when Latham made enquiries. Errors in the data due to possible leakage or blockage of the very long siphon tube in the late 1850s were noted. The tide gauge zero at Colaba (or the datum to which the readings are reduced) is assumed by Latham to be 81.21 ft above THD. This would give a mean annual MSL value 1 foot in excess of later (or nearest contemporary) MSL levels, so it appears there is an error of this order in the levels or the datum. The average daily values for 1846 highlight potential datum shifts of up to 1 foot, which also gives monthly mean values with an anomalously high variation through 1846 (figure 10). The construction of the tide gauge involved cord running over a large pulley wheel, and slippage or poor adjustment of this may have been a source of error. It was noted by Parkes (1868) and others that this data from Colaba was problematic, but that the values for 1846 were probably the best of the series.

Figure 10: Daily averaged MSL values from 1846 as calculated from the reduced observations from the self registering tide gauge at Colaba.

The Colaba tide gauge pipe-work had broken down by 1866 (Chambers 1866, pg 38). Other tide data was recorded for just over four months of 10 minute observations on a tide staff (January to June of 1867) before Princes Dock was built, at the old dock at Carnac Bunder (Ormiston 1867) which used a low water reference datum 72 feet above THD (Parkes 1868, Thompson et al 1868). It is remarkable that this 72 ft (Old dry dock datum, or Mean Low Water Ordinary Spring Tides, which is very close to the elevation of the blocks of the old dockyard) has remained the tide gauge reference point at Princes Dock up to recent times (see Indian Tide Tables, e.g. 1961). Annual data from Princes Dock is available from 1888 to 1920 in the PSMSL ancillary series, and monthly RLR data is also available. This data can be used to cross check the data over this period from Apollo Bandar.

Further data, but with known datum information is available for 1867, 1872, and 1874. The longest time series, from Apollo Bandar, is available from 1876 onwards (Baird 1880) as monthly and annual values (Eccles 1901). This tide gauge site provides data for the PSMSL series, essentially continuous from 1878 (Burrard 1912) to 1993. The data from 1931 to 1958 is derived from HW and LW values rather than from the hourly (or more frequent) tide gauge readings, and this introduces an average positive offset of around +34mm in the PSMSL RLR records (as at January 2015).

This offset should be accounted for if the data is to be used for long term sea level studies (figure 11). The offset is estimated from analysis of the overlapping monthly records of half tide level (mean of high and low waters) and MSL recorded in the 1963 IAOP Publication 24. As a further check, the difference between HTL and MSL is estimated as 34mm from early 20th century averaged annual records (Chugh 1961). For this regional note 34mm is subtracted from the 1931 to 1958 annual PSMSL data (as at January 2015) and this updates the data from Mumbai used in Hogarth 2014.

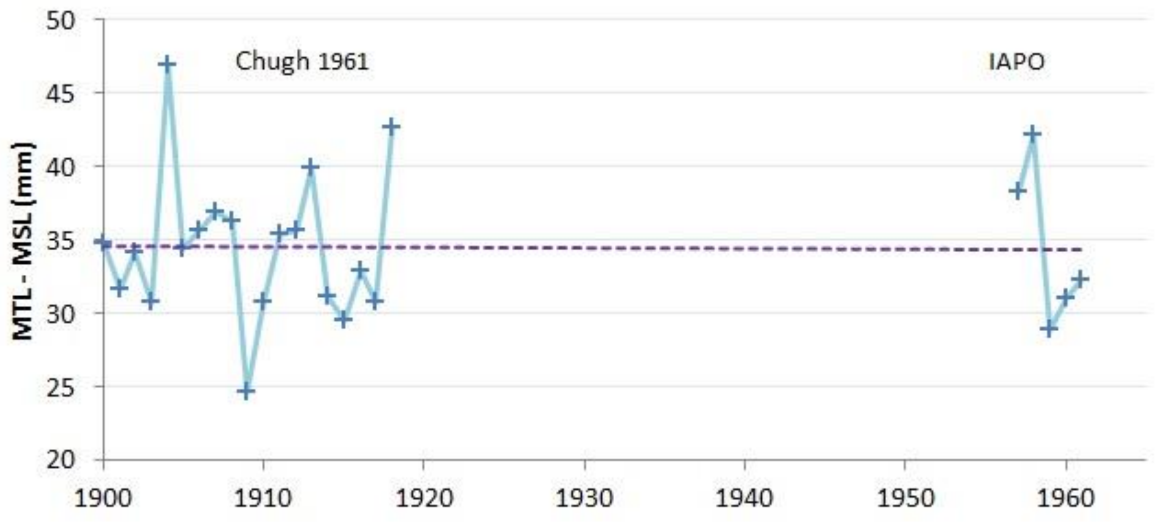

Figure 11: Plotted annual mean difference between MTL and MSL for Mumbai , the best fit offset is relatively constant for the years overlapping data has been analysed, at just below 35mm.

