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TECHNICAL NOTE

Is the Sea Level Stable at Aden, Yemen?

Albert Parker[1] · Clifford D. Ollier[2]

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Abstract

Background The sea level records since the start of the twentieth century show oscillations with many periodicities up to multi-decadal. The sea level may then change because of local factors such as subsidence or uplift, and global factors such as mass addition and thermal expansion of the oceans.

Purpose We use non-aligned data from the tide gauges of Aden, and the tide gauges of Mumbai and Karachi, to reconstruct the most likely pattern of sea levels for these three locations of the west Indian Ocean.

Methods Linear and parabolic fittings of monthly average mean sea levels (MSL) from the different tide gauges of the three locations were carried out. Alignment of the different data sets based on historical information, similarity of patterns, and break point alignment was done.

Results Analysis of the tide gauge data of Aden, Yemen shows that without arbitrary alignment of data, Aden exhibits very stable sea level conditions like those in Mumbai, India and Karachi, Pakistan, without any significant sea level trend.

Conclusion The reconstructed tide gauge records of Aden, Mumbai and Karachi are perfectly consistent with multiple lines of evidence from other key sites of the Indian Ocean including Qatar, Maldives, Bangladesh and Visakhapatnam. The sea levels have been stable since the start of the twentieth century in Aden similar to Karachi and Mumbai.

Keywords Tide gauge records · Discontinued measurements · Alignment of data · Sea-level rise · Sea-level acceleration

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✉ Albert Parker
albert.parker.2014@gmail.com

[1] Bundoora, Australia

[2] School of Earth and Environment, the University of Western Australia, Crawley, Australia

1 Introduction

The sea-level rise measured by a tide gauge is relative, and it is the result of both the land and the sea movement. The sea movement exhibits very well-known inter-annual, decadal, and multi-decadal oscillations. What is proposed as a single record in databases such as the Permanent Service for Mean Sea Level (PSMSL) (PSMSL 2017a) is often the composition of data collected by different instruments, sometimes in different locations or over different time windows, with significant gaps in between one measurement and the others. This is the case of the Aden, Yemen tide gauge that is the only tidal location of the Arabian Peninsula spanning a time window long enough to infer a trend and acceleration of the relative sea level (assuming there was continuous measurement and no quality issue). In Aden, similar to Karachi and Mumbai and other tide gauges of the area, a single-tide gauge record is the result of multiple sets of data subjectively coupled together. While a new tide gauge is recording since about 2007, the alignment of the previous data is continuously changing.

The sea levels of the north Indian Ocean including Aden, Karachi, and Mumbai were analysed by Unnikrishnan (2007) and Unnikrishnan and Shankar (2007). Annual-mean relative sea-level data up to the year 2004 were downloaded from PSMSL. These values reflect prior versions of the data aligned by PSMSL that we may call (n-2). The data are shown in Fig. 5 (from Unnikrishnan 2007). In the case of Aden and Karachi, the new data from the new tide gauge are missing. For Mumbai, there is already 1 year of the new data. Trends are given in Unnikrishnan and Shankar (2007).

In Aden, with data 1880–1969, the trend was + 1.21 mm/year.

Per the US National Oceanic and Atmospheric Administration (NOAA) Centre for Operational Oceanographic Products and Services (NOAA 2017a), with data from an intermediate version of a single-tide gauge record by PSMSL we may call (n-1), the sea-level trend in Aden is + 3.02 mm/year based on the monthly average mean sea-level (MSL) results 1879–2011, Fig. 6a (image from NOAA(2017b) downloaded on September 13, 2017).

Using the online analysis tool of Burton's sealevel.info (Sealevel.info 2017a), with data from the latest update of the PSMSL database that we may call version n, with 2 more years of data, but also with some other corrections, see the data before the year 1900 shifted up, the sea-level trend in Aden is + 1.35 mm/year based on the MSL results 1879–2013, Fig. 6b (image from Sealevel.info (2017b) downloaded on September 13, 2017). Worthy of note, the acceleration is now large and positive.

Realignments of past data and addition of new data possibly misaligned have, therefore, increased the trend to + 3.02 mm/year from + 1.21 mm/year, Fig. 6a vs. Figure 5, and then reduced the trend to 1.35 mm/year, Fig. 6b vs. a.

The analysis of an arbitrarily adjusted and extended Aden tide gauge to motivate the latest shift of data from version (n-1) to version (n) may be found in the PSMSL note of 2016 (PSMSL 2016).

The previous arbitrary shift of the data 1879–1893 vs. 1916–1933 in the "revised local reference" (RLR) is corrected in this report. The arbitrarily adjusted and extended Aden tide gauge data are here correlated to a similarly unlikely version of the Mumbai tide gauge also extended and further "corrected" for the specific study, Fig. 7. This work reflects the new interest towards accelerating tide gauge records even if obtained at the expense of profiles with lower trend.

Figure 8a, b finally present the sea level trend in Mumbai, India and Karachi, Pakistan per Sealevel.info (2017c, d) with data from the latest update and revision version (n) of the PSMSL data base.

In Karachi, with data 1916–1992, the trend was + 0.61 mm/year, Fig. 5. Realignments of past data and addition of new data have increased the trend to 1.85 mm/year, Fig. 8a. In Mumbai, with data 1878–1993, Fig. 5, the trend was + 0.77 mm/year, not that far from the + 0.80 of Fig. 8b. In Mumbai, the annual average of 2004 is below the annual average of 1993, and the annual averages of 1960–1993 are generally lower than the annual averages of 1935–1960.

Like Aden, Karachi has a very large positive acceleration resulting from the alignments of many unaligned past records and the latest short record. For Mumbai, the trend is also due to an alignment of data continuously recorded (but misaligned in two sections), and the latest short record.

As the past data are continuously changing and addition of new data from different tide gauges coupled to realignments of prior data continuously changes the patterns of sea levels, the images in the Appendix help tracking these changes otherwise undetected (the new PSMSL RLR data sets replace the old PSMSL RLR data set at every revision) and have, therefore, reference value.

Differences with prior studies in the literature based on data sets not available any more are even more striking.

Pirazzoli (1986) noticed that the record for Mumbai between 1952 and 1962 reversed the entire rising trend for the previous 30 years.

Per Douglas (1991), the sea-level trend in Mumbai over the time window 1930–1980 was negative, − 0.3 mm/year.

In the latest PSMSL RLR, over the same time window, it is + 0.52 mm/year.

The sea levels in India, including Mumbai, and in Karachi, Pakistan, have been recently analysed and discussed in Parker and Ollier (2015) and in Parker (2016). In both cases, it was shown that the latest positive trends in the PSMSL RLR data are only the result of arbitrary alignments, and alternative and more legitimate alignments reveal very stable sea-level conditions.

