

Estimating absolute sea level variations by combining GNSS and Tide gauge data

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Indian tide gauges can be used to estimate sea level rise. To separate relative sea level rise from vertical land motion at the tide gauges, various GNSS stations have been installed in the last years at, or nearby, tide gauges. Using the PSMSL database, we have computed new sea level rise estimates for seven Indian tide gauges with realistic error bars. These error bars should be combined with the uncertainty of the vertical land motion to obtain the error bar of the absolute sea level rise. Using the GNSS properties of two inland stations, Hyderabad and Bangalore, as a proxy of the noise observed at the coastal stations, we conclude that around 5 years of observations are required to estimate the vertical land motion with an accuracy of around 0.1 mm/yr. Since the error by which the relative sea level rise can be estimated at the Indian tide gauges is mostly larger than 0.2 mm/yr, with the exception of Mumbai, such a small error of the vertical land motion is sufficient to cause no noticeable effect on the accuracy of the estimated absolute sea level rise.

[Keywords: GNSS, Sea level, Time-series analysis]

Introduction

Sea level is rising by 1-2 mm/yr globally¹ and will have a large impact on the coastal zone. Wallis and Church² estimate that it will affect around 187 million people by 2100. However, there are significant variations in the amount of sea level rise from region to region³. In the current research we focus on the sea level rise along the coast of India. This has already been studied by various researchers in the past such as Emery and Aubrey⁴, Das and Radhakrishna⁵ as well as more recently by Unnikrishnan and Shankar⁶ wherein they estimated sea level rise by ordinary least-squares. Recently, it is shown that this method can underestimate the real uncertainty of the estimates sea level rise by a factor of up to two because it ignores the temporal correlation that is present in the data⁷. Temporal correlation implies that each sea level observation is dependent on the previous values and is present in most geophysical time-series⁸. In ordinary least-squares it is assumed that all observations are independent.

A larger problem is the lack of information about the vertical stability of the tide gauges. In order to determine if it is the sea that is rising or if it is the land that is sinking, observations of the vertical land motions at the tide gauge sites are required. Once we have corrected for the vertical land motion, we obtain

the absolute sea level rise. Unnikrishnan and Shankar⁶ already mentioned that the uncertainty of the vertical land motion in India due to postglacial rebound is around 0.1 mm/yr. However, this is a large scale phenomenon that varies slightly over hundreds of kilometres while local effect in harbours is also common. For that reason we have seen in the last years a growing number of stations with Global Navigation Satellite System (GNSS) installed at, or nearby, tide gauges which measure vertical land motion directly. Due to the great earthquake of Sumatra and subsequent tsunami in 2004, the process of modernization of Indian Tide Gauge network got hastened to improve early warning capabilities. It is planned to install 36 state-of-the-art digital tide gauges co-located with dual frequency GNSS receivers at strategic locations all along the Indian coastline and its islands⁹. For example, this year a continuous GNSS station was installed at Goa. The objectives of this research are to estimate the relative sea level rise at tide gauge sites with GNSS capability and to investigate how the GNSS observations will improve the accuracy of the absolute sea level rise estimations.

Materials and Methods

The monthly tide gauge data set of the Permanent Service for Mean Sea Level (PSMSL), described by

Holgate *et al.*¹⁰, is widely used for the study of sea level change and will also be used in this study. Fig. 1 shows the location of seven tide gauges that are present in the PSMSL data base with more than 30 years of data and which have a GNSS station installed at the site^{9,11}. At Goa a continuous GNSS station was recently installed and the first two months of observations were processed with the GIPSY-OASIS II software¹² using the PPP method¹³ to produce daily solutions that were subsequently mapped into ITRF2008¹⁴. Fig. 1 also shows the location of the GNSS stations Hyderabad and Bangalore. The vertical time-series for these stations are publicly available (<http://sideshow.jpl.nasa.gov/post/series.html>) and contain for both stations around 10 years of observations. Unfortunately we were not able to obtain GNSS data from the other stations in India and we will use these two inland stations as a proxy of the noise properties we can expect at the coastal sites.