For the preliminary analysis (Hogarth 2014) the post 1988 gaps in the data were filled with appropriately offset values from the tide gauge at Okha (given that GIA values are identical and inter-annual correlation is high). The negative acceleration value obtained from the original PSMSL gappy Bombay data decreases. If the composite record is adjusted with the 0.31 mm/yr GIA value (consistent with the 0.296mm/yr nearest CGPS value) then it is feasible to further extend the Mumbai record up to the present with Altimeter data from an adjacent 1 degree square area.

Without the HTL correction above, the resultant century scale sea level acceleration for Mumbai is statistically very close to zero. The addition of the early data with known datum information results in a small positive effect. With the HTL corrected values the acceleration is now 0.0094mm/yr^2, which means that the corrected century scale acceleration now converges more closely with the average global value (Hogarth 2014).

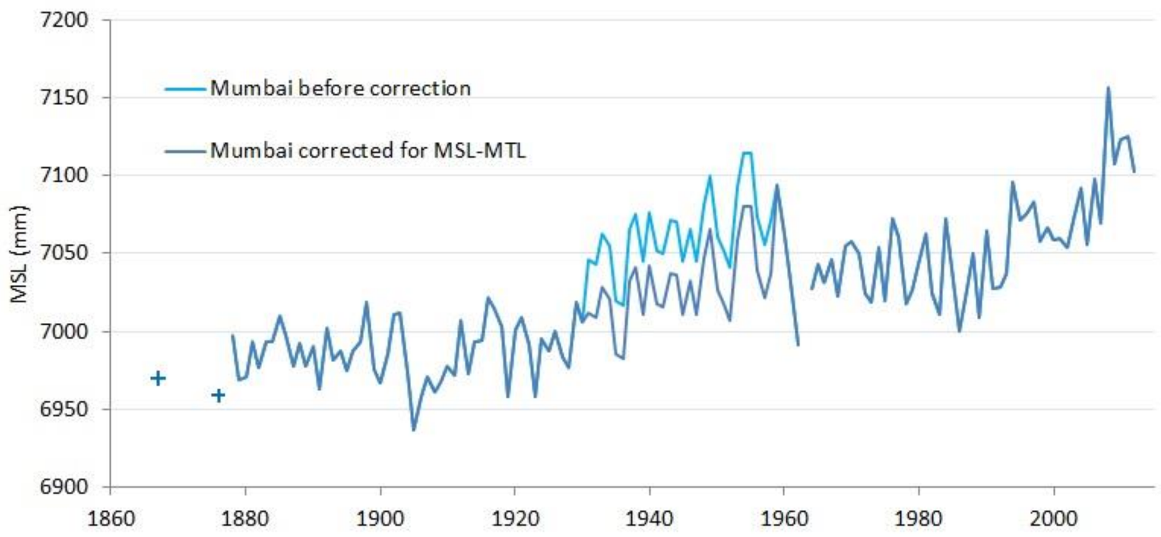

Figure 12: The extended annual time series for Mumbai, showing the effect of accounting for the significant difference between HTL and MSL at this location.

Notes on datums for early tidal work in Bombay

If the early tide data from Ross and the Colaba observatory could be connected to known datums or bench marks, this would allow a valuable further extension of the tidal data series for Bombay. As yet, this connection can only be approximated. This note summarises the effort by this author so far.

Daniel Ross, as an experienced hydrographic surveyor (in fact he was Superintendent of the first Admiralty Tide Tables and contributed to Whewells 14th Series on the tides), would have referred his tidal series to fixed vertical references. It was frequent practice to use the dock sill or block at the base of the tide staff as the harbour zero point. It was also usual to use a hydrographic chart datum some fixed offset below lower low water spring tide to allow safe keel clearance at low water. This can be used to give an approximate value for the datum for his data. For the Colaba data, the datum information is less clear. Montriou worked under Daniel Ross for some time, and following the common practice of surveyors in India at this time he used Lowest Low Water as the tide gauge zero, rather than Mean Low Water Springs (Taylor 1880). Ross was certainly consulted on the establishment of the Colaba tide gauge, and it is likely the datums were connected by levelling. The later reference to the Town Hall Datum for the Colaba gauge (Latham 1890) appears to be in error by around 1 foot (305mm).

