

# **Are sea-level-rise trends along the coasts of the north Indian Ocean consistent with global estimates?**

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## **Abstract**

Mean-sea-level data from coastal tide gauges in the north Indian Ocean were used to show that low-frequency variability is consistent among the stations in the basin. Statistically significant trends obtained from records longer than 40 years yielded sea-level-rise estimates between 1.06–1.75 mm yr<sup>-1</sup>, with a regional average of 1.29 mm yr<sup>-1</sup>, when corrected for global isostatic adjustment (GIA) using model data. These estimates are consistent with the 1–2 mm yr<sup>-1</sup> global sea-level-rise estimates reported by the Intergovernmental Panel on Climate Change.

**Key words:** regional sea-level rise, mean-sea-level, tide-gauge, north Indian Ocean,

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## **1. Introduction**

Apart from changes in the atmospheric variables, global sea-level rise is one of the good indicators of climate change. Increase in global atmospheric temperature has a direct effect on the ocean by causing a rise in ocean temperature and melting of glaciers. Both these processes lead to a rise in global sea level. There have been numerous studies of 20<sup>th</sup> century sea-level rise based on analysis of past tide-gauge data. This was made possible by the availability of monthly-mean sea-level data through the Permanent Service for Mean Sea Level (PSMSL; Woodworth and Player, 2003). The Intergovernmental Panel on Climate Change (IPCC) reported (Church et al., 2001) values between 1–2 mm yr<sup>-1</sup> for the 20<sup>th</sup> century sea-level rise based on tide-gauge data.

Though global sea-level rise has been studied extensively during the last two decades based on tide-gauge data, the same is not true of trends in regional sea level. The variability seen in regional sea level is less well understood owing to two causes. First, the distribution of

tide gauges is not uniform over the globe, and not many records from the tropics are long enough for a reliable estimate of sea-level trends. Second, vertical land movements make problematic the determination of changes at the coast, where the tide gauges are located. Global Positioning System (GPS) measurements to determine vertical land movements are often not available.

Satellite altimetric data, available since 1993, not only overcome this shortcoming, but also have the advantage of spatial coverage: global patterns of sea-level rise using altimetric data, particularly TOPEX/Poseidon, have been widely documented (Nerem and Mitchum, 2001; see Cazenave and Nerem (2004) for a review). The length of the satellite-based sea-level record is too small, however, for estimating long-term sea-level rise.

Studies on sea-level rise in the north Indian Ocean have been few, and are mostly based on tide-gauge data from India. Emery and Aubrey (1989) used monthly-mean sea-level data till 1982 at several tide-gauge stations along the Indian coast to estimate long-term trends in sea level. The trends showed considerable variability because even short records were included in the analysis. This inconsistency was also noted by Douglas (1991), leading him to conclude that the stations in the Indian subcontinent are not suitable for estimating global-mean sea-level rise. Using tide-gauge data all over the globe, Church et al. (2004) used reconstruction methods to determine the spatial pattern of sea-level variability during 1950–2000. These results were used to describe regional sea-level changes and suggest values close to  $2.0 \text{ mm yr}^{-1}$  in the north Indian Ocean, except the northeastern part of the Bay of Bengal, where values of more than  $4 \text{ mm yr}^{-1}$  are found.

In this paper, we make two points. First, we show that the data from several tide gauges along the coasts of the north Indian Ocean are consistent with one another and can be used for estimating regional sea-level rise. In doing this, we extend the work of Unnikrishnan et al. (2006), who used monthly-mean tide-gauge data till 1996 from India to estimate the trends for four selected stations; Mumbai, Kochi, and Vishakhapatnam showed an increase of about  $1 \text{ mm yr}^{-1}$  and Chennai showed a slight decrease. Studies on interannual and interdecadal sea-level variability also show a coherence along the coast of the north Indian Ocean (Clarke and Liu, 1994; Shankar, 1998; Shankar and Shetye, 1999). Second, we include GIA corrections of

vertical land movement and show that sea-level-rise trends for the north Indian Ocean coasts are consistent with global values.

