Journal of Coastal Research | 5 | 3 | 489-501 | Charlottesville, Virginia | Summer 1989

Tide Gauges of India[1]

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ABSTRACT

EMERY, K. O. and AUBREY, D. G., 1989. Tide gauges of India. *Journal of Coastal Research,* 5(3), 489-501. Charlottesville (Virginia), ISSN 0749-0208

India contains most of the tide-gauge stations of the northern Indian Ocean from which mean annual relative sea levels can be computed for estimating long-term trends. However, two records are too short, five have poor statistical confidence, and four appear to be much influenced by episodic high sea levels caused by cyclonic storm surges or monsoonal floods, or alternately by poor tide-gauge recordings. The five remaining station records that appear usable (three on the west coast and two on the east coast) reveal trends between +1.3 and -2.1 mm/year change of land level relative to sea level with an average of minus 0.7 mm/year, indicating relative sinking of land. The evidence is unclear whether these records document real sinking of land or real eustatic rise of sea level. Regardless of the present cause, increased submergence may be expected in coming decades owing to higher temperatures (greenhouse effect of worldwide burning of fossil fuels) that can expand the volume of ocean water as well as augment the return of glacial meltwater. The making and study of repeated precise leveling surveys on land combined with information from advanced geodetic technology may quantify the relative roles of sinking coastal land belts relative to inland areas (subsidence of coasts) versus increasing volume of ocean water causing intrusion of the ocean.

ADDITIONAL INDEX WORDS: *sea level, land subsidence, monsoonal floods, storm surges, India, Bangladesh.*

INTRODUCTION

There are only 12 tide-gauges records in India (Figure 1) that are useful for estimating changes of relative sea level, but they represent half of those for the entire Indian Ocean. Three other useful ones (at Aden, Mauritius, and Karachi) are present between South Africa and India, and three other useful ones (Rangoon, Andaman Islands, and Phuket) are between India and Australia. Because the tide gauges in India constitute the main source of knowledge about relative sea levels (or land levels) for the northern Indian Ocean region and serve as a basis for predicting future coastal flooding of lowlands (especially of Bangladesh and India), they warrant effort to understand their message.

Investigation of the tide-gauge records of India requires some knowledge of the effects of monsoonal rains in the interior, cyclonic storm surges along the coasts, and structure of the crust beneath Peninsular India. This knowledge helps one understand the relative roles of sinking coastal land belts relative to inland areas (subsidence of coasts) versus increasing volume of ocean water in causing intrusion of the ocean. More complete understanding appears to require acquisition and study of repeated precise leveling surveys on land combined with surveys using satellites (Very Long Baseline Interferometry, Differential Global Positioning System). Knowledge from such surveys may help reduce potential future disaster for the dense human habitation along the low coasts of India and Bangladesh.

ANALYSIS OF TIDE-GAUGE RECORDS

Tide-gauge records are useful for analysis of changing relative sea levels or land levels after the hourly levels for each full year of record are averaged to give mean annual relative sea level for that year and that station. Comparison with mean annual relative sea level for other years reveals short-term variability superimposed on long-term progressive changes. Uniform and contemporary changes in many stations may reflect real changes of sea level or regional changes of land level through time, but station-to-station differences in direction and rates more likely are caused by local movements of the land to which the tide gauges are attached,

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[1] *88038 received 6 June 1988, accepted in revision 8 September 1988.*