We will assume that both the secular relative sea level rise and the vertical land motion can be described by a linear trend. These trends in the tide gauge data and GNSS position time-series were estimated using the Hector software¹⁵. This software uses weighted least squares to estimate the trend together with a yearly, twice yearly periodic signal. For the tide gauge data also a signal with period of three times a year was included. The covariance matrix in the estimation process is based on a noise model and the values of its parameters are estimated

using the Maximum Likelihood method. We define noise to be all the random variations of the observations that are not captured by our simple model of a linear trend with a few periodic signals. For the tide gauge data the Generalized Gauss Markov noise model¹⁶ was used because Bos *et al.*⁷ show that this describes best the random behaviour in tide gauge data. For the GNSS data, a power-law plus white noise model was used¹⁷. The most important feature of these two noise models is that they are able to represent the temporal correlations that are present in the data. Once we have the values of the parameters used in the noise models of the GNSS time-series, we can predict the obtainable accuracy of the estimated vertical land motion at the tide gauge locations.

Results

Table 1 shows the estimated sea level rise values of Unnikrishnan and Shankar⁶ with their uncertainty and our results using a better noise model that takes into account the temporal correlation that exist within the data. The data for Chennai and Paradip were also analysed by Unnikrishnan and Shankar but unfortunately no sea level rise values were given.

In Fig. 2 we have plotted the monthly tide gauge values together with our estimated sea level rise and additional periodic signals. All time-series were given an arbitrary vertical offset to separate them.

In Fig. 3 we show the first two months of daily vertical displacements at our recently created continuous GPS station at Goa.

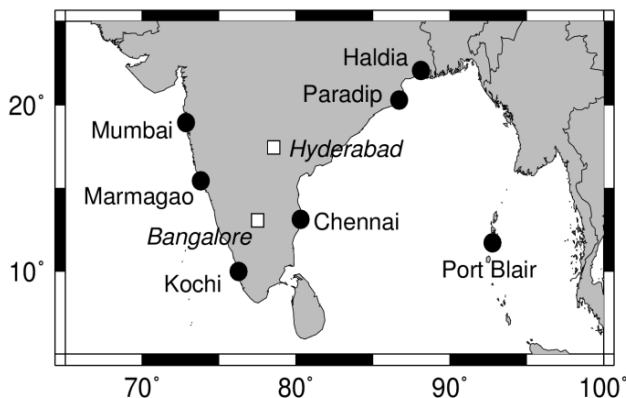


Fig. 1—Study region

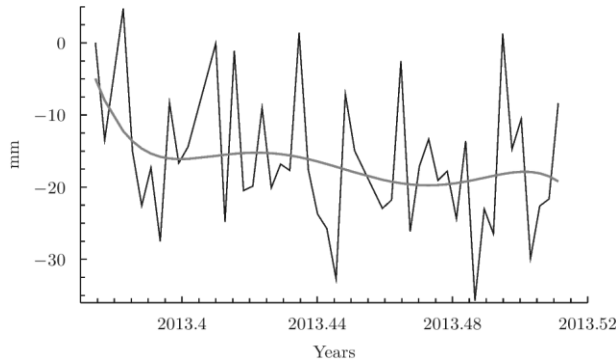


Fig. 3—The vertical land motion observed with GNSS at Goa (black) and the estimated vertical land motion level rise together with periodic signals with a frequency of one and two times a year (grey)

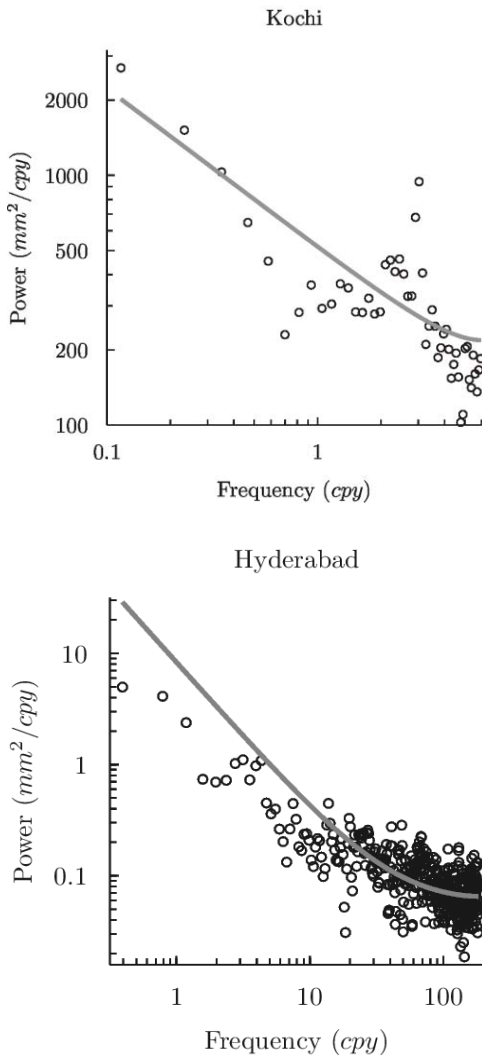


Fig. 4—The power spectral densities of the residuals for the tide gauge data at Kochi and the vertical GNSS displacements at Hyderabad