The Town Hall Datum is sometimes referred to as the DeLisle datum in early reference work on surveying, as well as in reports from Bombay (Tulloch 1869). The earliest reference to THD found by this author is from 1865. However, DeLisle, a surveyor, refers all of his levels to a datum 100 ft below the top of the Plinth of the Church Gate of the Fort of Bombay in his report on the water supply proposals of Bombay (DeLisle 1851). The Fort and Church Gate referred to was demolished in 1862. The site was close to St Thomas Cathedral and on a relatively level plane and sight-line with the Town Hall. The relationship between this Plinth datum and the Town Hall Datum, 100 feet below a mark on the lowest step of the Town Hall, is not clear from the information available (to this author).

Aitken (1868) refers to a datum 50 feet below Mean Sea Level (MSL) in Bombay , and Tulloch (1869) states that 29.7 feet should be added to bring elevations referred to this Aitken datum to the DeLisle datum, making MSL 79.7 ft above THD. Later (1873) Tulloch remarks that this Aitken MSL value differs by 0.6 ft from the MSL estimate of 80.3 ft referenced to THD derived by Ormiston from tide readings in 1867. This is too large to be accounted for by average seasonal variations and may provide a clue to the datum used at Colaba

A different LW datum was also used by Lt. Whish in his harbour survey of 1853. The Indian Tide tables state that a datum used by Whish is 0.820 ft above the "72 ft below THD" Chart Datum. Historical notes from Whish state mean spring rise of 12.25 ft, but to estimate HTL the difference between higher and lower spring tides are required (Anon 1870).

An early reference (Buist 1850) to height above datum of the bench marks in the Colaba Observatory gives an elevation of 64.0 ft above mean level of the sea for the top of the Pillar under the dome of the astronomical observatory. This final elevation was based on the rounded mean (64.3 ft) of four separate trigonometric determinations of 61.6, 61.8, 63.8 and 65.9 ft above Mean Sea Level from levelling work in 1839 (Strahan 1890, Ch II, pg 27 and Appendix B, pg 63). The relative height of this point to the tide gauge house floor was known to some precision (Montriou 1850, Buist 1851). It is possible that the tide gauge in Bombay used to give the Mean Sea Level reference for the levelling work was that of Ross, as his readings were taken only a few years previously and had been published. This same Colaba Pillar bench mark is later stated as having an elevation of 63 ft above MSL (referenced to THD) using more precise levelling referenced back to the tide gauge at Apollo Bandar and to the Town Hall datum (Strahan 1892). This is a rounded value, but again points to a difference between the pre-THD datum and the later THD of the order of 300mm. The precise datum information however remains elusive.

Chennai (previously Madras)

Tidal data (HW and LW as well as MTL) with a bench mark connection from 31st May to 10th October 1821 has been published for Madras (DeHavilland 1821). From the 1910 bench mark elevation data and interpretation of the inscription on the DeHavilland bench mark stone it appears that this 1821 mean tide level is around 1 ft higher than levels of the 1880s, even accounting for seasonal variations, and this was noted at the time. The conclusion that there had been relative land movement was discussed in the late 19th century. This difference is so large that it is improbable that it can be explained by realistic decadal sea level variations, and if this data was accepted at face value it would bias any derived acceleration values anomalously high. This very early data is therefore discounted from the analysis pending further investigative work on the datum.