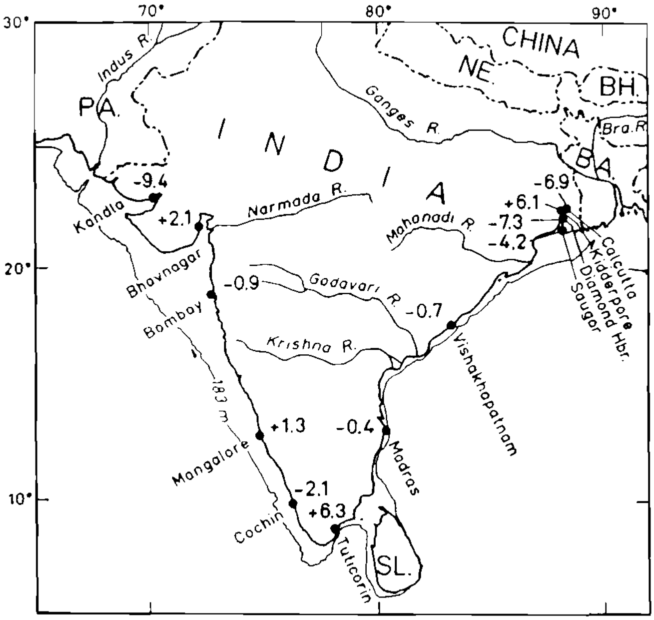


Figure 1. India and its most useful tide gauge stations. Names of adjacent nations are indicated by abbreviations as follows: PA—Pakistan, BA—Bangladesh, BH—Bhutan, NE—Nepal, and SL—Sri Lanka. Tide-gauge sites are indicted by dots and names of their cities; numbers are mean annual change of relative land level in mm computed from regression analysis of relative sea level records (Table 1).

local oceanographic conditions, or tide-gauge error. These movements can be caused by tectonism (local folding, faulting, or volcanism), isostatic compensation (to loading by water, sediment, or ice), landsliding, compaction of underlying sediments (especially in deltas), withdrawal of interstitial fluids (water or oil) for use by humans, and possibly other effects of human activities (overweighting of the ground by heavy construction, and changes in mean water levels in estuaries due to port/harbor dredging and filling).

There are only a few published previous studies of tide-gauge records from India. ROSSITER (1954) merely tabulated records for four stations, three of which he listed only to 1920. PIRAZZOLI (1986) was more up-to-date, listing only the longer records for six stations to 1978, plotting trends up to only 1973 for all but one of them, and noting especially that the record for Bombay between 1952 and 1962 reversed the entire trend for the previous 30 years. ARUR and BASIR (1982?) gave summary regressions for twelve Indian tide-gauge stations based upon years somewhat different from those published by LENNON (1976) and updates through 1982. As they included no data for their stations, we could not incorporate the additional years in our analyses. We attribute the somewhat different changes of mean annual land level (or relative sea level) obtained from the two sets of records to our generally earlier and later records. Arur and Basir also referenced two earlier studies of mean sea levels in India that are not available to us, but we list them for the possible benefit for later workers (CHUGH, 1961; ARUR *et al.*, 1979).

The twelve best quality tide-gauge records of India (LENNON, 1976; and updates on magnetic tape) are analyzed here (Table 1 and Figure 2). Records from two additional stations (Veraval and Marmagao, both on the west coast) were not included, because their time spans were less than 10 years. Records from two other stations on the east coast (Haldia and Tribeni) also were omitted because of short time spans and erratic results (low confidence levels). All four stations are listed in Table 1, but not elsewhere. Even these 12 remaining records leave much to be desired. Longest and most

Table 1. *Data for tide-gauge stations of India.*

STATION	N. LAT.	E. LONG.	TIME SPAN	SLOPE mm/yr— land level	T CONFIDENCE
Kandla	23°00′	70°14′	1950-1982	−9.4	0.74
Veraval	20°54′	70°22′	1955-1964	NC	NC
Bhavnagar	21°45′	72°14′	1937-1965	+2.1	0.74
Bombay (Apollo)	18°55′	72°50′	1878-1982	−0.9	1.00
Marmagao	15°25′	73°48′	1969-1978	NC	NC
Mangalore	12°51′	74°50′	1953-1976	+1.3	0.99
Cochin (Willingdon)	09°58′	76°16′	1939-1982	−2.1	1.00
Tuticorin	08°45′	78°11′	1964-1980	+6.3	0.69
Madras	13°06′	80°18′	1916-1982	−0.4	1.00
Vishakhapatnam	17°41′	83°07′	1937-1982	−0.7	1.00
Saugor	21°39′	88°03′	1937-1982	+4.2	0.97
Diamond Harbor	22°12′	88°10′	1948-1982	−7.3	0.99
Haldia	22°20′	88°06′	1970-1982	+3.9	0.71
Kidderpore	22°32′	88°20′	1881-1930	+6.1	0.96
Calcutta (Garden Reach)	22°33′	88°18′	1932-1982	−6.9	0.97
Tribeni	22°59′	88°24′	1962-1982	−48.3	0.58