## **2. Data and method**

The location of Indian-Ocean tide gauges with a data record longer than 20 years is shown in Figure 1. Annual-mean relative sea-level data for these stations are available till 2004 from the website of the PSMSL ([www.pol.ac.uk](http://www.pol.ac.uk)). Ideally, a record length greater than 60 years is desirable (Douglas, 2001) to determine trends in long-term sea-level changes. Such records, however, are few in the north Indian Ocean. Only the tide-gauge record at Mumbai extends to more than 100 years.

We first checked the sea-level records for inter-station consistency. We examined all records that have a duration of at least 20 years (see Table 1). The stations considered in the Arabian Sea were Aden (Yemen), Karachi (Pakistan), Kandla, Okha, Mumbai, and Kochi (India); the stations considered in the Bay of Bengal were Chennai, Vishakhapatnam, Paradip, Sagar, Gangra, Diamond Harbour (Kolkata) (all in India), Hiron Point, Cox's Bazaar (both in Bangladesh), Rangoon (Yangon) (Myanmar), and Ko Taphao Noi (Thailand). The stations located between Mumbai and Kochi had records shorter than 20 years and were therefore excluded from the analysis.

We then estimated the trends at stations that had a record longer than 40 years and which passed the consistency check. This was done using a least-squares fit to the annual-mean sea-level data. Stations with a statistically significant trend were retained.

The last step was the application of a correction for vertical land movement. Vertical land movements are associated mainly with two processes, local tectonic activity and glacial isostatic adjustment (GIA), the latter caused by post-glacial rebound of land. Since GPS estimates were not available, we could not account for local tectonic activity; hence, we excluded stations located in tectonically active regions. Estimates for vertical land movement owing to GIA are, however, available from models. We applied GIA corrections using the ICE-5G model (Peltier, 2001; 2004). The model results, available for tide-gauge stations worldwide, were also downloaded from the PSMSL website. ICE-5G results are available for two types of models,

VM2 and VM4. For the coastal regions of north Indian Ocean, the differences between the two in GIA corrections are about  $0.10 \text{ mm yr}^{-1}$ , with VM4 showing lower values. We used the VM4 model results, for applying the GIA corrections.

### 3. Results

The sea-level data from the north Indian Ocean show considerable interannual and interdecadal variability (see, for example, the annual-mean data in Figure 2). These changes are forced primarily by large-scale winds (Clarke and Liu, 1994; Shankar and Shetye, 2001; Han and Webster, 2002) and large changes in salinity (Shankar and Shetye, 1999; Shankar and Shetye, 2001). The wind-forced changes along the Indian west coast are largely forced remotely by winds in the Bay of Bengal (McCreary et al., 1993; Shankar et al., 2002) and the equatorial Indian Ocean (McCreary et al., 1993; Clarke and Liu, 1994; Han and Webster, 2002). This low-frequency variability is coherent along the coast of the north Indian Ocean (Clarke and Liu, 1994; Shankar, 1998; Shankar and Shetye, 1999), as seen in the significant correlation between sea level at Vishakhapatnam and Mumbai (Shankar and Shetye, 1999), but there are differences in the range between the east and west coasts of India (Shankar, 2000). That annual-mean sea level due to the large-scale winds tends to see-saw along the Indian coast, with its pivot at the southern tip of the Indian subcontinent, and that there exists a large along-shore gradient in salinity along the Indian coast leads to a differential response between the two coasts (Shankar and Shetye, 2001). Hence, in spite of the reported significant correlation between Vishakhapatnam and Mumbai (Shankar and Shetye, 1999), we preferred to check for consistency separately in the Bay of Bengal and the Arabian Sea. The cross-basin consistency was examined separately.