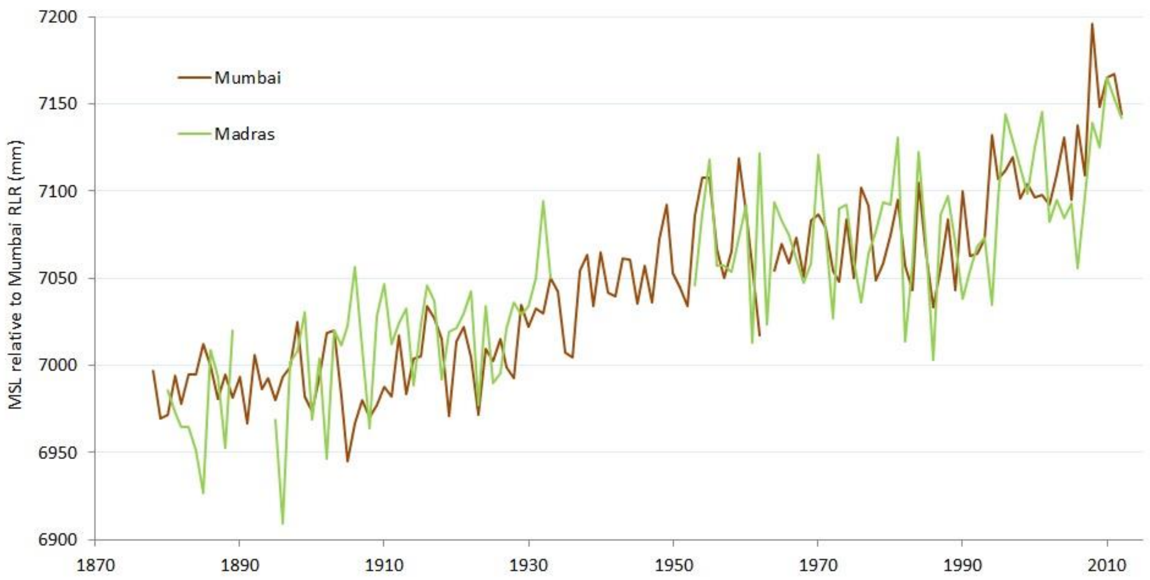

Figure 13: Chennai/Madras extended record adjusted with relative vertical land motion of 0.4mm/yr and superimposed on the extended data from Mumbai updated for this study.

Earlier attempts at fitting a tide gauge at the pier in Madras harbour proved problematic, but eventually a modified tide gauge was set up and working in October 1876, and observations were recorded every 15 minutes. However by February 1877 this too had been washed away (Taylor 1878). A new tide gauge was set up and was working from 1st February 1879 until damage to the piping caused by a cyclone in May stopped operations (Walker 1880b). A gauge was set up again in 1880 and this operated until October 1890. By this time the ongoing issues with the gauge and site meant that the tide gauge was closed down by the local government (Thuillier 1891). Tidal observations were resumed in November 1894 in a more suitable location and operated until 1921. The PSMSL data for Chennai/Madras is available from 1916 to 2010 with a large gap from 1921 to 1953. Annual data from Madras is available in the ancillary data from the PSMSL from 1880 to 1889, and from 1895 to 1920. This data and benchmark information allows the old and new datums to be linked and offset to RLR (the RLR diagram from the PSMSL also shows the old 1880 datum). This work has also used the Indian tide table predicted values and the difference values given in the Geodetic reports of the Survey of India (and earlier reports) to recover the annual MSL values for 1921 to 1933.

In total an extra 63 years have been added to the 45 years in the PSMSL record.

The original tidal benchmark was at the old lighthouse. The primary benchmark between 1894 and 1933 was BM31 (Stone laid in 1875) which was 15.714 ft above the MSL datum of 1910 (Burrard 1910), and 17.97 ft above TGZ (Tide Gauge Zero). Between 1953 and 1992 the datum was BM30 (14.632 ft above MSL datum of 1910), and from 1992 the primary benchmark was changed to BM23 (14.478 ft above MSL datum of 1910). There is a discrepancy in the more recent PSMSL RLR bench mark datum elevations compared with the 1910 values for the relative elevations of BM31 and BM23. This may partly explain the divergence in early MSL data from Madras and Vizagapatam.

Vishakhapatnam (formerly Vizagapatam)

Daily HHW, HW, LW and LLW values above the tide gauge zero are recorded for November 10th to December 9th 1860 (Walker 1880) referenced to the Vizagapatam "Permanent mark" on the Jetty. The mean tide level for this period was 2.47 ft below this bench mark, which corresponds to BM27. Ancillary annual data from the PSMSL is available from 1879 to 1884, and this is from the same site. The PSMSL data for Vishakhapatnam is available from 1937 to 2012. The datums can be connected through bench mark elevation data.