NC = Record too short; not calculated.

coherent is the record for Bombay (Apollo Bander)—105 years that begins in 1878 and ends in 1982. Its students-t confidence for the linear regression slope (confidence level that the true slope is within ±1 mm/year of the estimate) is 1.00, the same as for Cochin (Willingdon Island; 43 years), Madras (spanning 66 years), and Vishakhapatnam (spanning 46 years). Student-t confidence for Mangalore (24 years) also is excellent: 0.99. However, the record for Madras contains a 30-year gap of no information. The groupings at the beginning and end of the Madras record indicate the same direction of change as do the individual data points within each group; thus the Madras record is considered nearly as good as the ones for Bombay, Mangalore, Cochin, and Vishakhapatnam.

A gap of 26 years in the record for Kidderpore has considerable vertical displacement of high variability groupings of mean annual relative sea levels at each end. Perhaps this record and its cause led to abandonment of the Kidderpore station in 1930 and its replacement by the Calcutta (Garden Reach) station in 1932. The record for Kidderpore must remain intermediate in estimated quality, because its two individual groupings have no significant trend that would bolster confidence in estimates derived from gappy data. A shift in datum instead may be responsible for the large offset between data groupings. Also intermediate in quality are the records for Saugor, Diamond Harbour, and Calcutta, whose student-t confidences are 0.97 to 0.99, and have distinct groups of data points (Saugor), or are somewhat diffuse (Calcutta). The two nearby stations records from Haldia and Tribeni that were omitted have the same general characeristics.

Poorest are the records for Kandla, Bhavnagar, and Tuticorin, with student-t confidences of 0.69 to 0.74 (tabulated in Table 2). The record at Bhavnagar has no gaps in its 29-year span, but the data form three distinct groups, each too short to provide reliable indications of mean trend. The Kandla tide-gauge record (32 years) is similar in that respect to the Bhavnagar one, but it has only two separate groupings of data. The Tuticorin record (16 years) is little better, with the 1968 data point quite separate from all other ones. The strange groupings at Kandla, Bhavnagar, and Tuticorin have associated student-t confidences lower then 0.75 (Table 1) and do not deserve the same weighting as the ones for Bombay, Mangalore, Cochin, Madras, and Vishakhapatnam.

One can rationalize the groupings in Table 2 if many of the erratic records are due to periods of several years having much higher or lower than normal river discharge. For example, Kandla and Bhavnagar are within the narrow Gulf of Kutch and Gulf of Cambay, respectively, into each of which flow several rivers. The