Contrary to the adjusted data from tide gauges and the unreliable satellite altimeter data, properly examined data from tide gauges and other sources such as coastal morphology, stratigraphy, radiocarbon dating, archaeological remains, and historical documentation indicate a lack of any alarming sea-level rise in recent decades for all the Indian Ocean (Mörner 2007, 2010, 2014, 2016a). All the key sites indicate a sea-level rise of about zero mm/year, at least over the last 50 years (Mörner 2007, 2010, 2014, 2016a). Goa has changes in sea level almost identical to those obtained in the Maldives and in Bangladesh even over longer time windows. Mumbai and Visakhapatnam on opposite sides of the Deccan Plateau also suggest a virtually stable sea-level condition in the last 50 years. In Qatar, the coastal records indicate a long-term stability of the present coastal regime (Mörner 2015a, b, 2016b).

Here, we analyse the raw, or "metric", and the adjusted, or "revised local reference" (RLR) for the tide gauges of Aden, Yemen, Mumbai, India, and Karachi, Pakistan to answer the question 'Is the sea level stable at Aden, rising at about 1 mm/year or rising at above 3 mm/year?". The trends suggested by the three latest PSMSL RLR definitions of MSL are indeed in sharp contrast to other evidence.

2 Methods

The alignment of tide gauge data is difficult to perform with accuracy. It is always highly questionable to shift data collected in the far past without any proven new supporting material. In the case of Aden, we analyse the PSMSL alignments starting from the unaligned metric data, introducing possible break-points when there has been a change of tide gauge or there has been a suspicious alignment, and enforcing break-point alignment when connecting sets of data spanning sufficiently long-time windows. Finally, we also look for consistency in between neighbouring tide gauges. The analysis of the metric data in Aden is, therefore, coupled to the analysis of the metric data at Mumbai and Karachi.

3 Results

3.1 Data Analysis for Aden

The data of Aden, Yemen are the only long-term tide gauge record to consider understanding the sea-level rise in the Arabian Peninsula. Aden has data collected over a sufficiently long-time window, starting in 1879 and ending in 2013, despite many gaps. The single record is the composition of five different sets of data misaligned, very likely obtained from different tide gauges in different locations. Data are available from PSMSL (2017b) (Station ID: 44, Latitude: 12.788333, Longitude: 44.974167, Time span of data: 1879–2013, Completeness (%): 50).

PSMSL has two sets of data. The first is "*metric*", basically raw data. The second is data with historical adjustments not properly documented, the "*revised local reference*" (RLR), where PSMSL reduces the data set to a common reference point and re-aligns the data that were often misaligned to produce a long record.

While adjustments are certainly necessary to produce a tide gauge record that may be analysed to infer a trend of the local relative sea level, the way that the alignment is performed may introduce rising or decreasing trends even where the true sea level is oscillating without any trend. How can we perform a proper alignment of data when there are gaps of years and the tide gauge has been moved, destroyed, or replaced? It is hard to say, as there is usually no extra information to lead to a correct decision.

The metric data for Aden, Yemen, Fig. 1a, b, clearly show 5 sets of misaligned measurements: 1879–1893; 1916–1933; 1937–1956; 1957–1969; 2007–2013.

There may be other misalignments, as the sections of the older Aden data are taken from the several editions of the Publications Scientifiques (Pub Sci) which are available as pdfs on the PSMSL website. They are for: 1879–93 (A), 1916–1933 (D1), 1937–1956 (D2), 1957–1958 (E), 1959–1960 (F), and 1960–1964 (G). There is no information about the origin of the data 1964–1969. The letters refer to the editions of the Pub Sci. All data should be mean sea level (MSL) except for 1937–1956 which are MTL (high and low waters). The different sets explain the jumps in the metric data.

As far as the 1879–93 data are concerned, officially was the information in Pub Sci A led PSMSL in 2008 to determine an "RLR factor" for that set which looked anomalous. It was not till 2013 that PSMSL realized that there was more information available in the annual-mean values for 1894–1920 that tacked on to the 1879–93 data and were implied to be the same datum. Therefore, there could not be a jump given no gap in between. That, in turn, implied that the RLR factor for 1879–93 should be the same from the start of the record all the way to 1933. PSMSL also made a subjective correction to convert the 37–56 data from MTL to MSL.

From this figure, we may notice:

Each individual data set does not show any sign of rising sea levels.

From the data 1879–1893 and 1916–1933 considered aligned, the rate of rise is 0.139 mm/year. This record is 54 years long but with gaps.

From the data 1937–1956, the rate of rise is 0.488 mm/year. This record is only 20 years long and not long enough to infer any trend.

From the data 1957–1969, the rate of rise is 0.278 mm/year. This record is only 12 years long and not enough to infer any trend.

By considering the data 1937–1956 and 1957–1969 aligned (which they are clearly not), the rate of rise is 1.89 mm/year.

The alignment of the data collected with a new instrument after 2007 is probably also mistaken.

Starting from October 2007, there is a new tide gauge providing 1 min sea-level data to the Intergovernmental Oceanographic Commission (IOC) Sea Level Station Monitoring Facility Ostend. It is claimed that as the relationship for the prime bench mark remains the same, there is no need to alter RLR, but it does not seem the case. The alignment appears to be far from but perfect.

As reported in Global Sea Level Observing System (GLOSS) (GLOSS 2006), the Great Triangulation Survey of India (GTS) provided various benchmarks around