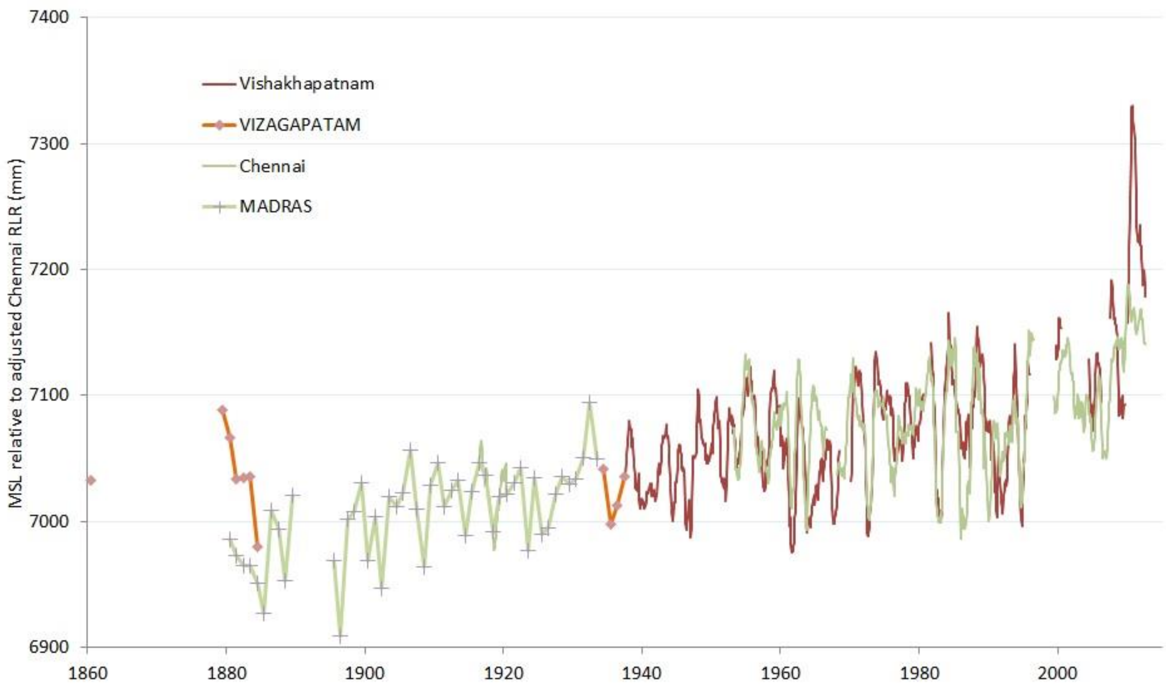

Figure 14: Extended annual and 12 month averaged monthly data for Vishakhapatnam and Chennai, (Madras) offset to minimise differences and overlaid to highlight the inter-annual scale similarities. The probable datum or land motion rate difference is shown by divergence of the data around the 1880s.

The infill data HTL (MSL) data from 1934 to 1938 is derived from the Indian tide table predicted values and the difference between predicted and actual values given in the Geodetic Reports of the Survey of India for these years. Individually the acceleration from Chennai is lower than the global average of order 0.01mm/yr^{2}whilst that from Vishakhapatnam is higher. It is probable that an unrecorded datum shift (or relative land motion difference) exists in at least one of these series.

Cochin.

There is early data from Cochin for the years 1886 to 1891 available from the ancillary time series in the PSMSL, whilst annual MSL data from 1884 and 1885 is available from the records of the Great Trigonometrical Survey of India.

The PSMSL data series starts in 1939, and runs with a few gaps up to the present. Although a composite record can be created using the bench mark information, there are large gaps. Nevertheless the record is useful as a buddy check on the other regional time series (Figure 15)

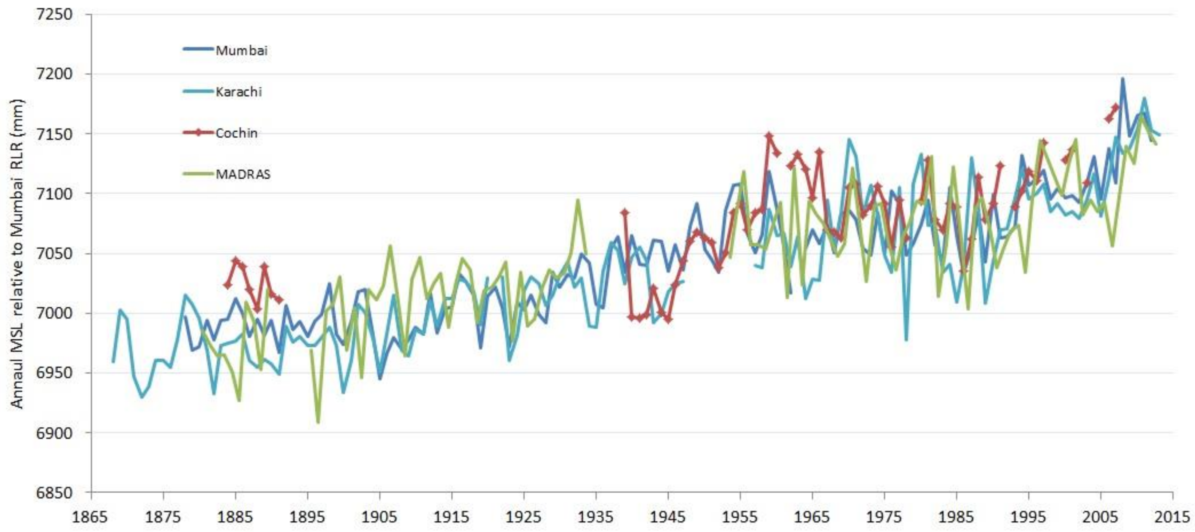

Figure 15: The gappy extended data from Cochin overlaid on three other long time series from around the Indian Ocean, showing inter-annual, decadal and centennial scale similarities and differences.

