while the light pulses travel from one mirror to another. From the start of the pulse to the detection of the pulse, this results in a change in the effective distance between the mirrors. Contrary to naive expectation, the total distance travelled by the two light pulses is seen to be unequal (Figure 4). It turns out that it was erroneous to expect Figure 1 *a* and *b* to yield the same result.

For the purpose of comparison with experimental results, the difference in the time of arrival can be calculated. This can be accomplished by writing the equations for the instantaneous positions of the mirrors from the frame of reference of the observer, calculating the time for the light pulse to travel each segment separately and summing them, to obtain the total time of travel for each pulse.

We are expecting an effect which is first order in velocity. Since the velocity of the inertial observer is much lesser than the speed of light, all contributions arising from higher orders of velocity can be ignored.

The difference between the time of arrival of the two light pulses at the detector is found to be

$$\Delta t \approx \frac{2l}{c^2} v,$$

where l is the length of the path, v the speed of the detector with respect to the rest frame of the mirrors and c is the speed of light.

Substituting $l = 1.5$ m (since the total path length was of the order of 2 m) in the above expression, we obtain

$$\Delta t = (3.33 \times 10^{-17}\ \mathrm{s}^2\ \mathrm{m}^{-1}) v,$$

The slope calculated above agrees well with the slope of the experimental plot in ref. 3.

Figure 4 shows the basic difference between our analysis and the analysis in ref. 3. In our analysis, with respect to the observer (detector), the world lines of the mirrors are inclined in the same direction, since all the mirrors have the same relative velocity with respect to the observer. In ref. 3, the world lines of the mirrors are shown to be inclined in different directions.

We have reanalysed the experiment in ref. 3 and have shown that the difference between the time of arrival of the two light pulses and its dependence on the velocity of the observer does not violate the principle of invariance of the speed of light. As explained above, the time of traversals corresponds to that of two different distances, and so they cannot be expected to be the same. The velocity dependence of the difference in the time of arrival naturally arises as the difference in the distance of traversal depends on the velocity of the observer. The experimental results of ref. 3 appear to be numerically in good agreement with the calculations performed using the special theory of relativity, without requiring any violation of the principle of invariance of the speed of light.

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EVAN JOHN PHILIP

School of Physical Sciences,
National Institute of Science Education and Research,
Bhubaneswar 751 005, India
e-mail: evanphilip@gmail.com

Estimation of Indian coastal areas inundated into the sea due to sea-level rise during the 20th century

The sea-level rise caused by climate change leads to inundation of coastal areas and may be a threat to the low-lying coastal regions[1,2]. Bindoff *et al.*[3] reported that the average rate of sea-level rise was 1.7 mm/year in the twentieth century and this rate was not uniform over decadal periods throughout the century[4–6]. The sea-level rise also varies in a regional scale and accordingly causes inundation along the coast. Unnikrishnan *et al.*[7] estimated the sea-level rise along the Indian coast. Their result indicates that the rate of sea-level rise at Mumbai is 0.78 mm/year during 1878–1994, at Kochi it is 1.14 mm/year during 1939–1997 and at Visakhapatnam it is 0.75 mm/year during 1939–1994; whereas the rate of decrease of sea level at Chennai is 0.65 mm/year during 1955–1994. In 2007 Unnikrishnan and Shankar[8] extended the above work and reported that sea-level rise occurs between 1.06 and 1.75 mm/year, with a regional average of 1.29 mm/year[8]. Nandy and Bandyopadhyay[9] show that the trend of annual sea-level rise along Hugli, West Bengal coast is 1.09 mm/year[9]. This indicates that some areas along the Indian coast might have gone under the sea during the above-mentioned period and this inundation might be different in the regional scale depending on the topography of the region. A report by the Geological Survey of India, Hyderabad shows that the coast between Azhikkod and Edavilangu has suffered a net loss of 2.093 sq. km area during the last century[10]. Similarly, the coast between Munambam and Nayarambalam has suffered a net loss of 4.675 sq. km during the last hundred years[10]. Kumaravel *et al.*[11] reported that erosion of 3.21 sq. km shoreline occurred in Cuddalore district in the east coast of Tamil Nadu. Kumar and Jayappa[12] studied a coastal stretch of 18 km from the New Mangalore Port in the north to Talapadi in the south of

Karnataka. All these studies[10–12] were conducted to estimate the seaward or landward shifting along small portions of the Indian coast from satellite images. But no study has been conducted so far to estimate the areas that went under the sea or inundated into the sea along the Indian coast due to sea-level rise. Thus an attempt has been made in the present study to estimate the Indian coastal area that went under the sea due to sea-level rise during the 20th century using SRTM and sea-level-rise datasets.