Figure 2 shows a comparison of each individual record with that of Mumbai for stations in the Arabian Sea and with that of Vishakhapatnam for stations in the Bay of Bengal. Only records longer than 40 years are presented. Also shown in Fig 2 is the curve based on reconstruction estimates, which are available at every  $1^{\circ}$  interval. Since Diamond Harbour is situated inside the estuary (Hooghly), the value from the nearest point (Sagar) was taken. A linear correlation was performed for each Arabian-Sea record with that of Mumbai and for each Bay-of-Bengal record with that of Vishakhapatnam (Table 1); this includes stations with records

shorter than 40 years. All records on the Arabian-Sea coast, except those at Kandla and Kochi, were well correlated with that at Mumbai, and all records on the Bay-of-Bengal coast, except that at Sagar, were well correlated with that at Vishakhapatnam. Unlike the Mumbai, Karachi, and Aden records, the record at Kochi was well correlated with that at Vishakhapatnam (Table 1). Kandla and Sagar, whose correlations were not significant even at the 90% confidence level, were not considered for trend estimates.

Linear trend estimates for those of the remaining stations that had a record at least 40 years length are shown in Figure 3 and Table 2. Some stations did not have a linear trend significant at the 95% confidence level. The computed standard deviation of the trend, as described in Douglas (2001), is also shown in Table 2.

The GIA-corrected values are also shown in Table 2 for those stations with a significant linear trend. The corrected trends ranged between 1–2 mm yr<sup>-1</sup> for stations in both Arabian Sea and Bay of Bengal, except for the northeast coast; this range is comparable to that estimated for global sea-level rise (Church et al., 2001).

#### **4. Discussion**

We have used tide-gauge data from the north Indian Ocean to show that low-frequency sea-level variability is consistent within the basin. The linear trends estimated for stations having a record longer than 40 years were in the same range as global estimates.

After eliminating stations that were not consistent with Mumbai and Vishakhapatnam and also stations whose estimated trends were not statistically significant, six stations were available for estimating sea-level rise in the basin. One of them, Aden, has a record going back to the 19<sup>th</sup> century, but the record ended in the 1960s. The other stations were Karachi, Kochi, and Diamond Harbour.

In the Bay of Bengal, the record at Sagar Island was not consistent with that at Vishakhapatnam. There was a large drop in sea level at Sagar just after 1960. Though a similar drop in sea level also occurred at Karachi, Mumbai, Kochi, and Vishakhapatnam also, the drop was not as large; data were missing during the 1960s at Chennai and Ko Taphao Noi. Shankar (1998) noted in particular the effect of data for 1961 on the correlations and discussed possible

reasons for it. This drop in sea level was related to the rainfall over India and the large-scale dynamics of the north Indian Ocean, but no quantitative evidence was shown.

Chennai and Ko Taphao Noi, two other stations with records long enough for estimating trends, did not pass the test for statistical significance of the trend. A possible reason for this is the presence of several gaps in the record at Chennai and the large interannual variability at Ko Taphao Noi. The large variability at Ko Taphao Noi is probably linked to large variations in the freshwater discharge of the River Irrawady, which empties into the Andaman Sea. Discharge data for 1978–1988, available from the Global Runoff Data Centre, show an annual average of  $96300 \text{ m}^3 \text{ s}^{-1}$ , one of the highest in the world, with a standard deviation exceeding 10%. Note, however, that the variability at both stations was coherent with that at Vishakhapatnam (Table 1), implying that a longer, less gappy record, by averaging over a few interdecadal oscillations, may yield a similar estimate for sea-level rise.

Another station in the Bay of Bengal with a long record was Diamond Harbour (Kolkata). The record here was consistent with that at Vishakhapatnam (Table 1) and showed a statistically significant trend. The estimated trend at Diamond Harbour, however, was  $5.74 \text{ mm yr}^{-1}$  (after correcting for GIA), considerably greater than that anywhere else in the basin. This tide gauge, however, lies in the delta of the River Ganga (a short distance upstream of the Hooghly estuary), whose subsidence rates are known to be up to  $4 \text{ mm yr}^{-1}$  (Goodbred and Kuel, 2000). Hence, Diamond Harbour was also not included for determining regional average sea-level rise.