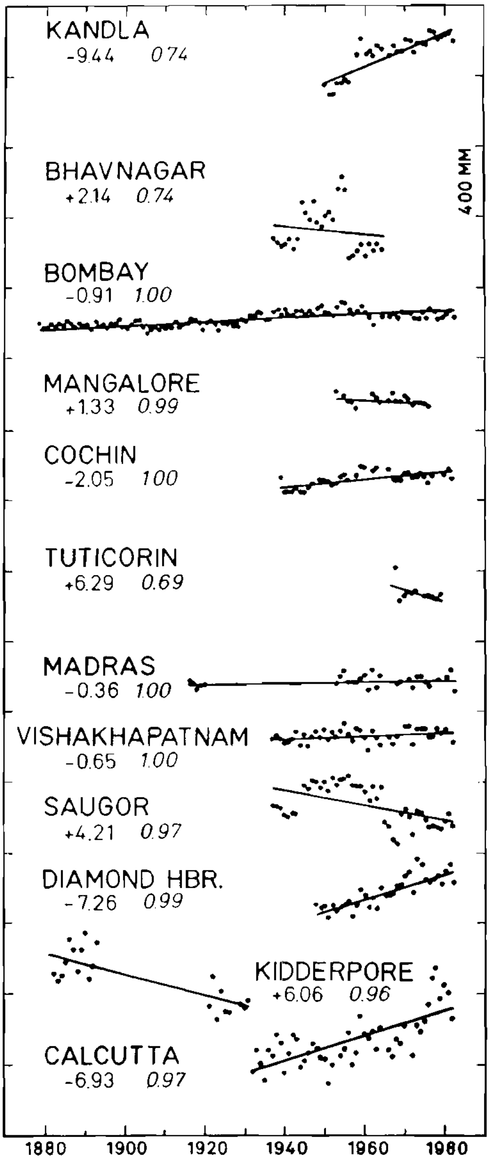


Figure 2. Mean annual relative sea levels at tide-gauge stations of India (from, compilations by Permanent Service for Mean Sea Level, Bidston Observatory, Birkenhead, Merseyside, England). The numbers indicate slope (mm/year) of regression line through data points, expressed as change of relative land level; and students-t confidence level in italics. See Figure 1 and Table 1 for positions.

group of stations in eastern India (Saugor, Diamond Harbour, Kidderpore, and Calcutta) border the Hooghly River, a former channel of the Ganges River and still a flood overflow channel.

Table 2. *Grouping of stations according to student-t confidence and nature of record.*

TIDE-GAUGE STATION	BEST	INTERMEDIATE	POOREST
Kandla			0.74
Bhavnagar			0.74
Bombay	1.00		
Mangalore	0.99		
Cochin	1.00		
Tuticorin			0.69
Madras	1.00		
Vishakhapatnam	1.00		
Saugor		0.97	
Diamond Harbor		0.99	
Kidderpore		0.96	
Calcutta (Garden Reach)		0.97	
average student-t confidence	1.00	0.97	0.72

These stations are about 300 km from the westernmost present distributary of the combined Ganges and Brahmaputra rivers whose enormous floods must raise the levels of the northernmost part of the Bay of Bengal. However, the records for the four stations (Figure 2) are rather dissimilar.

The five best quality tide-gauge records of Table 2 exhibit a range of relative land-level movements between + 1.3 and − 2.1, with an average of − 0.5 mm/year and an overall span of 3.4 mm/year. The four intermediate quality ones have a range between + 6.1 and − 7.3, with a span of 13.4 mm/year. The three poorest quality stations range between + 6.3 and − 9.4, with a span of 15.7 mm/year. Thus the trend from best through intermediate to poorest quality station records in terms of highest to lowest student-t confidence is paralleled by increased range of slopes of regression lines. These variations are believed due to erratic or episodic changes of relative sea level rather than to changes in quality of maintenance of tide gauges.

SHORT-TERM CHANGES IN SEA LEVEL

Sea level along coasts is influenced by floods that are caused by episodes of excess water from ocean (storm surges) or from rivers (precipitation). The floods from the ocean are caused by cyclones (hurricanes, typhoons) and are most frequent along the coasts of Bangladesh and eastern India where tide-gauge and storm records are poor (MURTY *et al.*, 1986). During the time span of best records (May 1960 to June 1985) total deaths were 453,000, or 18,000/year. Between 1737 and 1960 only the larger floods and their effects were recorded (often without mention of the month of occurrence); deaths total 1,069,000, or 4800/year. The 1737-1959 deaths clearly are grossly underreported. If we apply the annual rate for 1960-1985 to the entire time span since 1737, the total deaths would be about 4,500,000. To this must be added uncounted additional deaths due to starvation resulting from disruption of farming and transportation.