The surface elevation data over the Indian coastal region are obtained from the Global Land Cover Facility (GLCF). The 90 m SRTM scenes of US Geographical Survey (USGS) are utilized to compute the surface elevation over the region.

The onscreen visual interpretation technique is used to draw and measure the lengths of the Indian coastline. The whole Indian coastline is divided into four different parts, viz. Mumbai, Kochi, Chennai and Visakhapatnam (Figure 1). The division into sub-parts is based on the representative stations at which sea-level-rise data are obtained as published in the literature[7,8]. Both the boundary points of each coastline are assumed according to the topography and location of the representative stations. The slopes are calculated from the SRTM image at different points along the coast. The landward or seaward shifting of the coastlines is then calculated using the method shown in Figure 2 at various points along the Indian coastline. In Figure 2, s is the shifting of the coastline and is calculated at various coastal points using the sine formula $r/\sin(\theta)$, where r is the sea-level rise (in m) calculated during the 20th century and θ is the average slope calculated at various points along Indian coastline using the formula (given below). θ at any particular point is calculated by taking three different points (P_1, P_2, P_3) and by taking the corresponding terrain heights (h_1, h_2, h_3).

$$\theta = \frac{\theta_1 + \theta_2}{2},$$

where

$$\theta_1 = \tan^{-1}\left(\frac{h_2 - h_1}{x_1}\right),$$

$$\theta_2 = \tan^{-1}\left(\frac{h_3 - h_1}{x_1 + x_2}\right),$$

where h_i is the terrain height at the point P_i and x_i the Euclidean distance from P_i to P_{i+1}.

As mentioned earlier, the whole coastline is divided into four parts, the averages of the shifting of the coastline are calculated along Mumbai, Kochi, Chennai and Visakhapatnam. Finally, the areas inundated into the sea or exposed to the sea during the 20th century along the four coastlines are calculated by multiplying the shifting of the coastline at each representative station with the length of the corresponding coastline.

The Indian coastline with the representative stations are shown in Figure 1. The red-coloured coastline is represented by Mumbai, blue-coloured coastline by Kochi, magenta-coloured coastline by Chennai and green-coloured coastline by Visakhapatnam. In Figure 1, the arrows facing landward along the coastline show the inundation of the coast and those facing seaward along the coastline show starvation of the coast. The lengths for each coastline along the Indian coast (Figure 1) are shown in Table 1. The coastline lengths along Mumbai, Kochi, Chennai and Visakhapatnam stations are 4187.59, 1148.77, 1277.63 and 1361.22 km respectively. The rate of sea-level rise/decrease at each of representative station (Figure 1) is taken from the literature[7,8]. As seen from Table 1, the rate of sea-level rise at Mumbai is 1.20 mm/year during 1878–1993 (ref. 8); at Kochi it is 1.75 mm/year during 1939–2003 (ref. 8), and at Visakhapatnam it is 1.09 mm/year during 1939–2000 (ref. 8); whereas the rate of decrease in sea-level at Chennai is 0.65 mm/year during 1955–1994 (ref. 7). In the present study, the rise in sea level during the twentieth century is calculated assuming the same rate

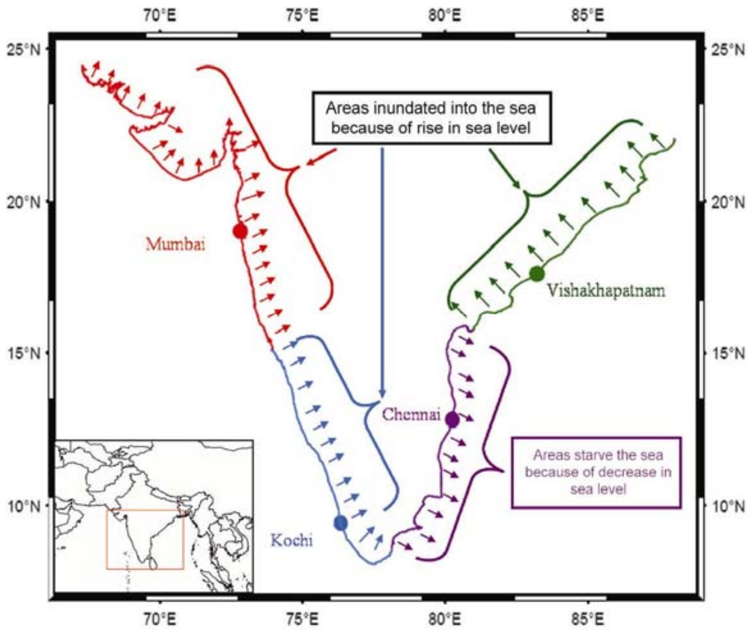
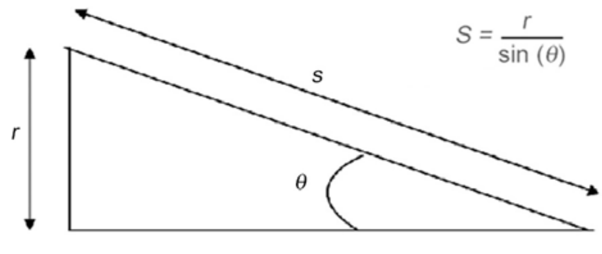