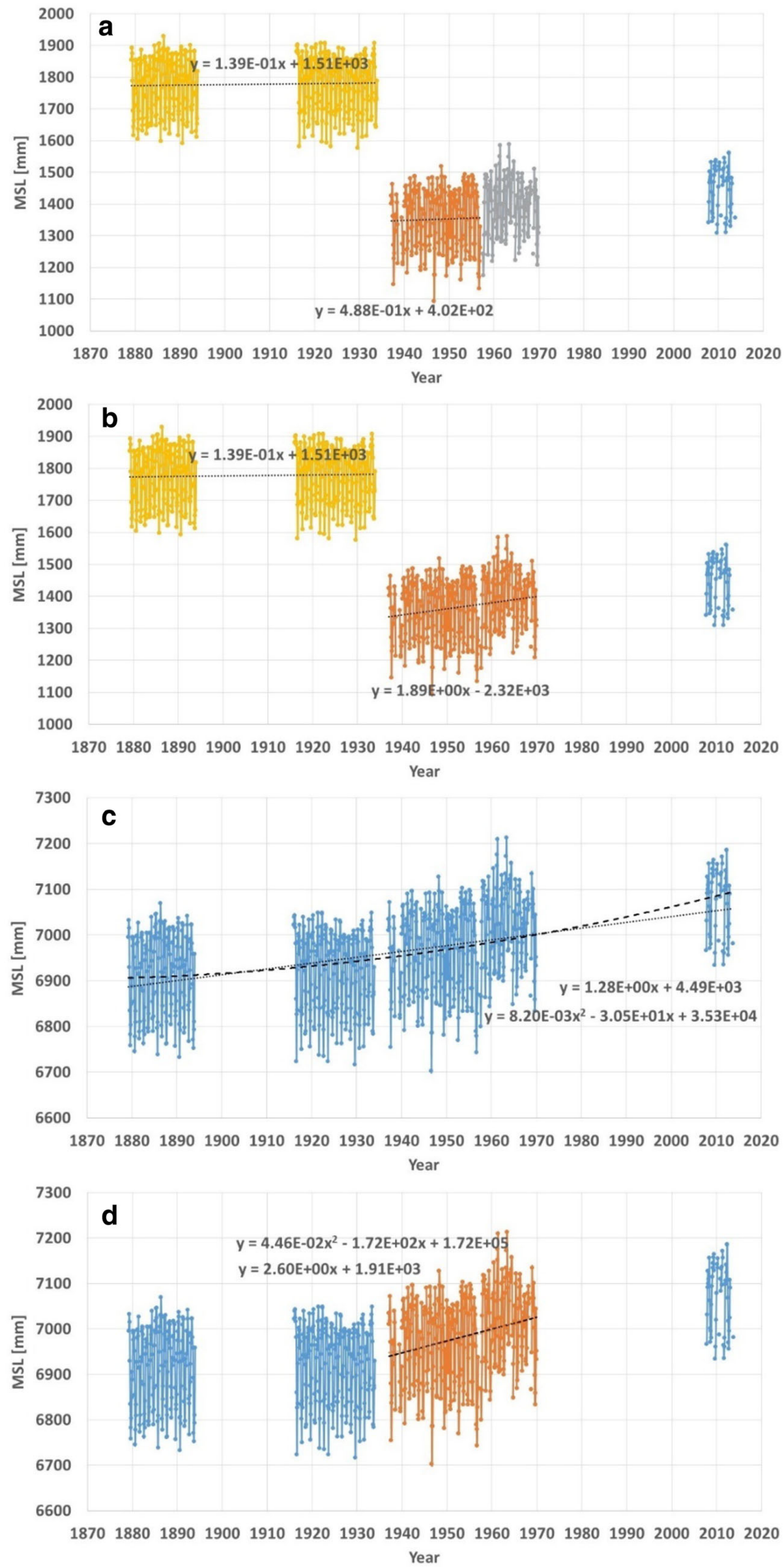

Fig. 1 Monthly average mean sea levels vs. time. **a** and **b** metric (raw) data for the Aden tide gauge. Data from PSMSL (PSMSL 2017c) downloaded September 12, 2017. **c** and **d** Revised local reference (RLR, adjusted) data for the Aden tide gauge. Data from PSMSL (PSMSL 2017d), downloaded September 12, 2017

Tawahi Port of Aden. However, the primary benchmark at Fairway House/Post Office House next to Post Office Pier was no longer existing at the time of the report, while the other remaining vertical bench mark at the North-East corner of the Port Engineers Office (PEO) and at the Pilots Pier tide gauge hut were in poor condition and in need of urgent repairs or replacement.

Problem of understanding sea levels when using different instruments over the years is that the sea levels fluctuate with very well-known inter-annual, decadal, and multi-decadal oscillations, so the sea level is not the same every year. In addition, you do not have any measure of the absolute position of the different instruments, as the global positioning system (GPS) tracking of fixed domes is only recent and still inaccurate, not many tide gauges have a nearby GPS dome, not many tide gauges with a nearby GPS dome have their position tracked vs. the GPS dome. The alignment of the data collected with a 40 years long gap is often completely arbitrary.

The RLR data for Aden, Yemen, show that the misaligned measurements have been composed to produce a high trend, high acceleration record. After the latest PSMSL corrections and addition to generate the RLR data, there is a trend of + 1.28 mm/year and a large acceleration of + 0.0164 mm/year^2 in the 134 years long but 50% complete tide gauge record.

Within the short time window 1937–1969, the trend has been increased to + 2.60 mm/year from the + 1.89 mm/year of the previously misaligned data. One would have expected the data 1937–1956 to be shifted up vs. the data 1957–1969. The adjustment has done just the opposite, and the data are being shifted down. Similarly, the data before 1937 have all been shifted down. The data collected since 2007 have not been moved vs. the data collected 1957–1969.

There is a RLR diagram for the adjustments and few notes in the station documentation detailing some of the recent corrections that are responsible for the RLR trend. 5.141 m are added to data values up to 1933 to refer to RLR of year 1964. 5.625 m are added to data values 1937 onwards to refer to RLR of 1964. In 2013, the historic data for Aden 1879–1933 has been reviewed. The RLR factor for that period has been reset. In 2016, a value of MTL–MSL = 16 mm has then been applied to the RLR data for the period 1937–1956.

It must be mentioned that other data were collected for Aden, but they are not used by PSMSL. As written in PSMSL (2016), there are also early automatic tide gauge data for a few months of 1846 with the lack of information about the vertical datum despite being tabulated, reduced to a nominal MSL and published, as well as early annual data for 1877 and 1879 published in the Great Trigonometrical Survey (GTS) records. A new self registering tide gauge was set up in 1879 and the PSMSL record starts in this year.

As reported by the Global Sea Level Observing System (GLOSS 2004), there was in that year operational a tide gauge that is measuring without any major problems since 2001. Yet, no calibration operation was carried out and no data retrieval or processing or archiving system was in use. Within Aden Harbour, a level gauge was deployed in 1969. This instrument had operated well up till 1994, but PSMSL declares that they stopped getting data in 1969, and data transmission was only resumed in 2007. The report mentioned that a new generation tide gauge was installed at the entrance of Aden Harbour same year 2004. It was equipped with other sensors and data transmitted in real time through VHF to a processing unit located near the Aden International airport.

As better clarified in GLOSS (2006), tide gauges have operated at the Port of Aden from 1879 up to approximately 1986, and later from 2000 to present date. The data have only been submitted to IOC GLOSS/PSMSL for the period of 1879–1969. Tide gauges have previously operated from the Post Office Pier, Tawahi at Aden and from the existing tide gauge hut at Pilots Pier, Tawahi. From approximately 1974 up to around 1986, a Munro float tide gauge was located at the Pilots Pier tide gauge hut. The instrument has been removed from the tide gauge hut. The tide gauge hut at the Pilots Pier was used for the Tide Monitor pressure gauge operated from 2000 to 2005. A similar gauge operated at Al Hudayda from 2001 to 2002. An integrated weather station/sea-level/wave gauge system was installed in 2004 and was fully operational in 2006 at the Port Control Tower, Ras Marbut, Steamer Point at Tawahi. This is the only operational tide gauge in Aden as per 2006.