Calcutta

Although an extended preliminary composite time series can be created from the Calcutta data, there are issues due to datum uncertainties, and the nature of riverain and deltaic sites. Factors other than sea level rise, such as sediment loading and river flow changes have in the past confounded attempts to derive regionally representative SLR and SLA (sea level acceleration) values. Calcutta is also associated with subsidence which became evident in the second half of the 20th Century, although the tide gauge site, being set in the river channel, was less affected than bench marks away from the river (Survey of India 1950). In Calcutta, there is a clear sequence of increasingly positive river level trend post 1930 in the six tide gauge records moving North (upriver) from the estuary mouth, which is at odds with the older (Kidderpore) data from 1881 to 1931 (filled with the ancillary 1894 to 1920 time series from PSMSL) which has an almost equally significant negative trend up to 1930 (Chugh 1961, Nandy 2011). This could be interpreted as acceleration in the tide level component of the tidal river level, compounded with a secular increase in rainfall and increased river flow, as well as components of subsidence in the region close to the old city. It is interesting to examine the available published data to explore this.

Published Historical Data for Calcutta

The earliest systematically recorded data from India is from the Kidderpore docks, Calcutta, (Kyd 1833) with published diagrams for high and low water values for 1806, 1823 and 1826, and annual Highest HW and lowest LW from 1806 to 1827. These are referenced to lowest low water of the river. In order to reduce this data to the old Kidderpore dock sill datum (which has remained as a reference since these early records), LLW is given as 1 foot 10 inches (Sarma 1986) above this old dock sill level. Moving forward in time, HHW, HLW, LHW, and LLW for the years 1838 and 1839 are given in a letter from the superintendent of Kidderpore Docks, but without a datum reference (Gordon, 1848). High and Low Water Spring and Neap values are given for July 1843 to June 1844 (Beardmore 1862), referenced to the old dock sill. A published average river level for a further three year of data from 1845 to 1847 is available from HW and LW values given in a Survey of Calcutta (Simms 1851). A gauge datum correction and additional monthly mean river level for the dry season, February and March for the years 1847, 1848, 1850 and 1851 is tabulated in a note from the Great Trigonometrical Survey (Walker 1865). A year of High and Low Water data is given in diagram form for 1863 for Middle Point, Hoogly Point (near Diamond Harbour) as well as Moyapoor which is closer to Kidderpore (Leonard 1865). The bench mark BM29, set in 1862, inscribed "No. 4, 25.35" was measured as 26.126 ft above the old dock sill from levelling work (Burrard 1910b). It is reasonable to correct the contemporary water level data for this datum offset. A self registering gauge was set up at Kidderpore in December 1871, and mean annual MSL results for 1873 to 1877 were published (Baird 1882). A bench mark was set (BM26) inscribed "23 feet above datum, Dock-sill" (Burrard 1910b), although the tide gauge readings were primarily referenced to a tide staff in the docks. BM26 was actually 23.42 ft above the dock sill. Again this short data series can be corrected to refer to the dock sill datum. A new self-registering tide gauge was set up in the Kidderpore docks in March 1881, in the main river channel, and monthly and annual MSL data up to the end of 1893 and then from 1921 to the end of 1931 (based on HW and LW) is available from the PSMSL. This was referenced to the tide gauge zero set by levelling to the actual dock sill level. Annual MSL data from 1894 to 1920 is available in the PSMSL ancillary series, and monthly and annual data from Garden Reach near Kidderpore is available from 1932 to the end of 2010 with some gaps. The data from 1932 to 1958 is based on HW and LW. Subsequent data is MSL from hourly or better readings.