In the Arabian Sea, one of the stations whose record was not consistent with that of Mumbai is Kandla, which is located in Kachch (Kutch), a region known for tectonic activity. This region experienced a massive earthquake in 2001 (see for instance, Jade et al., 2003). The other station was Kochi, which, nevertheless, is well correlated with Vishakhapatnam and has a statistically significant trend. The reason for the sea level at Kochi being correlated better with the sea level at Vishakhapatnam than with that at Mumbai is the complex web of large-scale dynamics and salinity changes along the Indian coast. Low-salinity waters advected from the Bay of Bengal have a large influence on the salinity at Kochi and farther north along the Indian west coast (Shetye et al., 1991; Shankar and Shetye, 1999; Han et al., 2001). A large fraction of the low-salinity waters are, however, trapped in the Lakshadweep High (Shenoi et al., 1999,

2005; Han and McCreary, 2001; Rao and Sivakumar, 2003), which forms off southwest India during winter (Bruce et al., 1994; Shankar and Shetye, 1997), when the low-salinity waters are advected into the southeastern Arabian Sea; as a consequence, only a fraction of the low-salinity waters are advected farther poleward along the west coast to Mumbai. This results in the high correlation between Kochi (located in southwest India) and Vishakhapatnam, but in a lower correlation between Kochi and Mumbai.

Note that the sea-level rise trends estimated for Aden, Kochi, and Diamond Harbour are higher than those at Mumbai, Vishakhapatnam, and Karachi. A likely reason for the somewhat higher value at Aden is the termination of the record after the interdecadal peak in the 1960s. The record at Mumbai also yielded a higher value for this period (1.60 mm yr<sup>-1</sup> with GIA correction included). The rate of rise at all these stations (Table 2), with the exception of Diamond Harbour, is nevertheless within the globally estimated range of 1–2 mm yr<sup>-1</sup>.

In conclusion, therefore, we use the estimated trends for Aden, Karachi, Mumbai, and Kochi in the Arabian Sea and for Vishakhapatnam in the Bay of Bengal. The sea-level rise estimated from these stations is between 1.06–1.75 mm yr<sup>-1</sup>, with an average of 1.29 mm yr<sup>-1</sup>. Given the problems noted above with some of the records, the average estimate for the basin is likely to be towards the lower end of this range. Moreover, consistency was checked by determining the trend of the Mumbai record for the same period as that of Aden and Karachi. Similarly the trend for Vishakhapatnam was estimated for the same period as that of Kochi and Diamond Harbour. The regional trends obtained from reconstruction estimates (Church et al., 2004) are higher (Table 2) and do not show as much spatial variation as do the above estimates. These reconstruction estimates, however, also show a high trend in the northeastern Bay of Bengal, particularly at Diamond Harbour, where the trends from tide gauge and reconstruction estimates match well.

The estimated trends are consistent with the global estimates reported in the Third Assessment Report (TAR) of IPCC (Church et al., 2001), suggesting that the sea-level trends in the north Indian Ocean are comparable to global estimates. Studies since TAR have shown that the estimates lie closer to 2.0 mm yr<sup>-1</sup> rather than 1 mm yr<sup>-1</sup>. For instance, Douglas (2001) found a global mean of about 1.8 mm yr<sup>-1</sup> for the past 70 years from the best 25 records chosen from

stable land regions. The estimate of Holgate and Woodworth (2004), based on data for 177 stations divided into 13 regions, give a rate of  $1.7 \pm 0.4 \text{ mm yr}^{-1}$  for the sea-level rise for 1948–2002. The present study indicates that the estimates for the north Indian Ocean are consistent with global estimates, though somewhat lower. Longer time series are needed to consider including them for the calculation of global mean sea-level trends. Nonetheless, they are highly useful for regional applications such as assessing the vulnerability to future sea-level rise.