Researchers must be cautious with any time series that comes in chunks like Aden, but there are some similarities with Mumbai, the nearest long record although across a large ocean, that may help address the issues.

Finally, officially, the radar data were aligned to benchmarks using dipping measurements. There are offsets in using radar data which must be estimated by either dipping or tide pole measurements. The Aden installation happened at about 2008 as gauges in several places in Africa and the Indian Ocean, and the same methods were used for all of them.

3.2 Data Analysis for Mumbai and Karachi

The data available for the nearby locations of the Arabian Peninsula, such as Salalah, Masirah and Muscat B, in Oman, and Mina Sulman, in Bahrain are too short and fragmentary to help with the alignment of the data in Aden, Yemen. The 3 tide gauges of Oman are short records, not even 20 years in the longest tide gauge record of Masirah. The tide gauge of Bahrain started recording in 1979, but the completeness is only 66% for a 6-year gap 1997–2003, and no further update since 2007. As, in Aden, there are only few years of data over the same time window to compare with (in Aden, after the tide gauge measurements stopped in 1969, the measurements from the new installation only restarted at the end of 2007 and appear to have been so far quite troublesome, with many gaps), there is no help that can came from the neighbouring tide gauges of the Arabian Peninsula. It is necessary, though difficult, to correlate the relative sea level in Aden with the relative sea level in other locations of the Indian Ocean, such as Karachi, Pakistan and Mumbai, India.

Contrary to what is claimed in PSMSL (2016), there is no reason to expect that Aden may have a strong correlation to Mumbai and Karachi. In addition, these other two tide gauges also suffered of arbitrary corrections Parker and Ollier (2015) and Parker (2016).

Data for Mumbai may be found in PSMSL (2017e) [Station ID: 43, Latitude: 18.916667, Longitude: 72.833333, Time span of data: 1878–2011, Completeness (%): 91]. The metric and RLR data for Mumbai, India, Fig. 2, clearly show 3 sets of misaligned measurements: 1878–1936; 1937–1994; 2005–2011.

Notice especially that the data 1878–1936 are closed by the December month, and the data 1937–1994 start with the January month, so there is virtually no time gap, yet there is a 677-mm sudden difference between the measurements collected before and after the so-called breakpoint. From the raw data, Mumbai exhibits a very small rate of rise since 2005. If we look at the metric raw data, we may notice that the trend 1878–1936 is a + 0.60 mm/year, while the trend 1937–1995 is largely negative, − 0.72 mm/year. Combining the two trends, one would expect over the longer time window 1878–1936 a small negative trend.

In the RLR data, the small negative trend 1878–1995 is transformed in a + 0.68 mm/year positive trend, that with the latest data 2005–2011 further increases to + 0.80 mm/year. The alignment of the data collected after 2005 with the data collected prior of 1994 does not seem perfect.

There is an RLR diagram for the adjustments and few notes in the station documentation detailing some of the

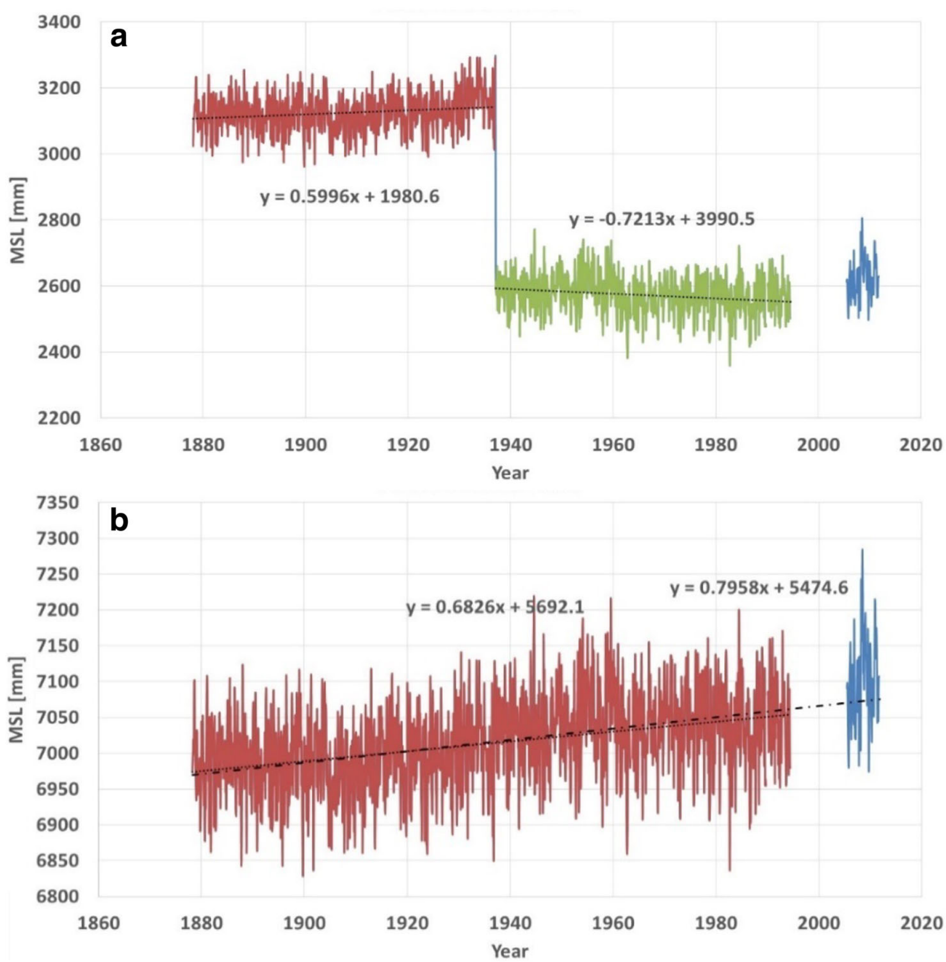

Fig. 2 Monthly average mean sea levels vs. time. **a** metric (raw) data for the Mumbai tide gauge. Data from PSMSL (PSMSL 2017f) downloaded September 12, 2017. **b** Revised local reference (RLR, adjusted) data for the Mumbai tide gauge. Data from PSMSL (PSMSL 2017g), visited September 12, 2017