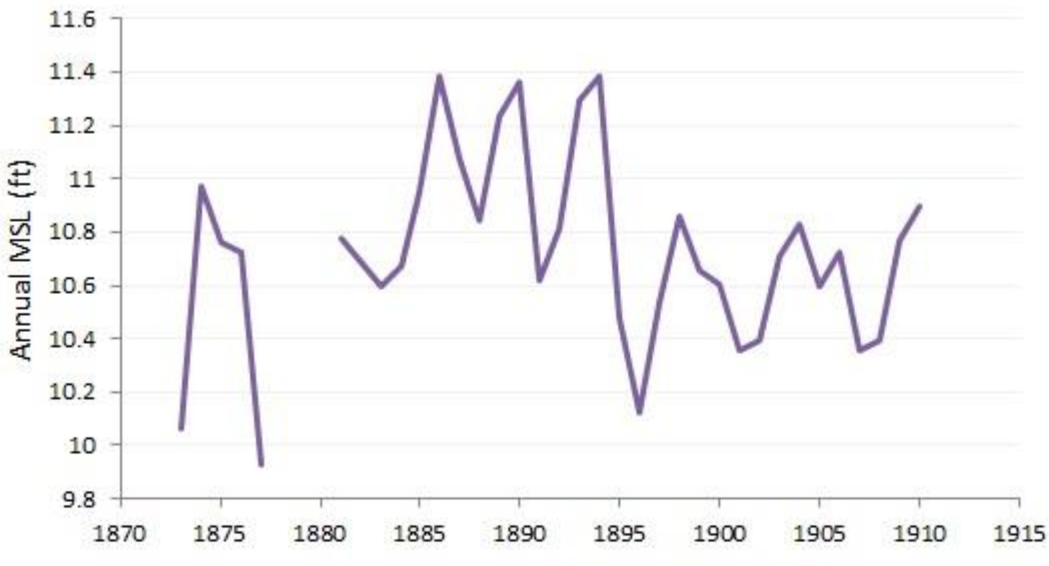

Figure 16: Annual Mean River Level from Kidderpore showing the suspected datum step around 1894, (compared with the earlier and later data)

Issues and corrections

The Kidderpore data from 1885 up to 1894 appears to have a different datum or a +0.4 ft offset to the later data from 1921 onwards, and also to the later ancillary data as well as the earlier 1870s data (figure 12). As early as 1895 this was reported as anomalous when the annual mean level dropped by 0.25 ft below the value for the previous year. By the early 20th century the step of 0.4 ft was noted, and it was suggested this was possibly due to changes in river flow rates. However contemporary comments indicate that if anything, river flow rates should have given an opposing effect. In the 1895 general report on the Great Trigonometrical Survey it is mentioned that the Kidderpore tide gauge house piling supports moved when vessels passed, but more pertinently a gauge zero offset of 0.105 ft was noted upon the inspection for that year. It is not known if this was accounted for in the published results. It is also possible a physical datum shift occurred in the reference point because in 1894/1895 the tidal bench marks were moved as part of the new dock works. The primary tidal observatory was rebuilt in April 1917, and moved to Garden Reach in 1932.

Comparing to the data from Diamond Harbour, there is a probable datum shift in 1975 of around +200 mm in the Garden Reach data (figure 17). This biases the long term acceleration component high, and a more accurate estimate of river level rise may be derived if a composite of Diamond Harbour and Calcutta is used.

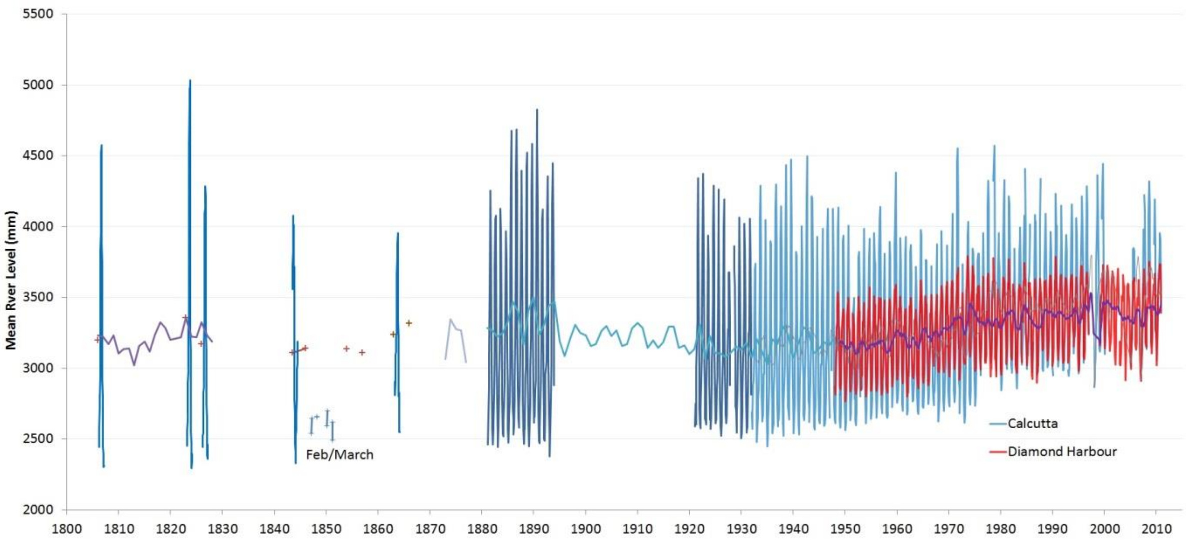

Figure 17: All of the published monthly and annual data found by this author to date from Kidderpore, Garden Reach and post 1950 data from Diamond Harbour, corrected as far as possible for datum shifts as well as differences between MTL and MSL, all referenced to the Old Kidderpore Dock Sill.

The usefulness of the data from this site is obviously compromised by the influence of several factors other than tide. However, the length of the data series, and the general long term variation and secular trend make this corrected data useful in terms of providing some context and constraints for the Indian Ocean sites discussed here. It can be seen that the Tidal River level remained relatively stable through the 19th century, whereas a pronounced positive but variable trend starts diverging away from the long term linear fit somewhere in the 20th Century, even for Diamond Harbour, which is less affected by significant urban subsidence. This generalised pattern is common to other very long series.