### **Acknowledgements**

We acknowledge the Permanent Service for Mean Sea Level (PSMSL), Proudman Oceanographic Laboratory, U.K., for making available the monthly-mean sea-level data and Prof. W.R. Peltier, University of Toronto, Canada, for the ICE-5 G model results for making GIA corrections. The discharge data for Irrawady are from the Global Runoff Data Centre (D-56002 Koblenz, Germany). We thank Dr. John Church and Dr. Neil White, CSIRO, Australia for making available the sea-level reconstruction estimates. The work was supported by the Department of Ocean Development, New Delhi. This is NIO contribution XXXX.



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### Figure captions

1. Location of tide-gauges with records longer than 20 years in the north Indian Ocean.
2. Annual-mean sea-level for several tide-gauge stations in the north Indian Ocean; stations on the left (right) are from the Arabian Sea (Bay of Bengal). The dark line shows the record at the respective station and the light grey line shows the record at Mumbai (Vishakhapatnam) for stations in the Arabian Sea (Bay of Bengal). For Mumbai, only its record is shown (dark). The record at Vishakhapatnam (dark) is compared with that at Mumbai (light grey line). The dark grey line indicates the reconstruction estimate for the station for 1950-2001 (Source: Data provided by Dr. John Church and Dr. Neil White). To draw this curve, the mean of sea-level for the entire series for the respective station is added to the reconstruction estimated values. The ordinate for the station Sagar covers a longer range than other stations.
3. Annual-mean sea-level and the linear fit for selected tide-gauge stations in the north Indian Ocean. The trends, standard deviation from a linear fit and confidence limit are also shown.

### Table Captions

Table 1: Linear correlation coefficient for the annual mean relative sea-level for tide gauge records at stations in the Arabian Sea (Bay of Bengal) with that of Mumbai (Vishakhapatnam).

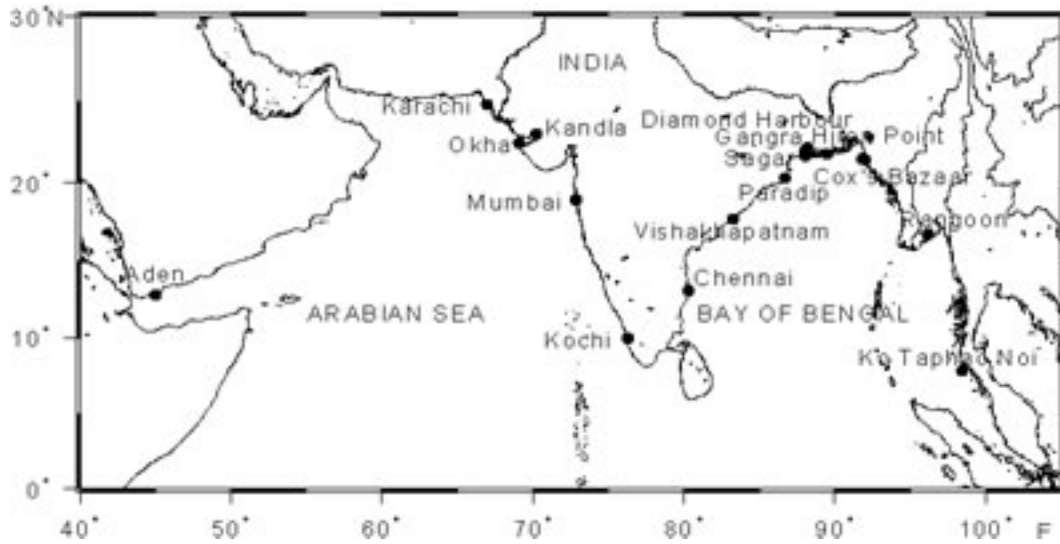
Table 2: Sea-level-rise estimates for selected tide gauge stations along the coasts in the north Indian Ocean. GIA corrections are taken from ICE5G-VM4 model of Peltier (Source: PSMSL website). Trends shown in brackets for stations Aden and Karchi correspond to the trends for Mumbai for the period corresponding to that of the station. Similarly, the trends shown in brackets for Kochi and Diamond Harbour correspond to the trend for Vishakhapatnam for the same period. The standard deviation of the trend from a linear fit is also shown in the same column. The last column shows the trends obtained from the reconstruction estimates of Church et al. (2004).