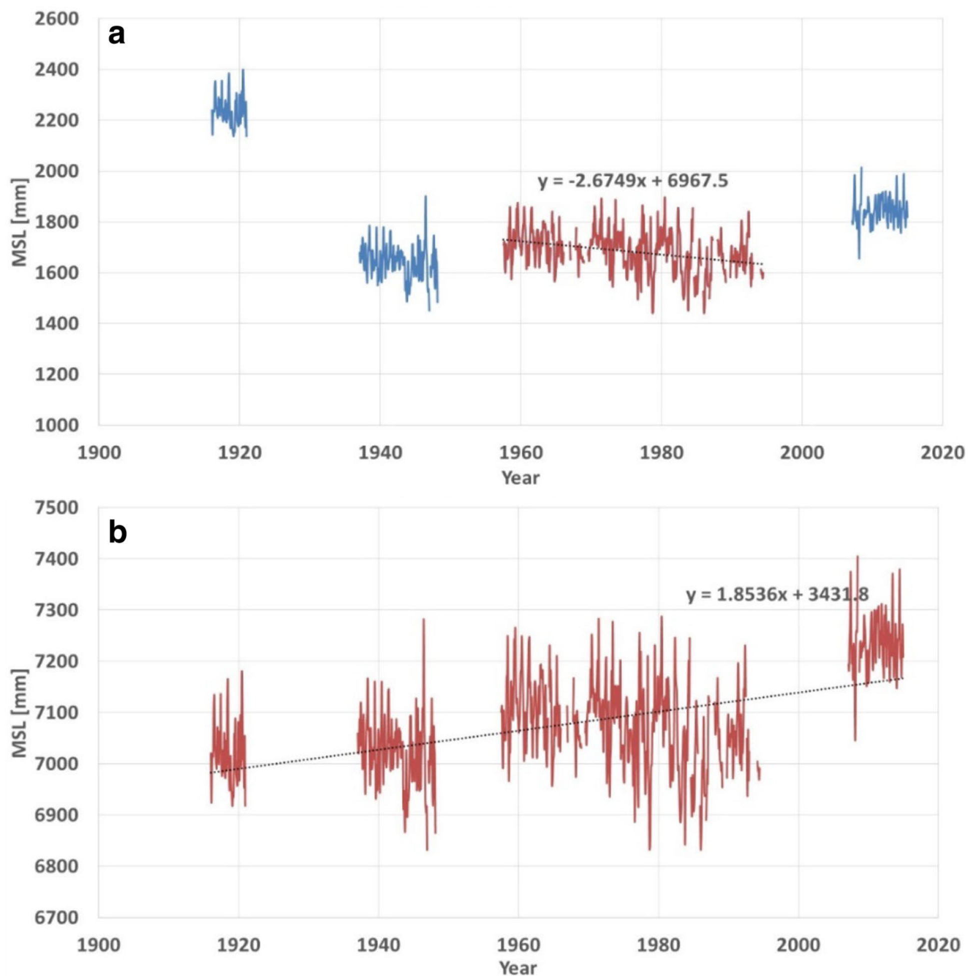

Fig. 3 Monthly average mean sea levels vs. time. **a** Metric (raw) data for the Karachi tide gauge. Data from PSMSL (PSMSL 2017i) downloaded September 12, 2017. **b** Revised local reference (RLR, adjusted) data for the Karachi tide gauge. Data from PSMSL (PSMSL 2017j) downloaded September 12, 2017

recent corrections that are responsible for the RLR trend for Mumbai. The benchmark and datum details for 2005 are assumed to remain the same as previously used. In 2010, the benchmark was found to be different for the historic data up to 1936 and 1937 onwards. In 2016, a value of MTL–MSL = 31 mm was applied to the RLR data for the period 1931–1958.

The latest RLR data are not consistent with past works such as Unnikrishnan (2007), Unnikrishnan and Shankar (2007), Douglas (1991), Pirazzoli (1986), and with the recent work Parker and Ollier (2015).

Data for Karachi may be found in PSMSL (2017h) (Station ID: 204, Latitude: 24.811667, Longitude: 66.975, Time span of data: 1916–2014, Completeness (%): 57). The metric and RLR data for Karachi, Pakistan are presented in Fig. 3. Karachi seems to suffer from the same issues as Aden, with four misaligned sets of data: 1916–1920; 1937–1948; 1957–1995; 2007–2014.

These data show individually very little rise, and a lowering in the longest continuous record. Then, the RLR has a large trend introduced by arbitrary alignment. The metric trend 1957–1995 is negative, − 2.67 mm/year. In the RLR, the trend 1916–2014 is now + 1.85 mm/year. This is the result of the measurements 1916–1920 having been shifted down, the data 1937–1948 shifted down vs. 1957–1995, and the data from the novel tide gauge relocated in another place claimed to be aligned with the old tide gauge. The alignment of the data collected after 2005 with the data collected prior of 1995 does not seem perfect.

There is an RLR diagram for the adjustments and few notes in the station documentation detailing some of the recent corrections that are responsible for the RLR trend also for Karachi. It is noted that the gauge at Karachi has been re-sited and is now no longer on Manora Island. However, the new gauge is claimed to have been levelled into the old one. The relationship for the prime bench mark is supposed to be the same and that there is no need to alter the RLR. In 2016, a value of MTL–MSL = 10 mm has been applied to the RLR data for the period 1937–1948.

The latest RLR data are not consistent with the recent work Parker (2016).