Other data from the Indian Ocean

Old 19th century data also exists for other sites, and some of these have continuous annual data from the late 19th Century to the 1920s e.g. Port Blair, Moulmein (Mawlamyine), and Rangoon (Yangon). These sites are characterised by relatively high quality records with high correlation over this early period, but since this time, gaps in the record, and poor datum control combined with other effects (tectonic level changes at Port Blair, and water extraction related subsidence at the other two sites) limits their utility for overall 20th century analyses. The earlier data however serves as a sanity check for the other regional data from this period.

Conclusions.

The extended and corrected time series for the Indian Ocean appear to resolve many of the issues and differences in the previously reported tide gauge data sets for the region. The high degree of coherence in the long term MSL variation that is evident over large stretches of coastline in the Western and Eastern seaboard of the USA, or along the Western coast of Australia, or at the various sites in Northern Europe, is now also evident in these Indian Ocean tide gauge time series (Figure 18). This is suggestive of a global centennial scale pattern of sea level rise and acceleration of order 0.01mm/yr^2, recently summarised in Hogarth (2014) which better quantifies previous work on global sea level acceleration (Woodworth et al 2009, 2011, Church and White, 2011). It is hoped that this date can be further refined and possibly further extended as part of ongoing global data archaeology efforts (Nagarajan et al 2007, Caldwell 2013, Talke and Jay 2013), and used to improve long term assessments of global MSL and further reduce the uncertainty in regional and global sea level trend analysis.

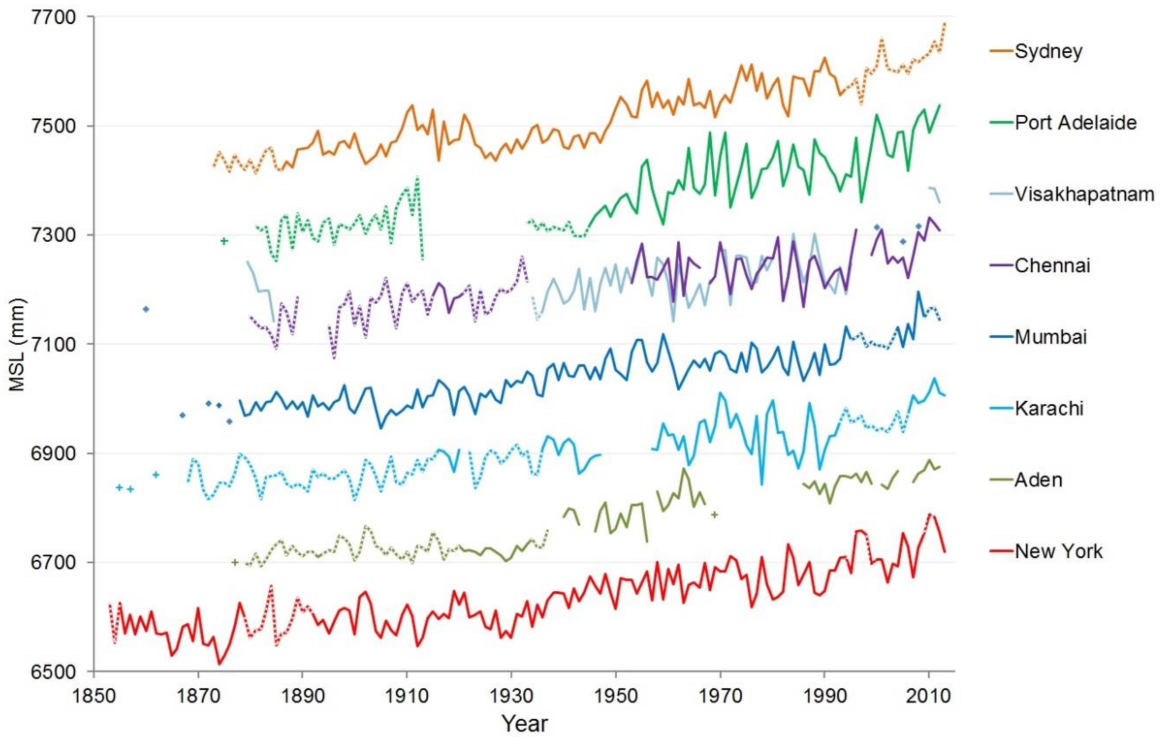

Figure 18: Some of the extended Indian Ocean time series shown in relation to other long time series from the Northern and Southern hemispheres. The dashed lines indicate where data has been infilled or extended in this analysis.

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