As we mentioned in section 2, we do not use ordinary least squares but weighted least-squares with different noise models for the tide gauge and the GNSS data. That this is necessary can be seen from the power spectral density plots, computed using Welch’s overlapping periodogram method, shown in Fig. 4 for the residuals (difference between observations and estimated trend) of the tide gauge data at Kochi and the GNSS data at Hyderabad. Fig. 4 also shows the power spectral density of the used noise models in gray and show clearly increasing amplitude at the lower frequencies. If there was no temporal correlation, these power spectral densities should have been flat, see also Agnew⁸.

Discussion

Figure. 2 shows that the annual sea level variations at Paradip and Haldia, located in the Bay of Bengal, are much larger than at Mumbai and Marmugão, bordering to the Arabian Sea. This has a negative effect on the accuracy by which the secular sea level rise can be estimated. The data span at Marmugão is similar to that of Paradip and Haldia but from Table 1

Table 1—Estimated relative sea level rise values with their standard deviation in mm/yr as listed by 6 and computed by us.

Tide gauge	Unni. & Shan. (mm/yr)	Bos et al. (mm/yr)
Mumbai	0.77±0.08	0.80±0.13
Marmugao (Goa)		1.00±0.36
Kochi	1.31±0.23	1.60±0.35
Chennai		0.32±0.20
Paradip		1.15±0.70
Haldia		2.66±0.64
Port Blair		2.03±0.39

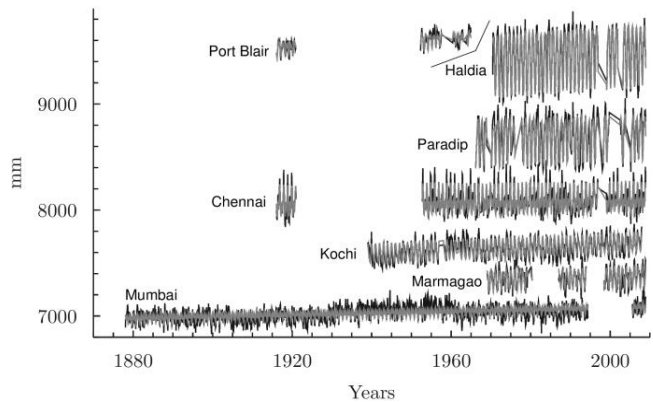


Fig. 2—Monthly tide gauge data (black) and the estimated relative sea level rise together with periodic signals with a frequency of one, two and three times a year (grey)

it is clear that the uncertainty of the estimated sea level rise is almost half to that of the latter two gauges. Table 1 shows also that our values are in agreement with those of Unnikrishnan and Shankar⁶ but that our uncertainties are almost twice as large. This is caused by our use of a more realistic noise models and as a result, their uncertainties should be considered being too small.

The large difference of 1.5 mm/yr in estimated relative sea level values between Paradip and Haldia is intriguing because the stations are only around 250 kilometres apart. Here GNSS observations are essential to determine if this difference is real or if Haldia is sinking.

The power spectral density plots of the residuals of the tide gauge data show a strong peak at a frequency of three times a year. In the analysis we tried to model this by including a period of three times a year but this did not remove the peak significantly. It is beyond the scope of the current research to investigate this phenomenon but it is likely that the signal with a period of around 120 days varies slightly over time in amplitude and frequency which broadens the peak. Such a broadened peak cannot be modelled by a single periodic signal. Furthermore, Fig. 4 shows that the Generalized Gauss Markov noise model describes the observed power spectral density correctly which supports our claim of that we are using a realistic noise model. Das and Radhakrishna⁵ concluded that a third order autoregressive noise model, abbreviated to AR (3), would fit the tide gauge observations best. However, an AR (3) noise model would produce