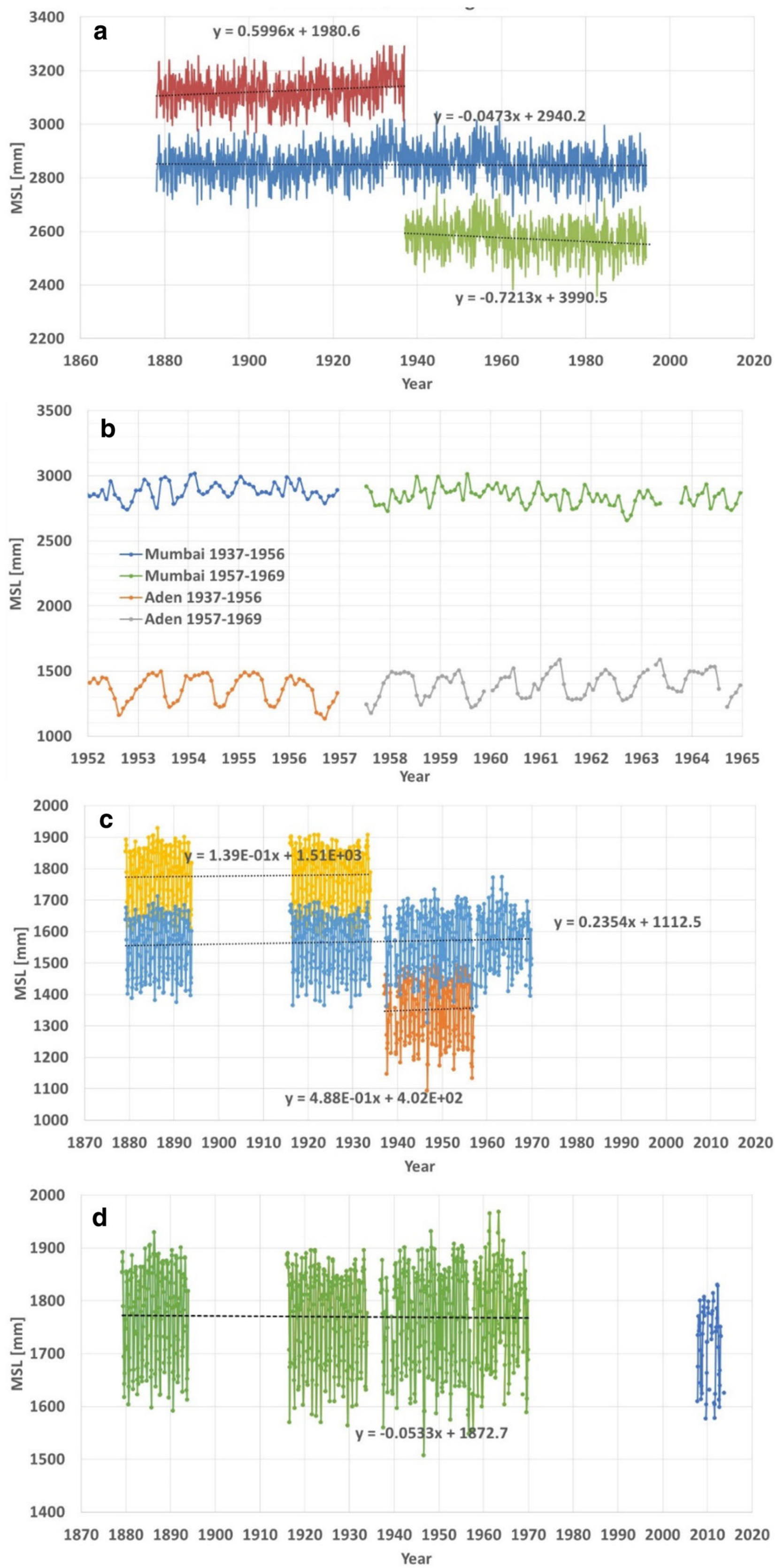

Fig. 4 Monthly average mean sea levels vs. time. **a** Aligned metric data in Mumbai. **b** Aligned metric data in Mumbai and misaligned metric data in Aden. **c** Aligned metric data in Aden. **d** Alternative aligned metric data in Aden

3.3 Aligned Data in Aden

The metric (raw) data show misaligned results. The metric data are the data as originally provided, or suffering from historical adjustments. What are more dangerous are the corrections recently introduced to the past to magnify the sea-level trend or the acceleration. As shown in the prior section, the adjustments introduced by PSMSL to make the RLR are arbitrary in Aden, Karachi, and Mumbai.

While the metric data do not tell us, which is the correct trend, they tell us that the alignments made to produce the RLR are very likely wrong, because they are inconsistent with the individual measurements components, none of which showing any sign of increasing sea levels, and because the adjustments are always in the direction to produce a large rise in sea level.

The sea-level histories of Mumbai and Karachi have been previously addressed in Parker and Ollier (2015) and Parker (2016) where it was shown that the sea levels have been stable for about a century in both locations.

In case of Mumbai, there is no gap in between the measurements. Therefore, it makes sense to compute the relative shift of the data up to December 1936 vs. the data from January 1937, both of sufficient length and completeness, by requiring same linear trend values at the discontinuity. Figure 4a presents the result of the aligned metric trend in Mumbai. The latest data 2005–2011 are difficult to align, because they only cover 6 years of data after a 10-year gap and we prefer not to use these data. The new alignment of the data 1878–1936 and 1937–1994 seems by far superior to the one proposed by PSMSL. The aligned metric data 1878–1994 show a trend of − 0.05 mm/year, i.e., nearly perfect stability, as previously highlighted in Parker and Ollier (2015).

The metric data in Mumbai help to align the metric data in Aden. While in PSMSL (2016), the Aden tide gauge result is reshaped for similarity with a questionable reconstruction of the Mumbai tide gauge result, here, we look for similarity with the more reliable record of Fig. 4a.

In Aden, the metric data 1879–1893 and 1916–1933 are already better aligned than in the previous RLR versions, and there is absolutely no reason to shift down the data 1879–1893 vs. the data 1916–1933.

The data 2007–2013, similar to Mumbai, are impossible to align, as they are 6 years of data after a gap of 38 years.

The correlation between Mumbai and Aden is anything but perfect. However, the comparison of the data over a time window of 20 years covering the break-point in between December 1956 and July 1957 gives interesting clues.

While, in Mumbai, the data collected before December 1956 are higher than the data collected after July 1957 (the peaks and valleys are higher), in Aden, the peaks and valleys are higher after July 1957 than they were before December 1956, Fig. 4b. Therefore, if a shift should be make for compliance with neighbouring tide gauge results, the data after July 1957 must be shifted down and not further up as done in the RLR. We shift down of 30 mm the data measured July 1957–December 1969. This measure is certainly not less motivated than shifting down the data January 1937–December 1956 of 16 mm as done in the RLR by PSMSL. An even larger downward shift is plausible.

The data 1879–1933 and 1937–1957 are finally aligned, Fig. 4c using the same approach followed for Mumbai in Fig. 4a. The relative shift of the data up to 1933 vs. the data from 1937, both of sufficient length and completeness, is performed by requiring the same linear trend values at the discontinuity in 1935. The sea-level trend 1879–1969 is now + 0.23 mm/year.

Alternatively, Fig. 4d, the Aden data 1879–1969 may also be aligned by considering four sets of data and discontinuities in January 1905, June 1935, and March 1957, and requiring same linear trend values at the discontinuities. The sea-level trend 1879–1969 is now − 0.05 mm/year.

The aligned metric records of Mumbai and Aden consistently show stable sea levels up to 1995 and up to 1969. The stability of the Mumbai sea levels was also previously proven in Parker and Ollier (2015). A similar stable sea level has been demonstrated in Parker (2016) for Karachi.

The tide gauge result of Aden is perfectly consistent not only with the tide gauge results for Karachi and Mumbai. It is also consistent with the multiple lines of evidence, tide gauges, coastal morphology, stratigraphy, radiocarbon dating, archaeological remains, and historical documentation, for a stable sea level of about zero mm/year experienced over the last 50 years in all the key sites of the Indian Ocean (Mörner 2007, 2010, 2014, 2015a, b, 2016a, b).