Compilations of cyclonic storm surges by MURTY *et al.* (1986) show that both the monthly average number of deaths and heights of water levels (surge plus tide plus waves) reach their maxima during May and October (Figure 3A, B). These are the months when the cyclones are most frequent, owing to largest temperature difference between ocean surface and of air brought by the monsoon and to the retarding effect of high river levels produced by monsoonal rains during the intervening summer months. This retardation of surges is analogous to retardation of tidal bores by flooding rivers. Floods from storm surges rarely penetrate inland more than 100 km.

In contrast are the heavy monsoonal rains that begin during June with winds from the southwest and end during September when the winds reverse to come from the northeast. The monsoon brings more than 75 percent of the annual rainfall to most of India and Bangladesh. Discharges of the rivers reach their maxima about a month after peak rainfall, in August and September (Figure 3C), very different from the dates of maximum cyclonic storm surges.

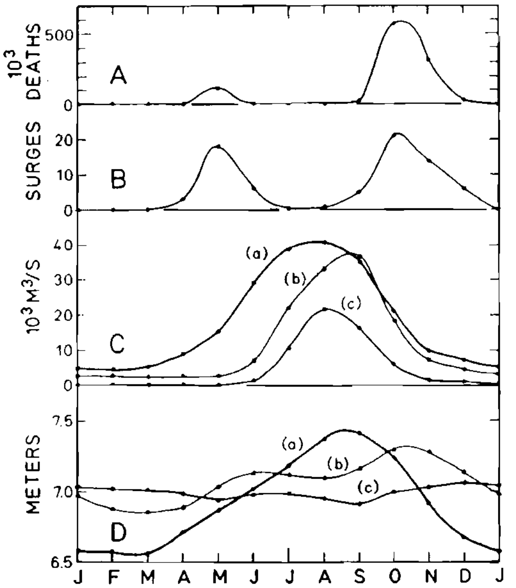


Figure 3. Climatic controls on monthly average sea levels in India and Bangladesh.

A. Total number of casualties by month during the past century caused by cyclonic storm surges (from MURTY *et al.*, 1986).

B. Total monthly number of cyclonic storm surges during the past century (from MURTY *et al.*, 1986).

C. Average monthly discharges of rivers according to compilations by UNESCO (1974, 1979, 1985).

a. Brahmaputra at Paksey (Bangladesh) 1969-1975, and at Pandu (India) 1976-1979.

b. Ganges at Bahadurabad (Bangladesh) 1969-1975.

c. Total of Godavary at Polavarum (India) 1969-1979.
Krishna at Vijayawade (India) 1969-1979.
Narmada at Garudeshwar (India) 1969-1979.

D. Monthly sea levels computed from Lennon (1976) and updates for years 1937-1963.

a. Average for Saugor and Calcutta (Garden).

b. Vishakhapatnam.

c. Average for Bombay and Cochin.

Effects of variation in number and heights of cyclonic storm surges and of river discharges are not evident in existing poor published records of mean annual sea levels. Perhaps they should not be expected in view of the relative shortness of the floods and their usual recurrence every year. However, the average monthly sea level at different tide-gauge stations do reveal close relationships (Figure 3D). The sea-level curves at Saugor and Calcutta are broader than the discharge curve of the nearby Ganges-Brahmaputra rivers, perhaps indicating effects of cyclonic storm surges near the beginning and end of the monsoonal river discharge. The sea-level curve for Vishakhapatnam and the average one for Bombay and Cochin have possible double peaks, perhaps indicating more influence by surges than monsoonal floods. These stations are affected by much smaller rivers than are Saugor and Calcutta.

LONG-TERM CHANGES IN SEA LEVEL

General

Tide-gauge records of India may be influenced not only by short-term variations caused by storm surges and river floods but by long-term local movements of land and general rise of sea level caused by return of glacial meltwater and heating of the ocean. Because the relative importance of long-term changes in land levels and sea levels is uncertain in many regions, the term relative sea-level often is the preferred term. For India, let us investigate the likelihood that land movements may be important.