Table 1

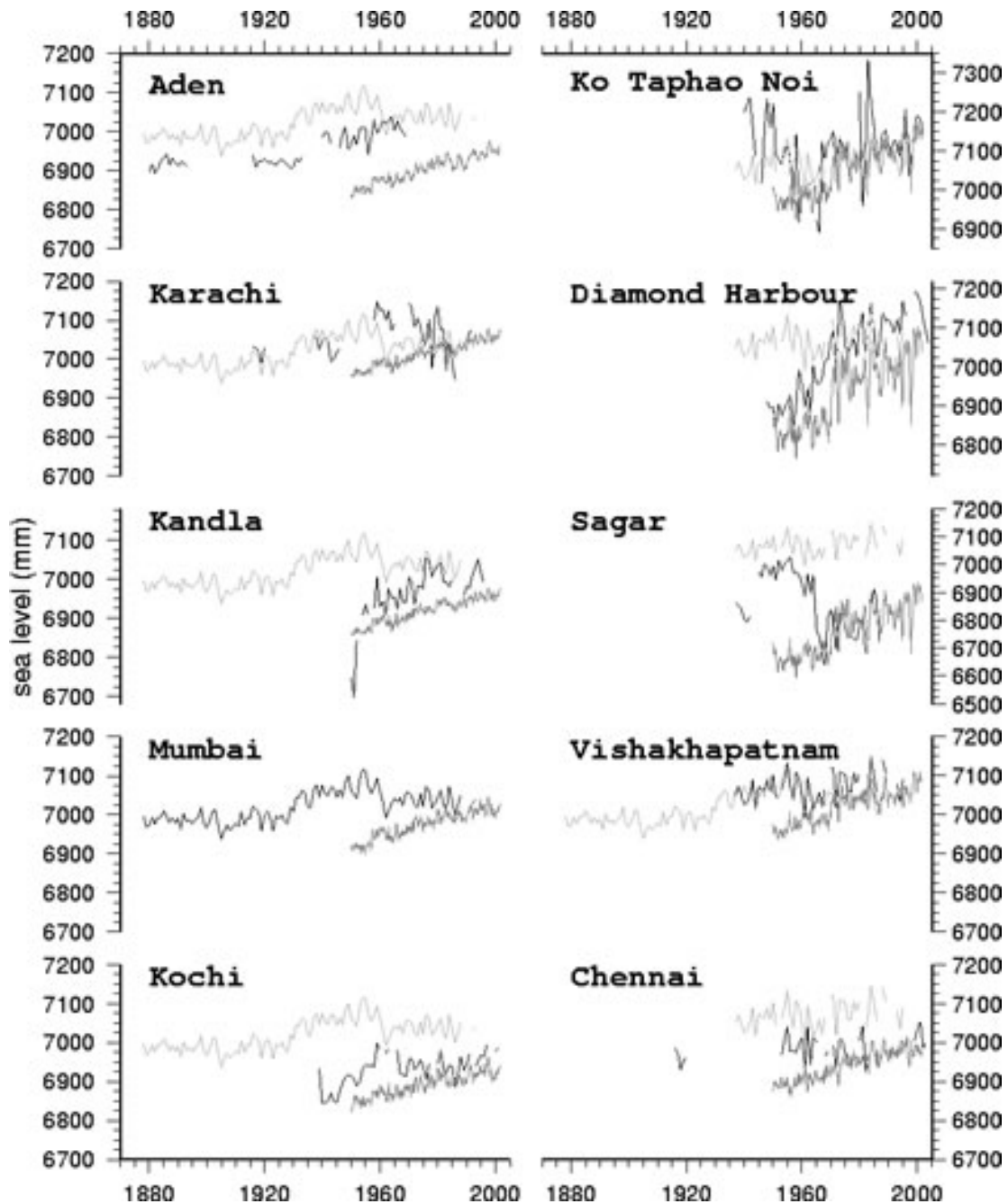
Station (duration of the record)	Number of years of data availability	Reference station for correlation	Linear correlation coefficient	Confidence limit (%)
Aden (1880-1969)	58	Mumbai (1878-1993)	0.68	99.9
Karachi (1937-1992)	39	Mumbai	0.31	95
Kandla (1954-1996)	40	Mumbai	-0.04	< 90
Okha (1975-2004)	22	Mumbai	0.67	99.9
Kochi (1939-2003)	54	Mumbai	-0.04	< 90
Kochi (1939-2003)	54	Vishakhapatnam	0.43	99.0
Chennai (1916-2003)	34	Vishakhapatnam (1937-2003)	0.62	99.9
Paradip (1967-2003)	20	Vishakhapatnam	0.91	99.9
Sagar (1937-1987)	48	Vishakhapatnam	0.22	< 90
Gangra (1974-2002)	25	Vishakhapatnam	0.88	99.9
Diamond Harbour (1948-2004)	55	Vishakhapatnam	0.46	99.9
Hiron Point (1983-2003)	21	Vishakhapatnam	0.75	99.9
Cox's Bazaar (1979-2000)	20	Vishakhapatnam	0.43	90.0
Rangoon (1916-1962)	25	Vishakhapatnam	0.34	90.0
Ko Taphao Noi (1940-2002)	58	Vishakhapatnam	0.29	95