4 Conclusions

The tide gauge record of Aden is a composite derived from 5 distinctive sets of measurements, with the historical data, comprising 4 of these sets, ending in 1969, and the novel measurements with a new tide gauge, starting in 2007. By revising the alignment of the data up to 1969, and neglecting the misaligned new measurements, the sea levels are only very weekly rising at − 0.05 to 0.24 mm/year in Aden over the 20th century.

In Mumbai, the tide gauge record is the composite of 3 distinctive sets of measurements, with the historical data, comprising 2 of these sets, ending in 1994, and the novel measurements with a new tide gauge, starting in 2005. By revising the alignment of the data up to 1994, and neglecting the misaligned new measurements, the sea levels are perfectly stable over the 20th century.

In Karachi, the tide gauge record is the composite of 4 distinctive sets of measurements, with the historical data, comprising 3 of these sets, ending in 1995, and the novel measurements with a new tide gauge, starting in 2007. By revising the alignment of all the data, the sea levels were previously shown in Parker (2016) to be weekly increasing at +0.18 mm/year over the twentieth century.

The sea levels have, therefore, been stable in Aden, as at Karachi and Mumbai, over all the 20th century.

These and other key sites of the Indian Ocean indicate a stable sea level of about zero mm/year over the last 50 years, as shown in Mörner (2007, 2010, 2014, 2015a, b, 2016a, b), Parker and Ollier (2015) and Parker (2016).

Appendix—different versions of the Aden, Mumbai, and Karachi 471 composite records

See Figs. 5, 6, 7 and 8.

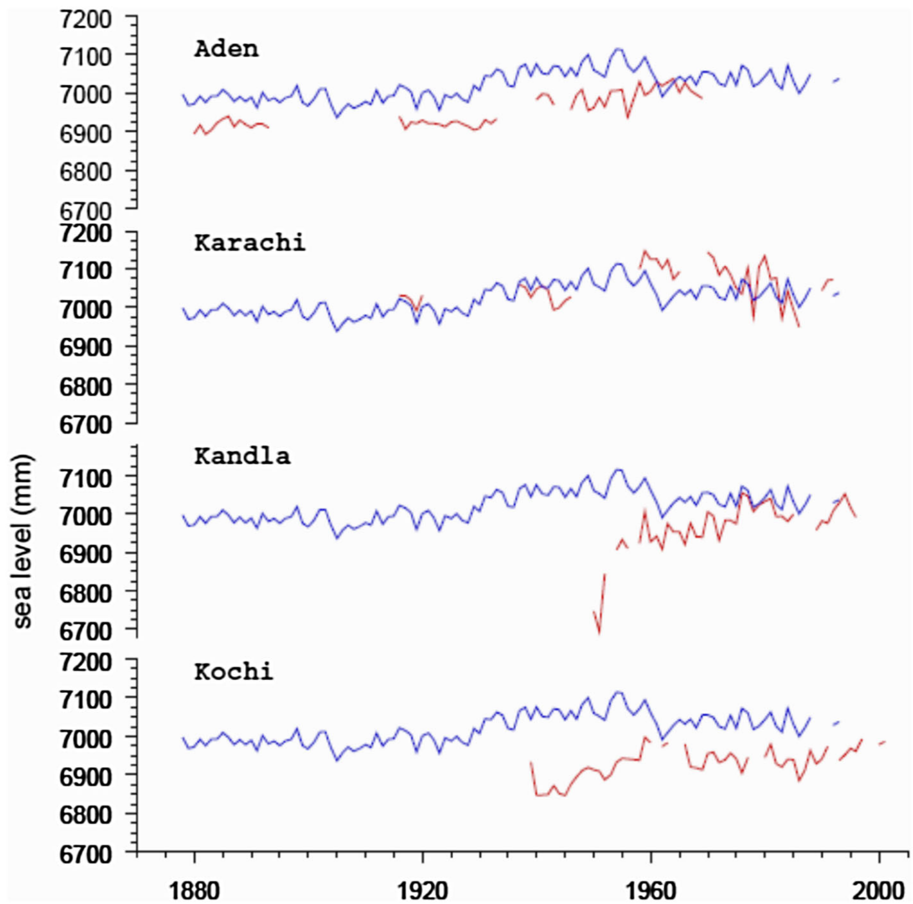

Fig. 5 Prior description of the sea-level patterns in Aden, Karachi and Mumbai. Image from Unnikrishnan (2007). The picture presents the tide gauge records (red) of Aden and Karachi, plus Kandla and Kochi compared with the Mumbai record (blue). These are annual and not monthly mean sea levels. The data were version *n*-2 of a single-tide gauge record from PSMSL