General Geological Structure

India has three main geomorphic divisions: Peninsular, Indo-Gangetic Plain, and Extra-Peninsular. These correspond with major tectonic divisions (KUMAR 1985, p. 46–56). Peninsular India consists mostly of Archaeozoic and Proterozoic metamorphic and intrusive igneous rocks (Figure 4), the Indian Shield, that was peneplained and broken into broad low plateaus separated by long narrow grabens before it became part of Asia. Separation from Antarctica began during Early Cretaceous about 127 myr BP by sea-floor spreading along the present Southeastern Mid-Indian Ridge with the northward path marked by the Laccadive Ridge on the west and the Ninetyeast Ridge (a hot-spot trail) on the east (HEEZEN and THARP, 1965; McKENZIE and SCLATER, 1971; CURRAY *et al.*, 1982). Between the Laccadive and Ninetyeast ridges are segments of oceanic crust impressed with magnetic signatures that reveal the northward movement of India (LARSON *et al.*, 1985). Collision of the Indian microcontinent with southern Asia occurred during mid-Paleogene (53 to 32 myr BP) followed by continuing penetration of about 2000 km (MOLNAR and TAPPONIER, 1981) at about 5 cm/year in the form of underthrusting by northern India and crumpling of both continental margins in unknown and probably changing ratios. This thickened crust continues to be uplifted isostatically to form the Himalaya Mountains (with most uplift about 10 myr BP; VALDIYA, 1984) and the plateau of Tibet.

East-west and northwest-southeast trending grabens formed during late Paleozoic times during the northerly travel of India, and they contain thick mostly terrestrial sediments of Paleozoic and Mesozoic age resting atop Pre-Cambrian basement and (for Godavari Graben—probably a failed rift, CURRAY and MOORE, 1974) on late Proterozoic sedimentary rocks. The massive Deccan Basalt fissure flows that originally covered about 10^6km^2 of west-central Peninsular India (Figure 4) to a maximum thickness of about 2 km were produced during the 67 to 60 myr interval (according to magnetic stratigraphy and K/A ages; COURTILLOT *et al.*, 1986), long before collision of India with Asia. Subsequently, the coastal regions of Peninsular India received a cover of marine and littoral Cenozoic sediments.

Extra-Peninsular India consists of the southern side of the Himalaya Mountains whose breadth continues northward to include Nepal, Bhutan, the southern margin of China, northern Pakistan, and Afghanistan. It also includes the western side of the Arakan-Yoma Mountains that are mostly within Burma. These two mountain chains are folded largely Mesozoic sediments (Figure 4) that had been deposited in Tethys Ocean before the collision of India with Asia closed that ocean. Associated are foredeep deposits, ophiolites, many thrust sheets, and intrusive igneous rocks—a very complex belt. The collision also produced extensive faulting and folding in China and elsewhere beyond the Himalaya Mountains (MOLNAR and TAPPONIER, 1975; TAPPONIER *et al.*, 1982).

The Indo-Gangetic Plain lies between Peninsular India and Extra-Peninsular India, and it is occupied by the Indus River at the west, the Ganges in the middle, and the Brahmaputra at the east. It contains more than 1 km thickness of terrestrial and littoral Cenozoic sediments (Figure 4) that were derived mainly from the uplifted mountains at the north and were deposited atop northern Peninsular India. The Indus and Ganges-Brahmaputra deltas at the western and eastern ends of the Plain continue beyond the Indian Shield and onto the deep ocean floor as deep-sea fans or cones. Geophysical studies of the Ganges Cone (CURRAY *et al.*, 1982) shows that the thickness of sediments reaches 15 km just beyond the Ganges Delta and progressively lessens southward for at least 3000 km. Morphology of the Indus Cone is well known, but its total thickness is not established, although in excess of 3.5 km (UDINTSEV, 1975; KOLLA and COUMES, 1987). These thicknesses of deltas are reasonable in view of the 1.67 x 10^9 tons/year of sediment brought by the Ganges-Brahmaputra (the largest of any river of the world) and of the 0.10 x