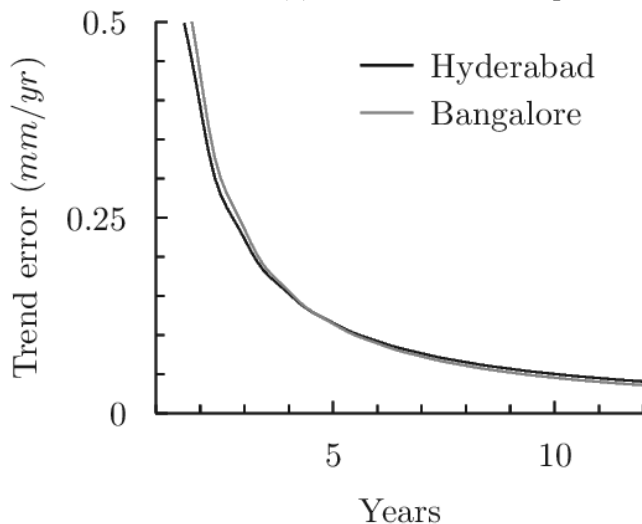


Fig. 5—The predicted accuracy of the estimated vertical land motion using the observed noise in the GNSS time-series at Hyderabad and Bangalore

a flattening of the power spectral density at the lower frequencies which we do not observe, see Fig. 4. Nevertheless, using an AR (3) noise model would already produce a very realistic trend error but unfortunately Das and Radhakrishna do not list any.

The two months of GNSS observations at Goa are too short to compute a power spectral density plot and to draw any conclusions yet about the vertical stability of the station. On the other hand, the 10 years of observations at Hyderabad and Bangalore are sufficiently long to accurately determine the noise properties. Fig. 4 shows that the power-law plus white noise model fits the observed power spectral density at Hyderabad well. At the high frequencies the power flattens out and is dominated by the white noise while at the lower frequencies the power increases exponentially for decreasing frequency. This is called power-law behaviour and in this case the slope of the power-law is around one, which is in agreement with most GNSS stations¹⁷. Using the values of the parameters of the power-law plus white noise models at Hyderabad and Bangalore, the accuracy of the estimated vertical land motion was predicted for various values of the observation span. The trend error values are plotted in Fig. 5 and show that the results are similar at both stations. With 10 years of observations, the trend error at these two stations is currently around 0.05 mm/yr. At Mumbai continuous GNSS observations started in January 2002¹¹ which means that, assuming similar GNSS noise properties, that the error of the vertical land motion is currently around 0.04 mm/yr. Together with the uncertainty of the estimated trend in the tide gauge data of 0.08 mm/yr, this produces an error of the absolute sea level rise uncertainty of 0.09 mm/yr. Without using the GNSS information we are left using the uncertainty of 0.1 mm/yr in the post-glacial rebound models which would give us an absolute sea level rise uncertainty of 0.13 mm/yr, showing the advantage of using GNSS observations. Of course the GNSS measurements actually observe the vertical land motion while the post-glacial rebound model is just a model and does not include potential local effects.

At Marmugão, where recently a new GNSS station was installed, the uncertainty of the estimated sea level rise is currently around 0.36 mm/yr. Using Fig. 5, we expect that the vertical land motion can be determined with the same accuracy within two years from now. If we then would combine the two uncertainties to obtain the absolute sea level we still

obtain a value of 0.51 mm/yr. Therefore, 5 years of GNSS observations seem desirable to reduce the error of the absolute sea level rise to 0.37 mm/yr. Similar computations can be made for the other tide gauges that have GNSS installed nearby for given installation date.

At Port Blair GPS measurements were only initiated after the Sumatra earthquake in 2004 and Paul *et al.*¹⁸ note that within 3 years vertical displacements of more than 20 cm were observed. This puts some doubt on the vertical stability of this tide gauge in the years from 1916-1964 when the tide gauge observations were made since this island is near to Indonesia which is an earthquake prone region.

Conclusions

Along the coast of India several tide gauges are located with more than 30 years of observations and which have GNSS installed at or nearby the station. In this research we investigated seven of them and estimated the relative sea level rise together with their uncertainties. We have shown that one should take into account the temporal correlation that exists in the tide gauge data to produce a realistic error bar. The trend errors of Unnikrishnan and Shankar (2007), which ignore this temporal correlation, are therefore too small by almost a factor of two.

To convert the estimated relative sea level into absolute sea level rise, information about the vertical land motion is required. Using the GNSS noise properties at the inland stations Hyderabad and Bangalore as a proxy of the noise observed at the coastal stations, we concluded that around 5 years of observations are required to estimate the vertical land motion with an accuracy of around 0.1 mm/yr. Since the error by which the relative sea level rise can be estimated at the Indian tide gauges is mostly larger than 0.2 mm/yr, with the exception of Mumbai, such a small error of the vertical land motion has no noticeable effect on the accuracy of the estimated absolute sea level rise.

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