Figure 1. Location map of the Indian coastline with four representative stations and four coastlines after the division. Red, blue and green-coloured lines indicate inundation and magenta-coloured line indicates starvation.



where, θ is the slope at the point, r the sea-level rise during the 20th century and s the shifting of the coastline per unit area.

Figure 2. Method for estimating slope.

Table 1. Areas inundated into the sea due to sea-level rise along Indian coast during 20th century

Representative station/coastline	Sea-level rise (mm/year) from Unnikrishnan *et al.*[7,8]	Length of coastline (km)	Shifting of the coastline along the representative stations (m)	Areas inundated into the sea (sq. km)
Mumbai	1.20	4187.59	4.049	16.957
Kochi	1.75	1148.77	7.831	8.996
Chennai	–0.65	1277.63	–3.679*	–4.700#
Visakhapatnam	1.09	1361.22	6.577	8.953
Total area inundated into the sea along the coast during the 20th century				34.906
Total area exposed to the sea along the coast during the 20th century				4.700

*Negative sign indicates that the coastline is shifting towards the sea.
#Negative sign indicates that the seawater receded from the area.

of increase/decrease in sea level. The landward/seaward shifting of the coastlines at various coastal points along the Indian coast (Figure 1) is calculated as described earlier. The averages of the above-mentioned shifting along each representative station (as shown in Figure 1) are calculated. The estimation shows that the landward shifting of the coastline is 4.049, 7.831 and 6.577 m along the representative stations Mumbai, Kochi and Visakhapatnam respectively (Table 1). Estimation along the representative station Chennai shows that the seaward shifting of the coastline is found to be 3.679 m (Table 1). Using the above landward/seaward shifting and the coastline lengths, the areas inundated into the sea along the Mumbai, Kochi and Visakhapatnam stations during the 20th century are calculated (Table 1). Similarly, the area exposed due to decrease in sea-level rise along Chennai station during the 20th century is calculated (Table 1). Table 1 shows that the areas inundated into the sea due to sea-level rise along Mumbai, Kochi and Visakhapatnam are 16.957, 8.996 and 8.953 sq. km respectively, and the area exposed due to decrease in sea level is 4.700 sq. km along Chennai.

The overall analysis shows that 34.906 sq. km of Indian coastal region has inundated into the sea during the 20th century. This inundation is due to the rise in sea level along the Indian coast. The landward shifting of the coastlines along Mumbai, Kochi and Visakhapatnam indicates that the sea-level rise caused a threat to the Indian coastal area during the 20th century. On the other hand, the seaward shifting of the coastline along Chennai indicates that decrease in sea level caused a starvation of the Indian coastal area during the period.

The above estimates are based on the increase/decrease in sea level along the Indian coast as published in the literature[7,8]; the slopes are obtained from 90 m SRTM Image, and the arc lengths measured along the Indian coast. Thus the estimates are associated with the errors that are already present in the SRTM datasets and also associated with the errors that occurred during division of the coastlines. However, the study could still estimate the inundation of Indian coastal areas into the sea due to sea-level rise during the 20th century. Thus the above results can be made more accurate by providing the slopes and appropriate boundary points from the further higher resolution images along the coastlines.

In conclusion, the coastal area that went under the sea along the Indian coast during the 20th century is found to be 34.906 sq. km. This inundation is mainly due to the rise in sea level along the coastal regions. The landward shifting of the coastlines indicates that the rise in sea level caused a threat of 4.049, 7.831, and 6.577 m along Mumbai, Kochi and Visakhapatnam respectively, whereas the seaward shifting of the coastline along Chennai shows a starvation of 3.679 m of Indian coastal area. These estimates are associated with the errors present in SRTM datasets and those occurring during coastline division. However, these estimates can be made more accurate by providing the slopes from further higher resolution datasets.

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S. NAYAK[1]
M. MANDAL[1,*]
A. ADHIKARI[2]
R. BHATLA[2]

[1]*Centre for Oceans, Rivers, Atmosphere and Land Sciences, Indian Institute of Technology Kharagpur, Kharagpur 721 302, India*
[2]*Geophysics Department, Banaras Hindu University, Varanasi 221 005, India*
**For correspondence.*
e-mail: mmanda@coral.iitkgp.ernet.in