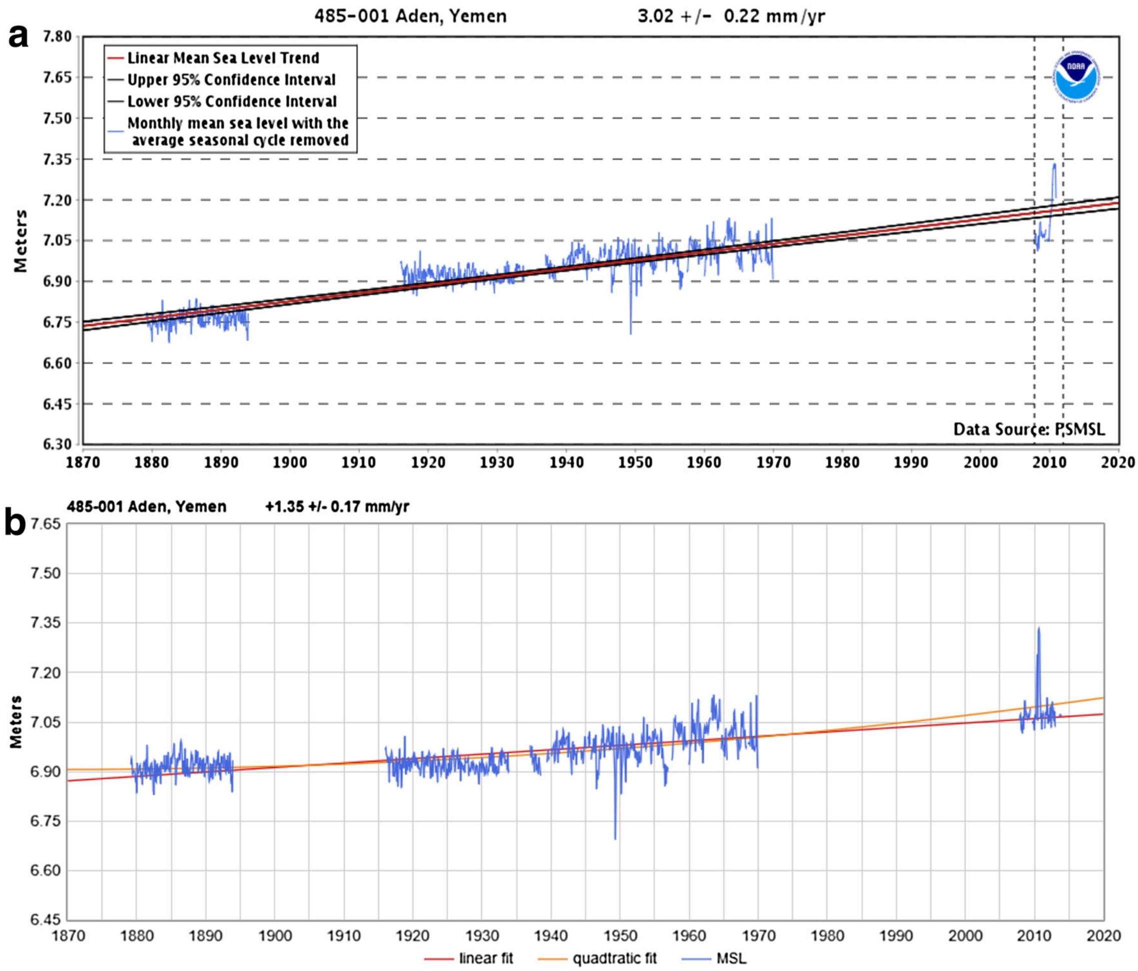

Fig. 6 Sea-level trend in Aden, Yemen per: **a** NOAA with data version n–1 of a single-tide gauge record from PSMSL (image from NOAA (2017b) downloaded on September 13, 2017). **b** Sealevel.info with data the latest version of a single-tide gauge record from PSMSL (image from Sealevel.info (2017b) downloaded on September 13, 2017)

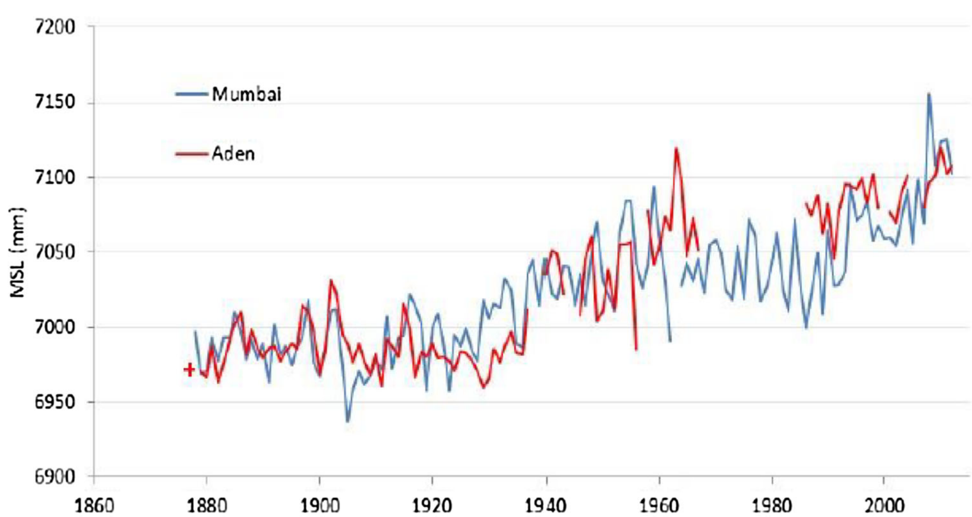

Fig. 7 Motivation of latest PSMSL description of the sea-level pattern in Aden and Mumbai. Image from PSMSL (2016). This is the extended annual data from Aden, overlaid on the corrected Mumbai data from this study, showing higher correlation than prior to the latest corrections. A relative vertical land motion difference of − 0.3 mm/year has been added to the Aden record

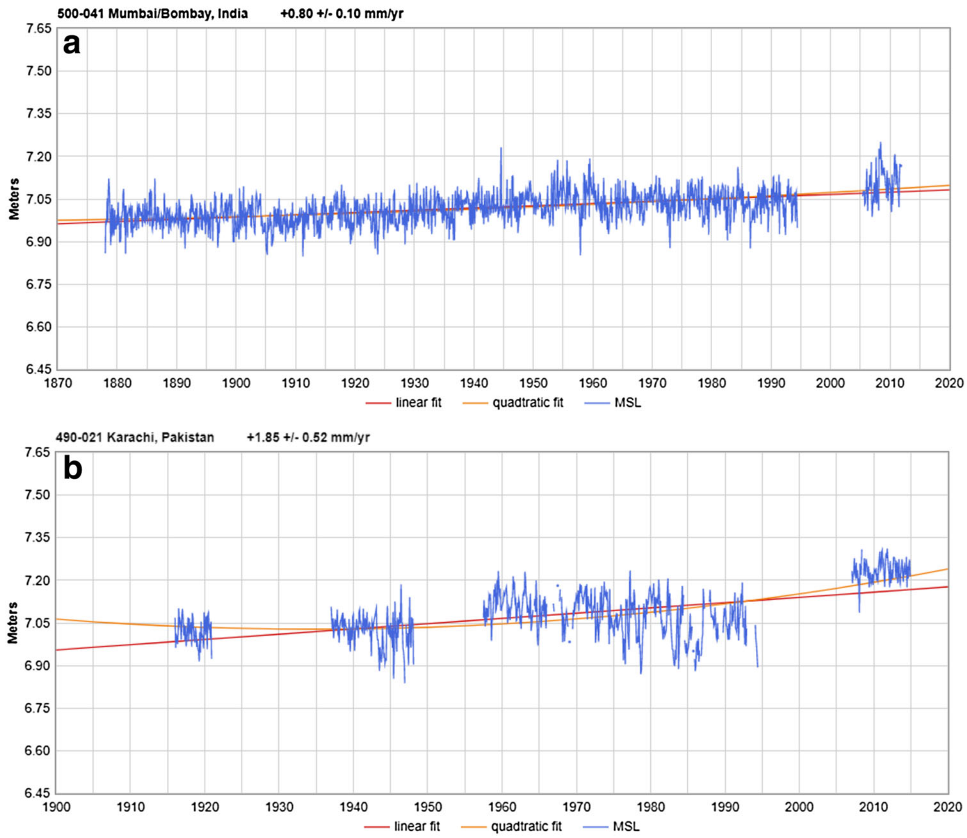

Fig. 8 **a** Sea-level trend in Mumbai, India per Sealevel.info based on version n by PSMSL (image from Sealevel.info (2017c), downloaded on September 13, 2017). **b** Sea-level trend in Karachi, Pakistan per Sealevel.info based on version n by PSMSL (image from Sealevel.info (2017d) downloaded on September 13, 2017)

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