Table 2

Station	Period of analysis	Number of years of data availability	Trends in relative sea level rise (mm yr <sup>-1</sup> )	Confidence limit (%)	GIA correction (mm yr <sup>-1</sup> )	Net sea level rise (mm yr <sup>-1</sup> )	Sea level rise from reconstruction estimates (mm yr <sup>-1</sup> )
Aden	1880-1969	58	1.21 ±0.16 (1.16)	99	-0.16	1.37	2.13
Karachi	1916-1992	44	0.61 ±0.32 (0.46)	90	-0.45	1.06	1.94
Mumbai	1878-1993	113	0.77 ±0.08	99	-0.43	1.20	2.06
Kochi	1939-2003	54	1.31 ±0.23 (0.73)	99	-0.44	1.75	1.68
Vishakha patnam	1937-2000	53	0.70 ±0.28	95	-0.39	1.09	2.42
Diamond Harbour (Kolkata)	1948-2004	55	5.22 ±0.43 (0.56)	99	-0.52	5.74	4.87

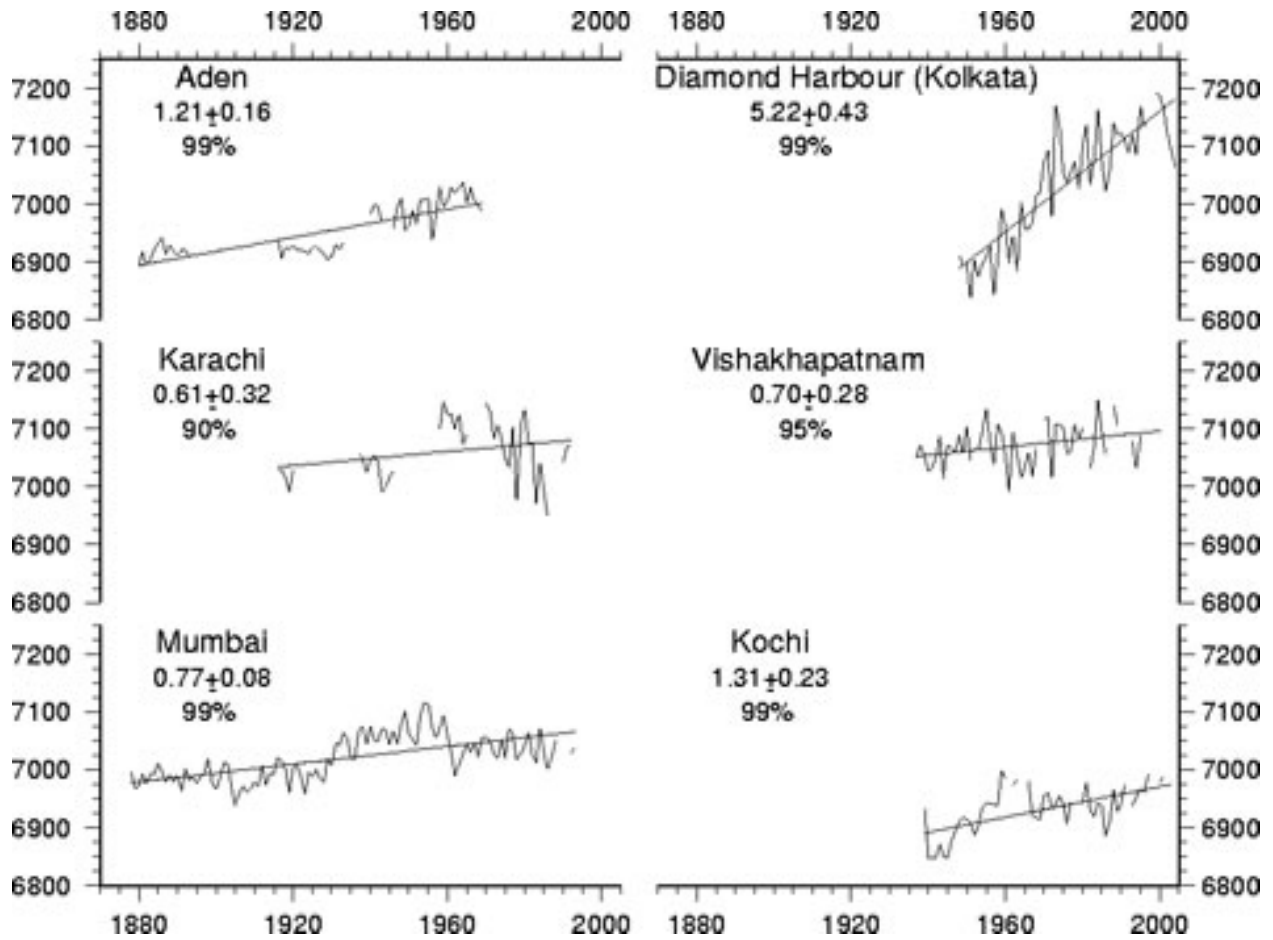


**Fig1:** Location of tide-gauges with records longer than 20 years in the north Indian Ocean.



**Fig2:** Annual-mean sea-level for several tide-gauge stations in the north Indian Ocean; stations on the left (right) are from the Arabian Sea (Bay of Bengal). The dark line shows the record at the respective station and the light grey line shows the record at Mumbai (Vishakhapatnam) for stations in the Arabian Sea (Bay of Bengal). For Mumbai, only its record is shown (dark). The record at Vishakhapatnam (dark) is compared with that at Mumbai (light grey line). The dark grey line indicates the reconstruction estimate for the station for 1950-2001 (Source: Data provided by Dr. John Church and Dr. Neil White). To draw this curve, the mean of sea-level for the entire series for the respective station is added to the reconstruction estimated values. The ordinate for the station Sagar covers a longer range than other stations.





**Fig3:** Annual-mean sea-level and the linear fit for selected tide-gauge stations in the north Indian Ocean. The trends, standard deviation from a linear fit and confidence limit are also shown.