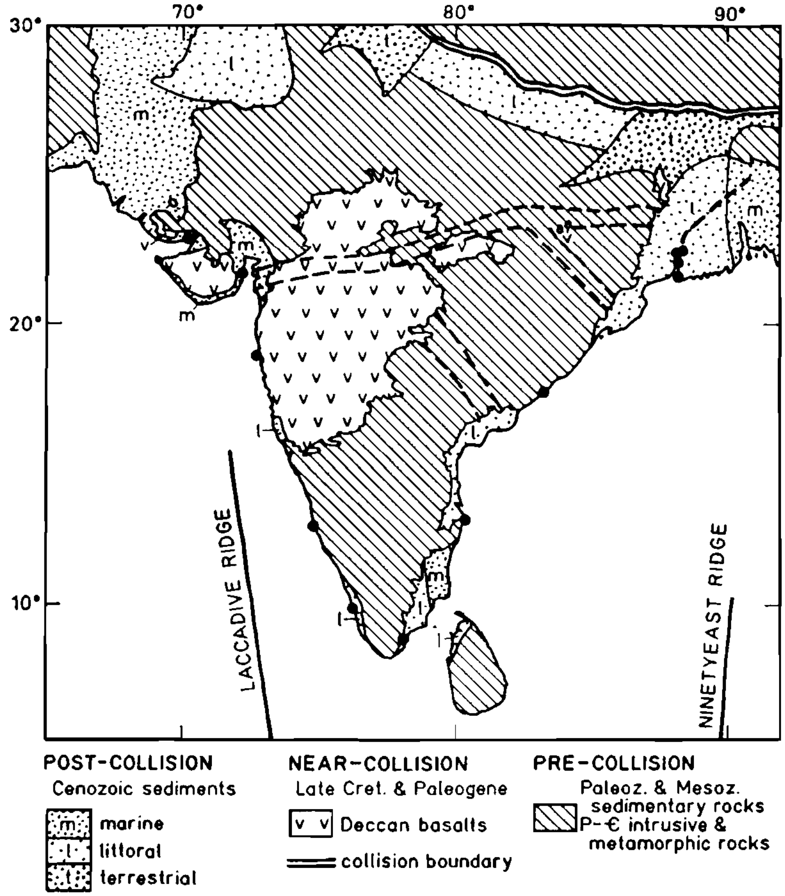


Figure 4. Generalized geological map of India and adjacent areas showing distributions of pre-, post-, and near-collision age rocks. The wide dashed lines outline late Paleozoic structures: long east-west one is the Normada-Son-Damodar Graben, southeasterly one at right is the Mahandi Graben, and southeasterly one at left is the Godavari Graben. North ends of axes of Laccadive and Ninetyeast ridges are indicated. From ROE (1962) supported by DIRECTOR of GEOLOGICAL SURVEY of INDIA (1958), YANSHIN (1966), UDINTSEV (1975, p. 118-119), and KUMAR (1985, p. 47). Wide dashed line through Bengal Basin is inferred edge of continental shelf during late Eocene (SENGUPTA, 1966).

10^9 tons/year by the Indus River (MILLIMAN and MEADE, 1983).

Gravity and Seismicity

The presence of widespread Pre-Cambrian metamorphic and intrusive igneous rocks on the Indian Shield of Peninsular India (Figure 4), showing little evidence of folding or faulting associated with the penetration of India into Asia, suggests that this part of India acted as a rigid piston (TAPPONIER *et al.*, 1982). Rigidity may be enhanced by the low heat flow that is typical of more ancient crusts (MOLNAR and TAPPONIER, 1981). Support for absence of post-intrusion tectonism is provided by a widespread pattern of only small free-air gravity anomalies (Figure 5). Only about 3 percent of the area of Peninsular India and Sri Lanka have anomalies higher than +100 mgals and essentially none lower than −100 mgals. These exceptional anomalies are widely scattered, indicating no systematic trends of uncompensated folding or faulting, unlike in Extra-Peninsular India.

Paucity of modern tectonic activity on the

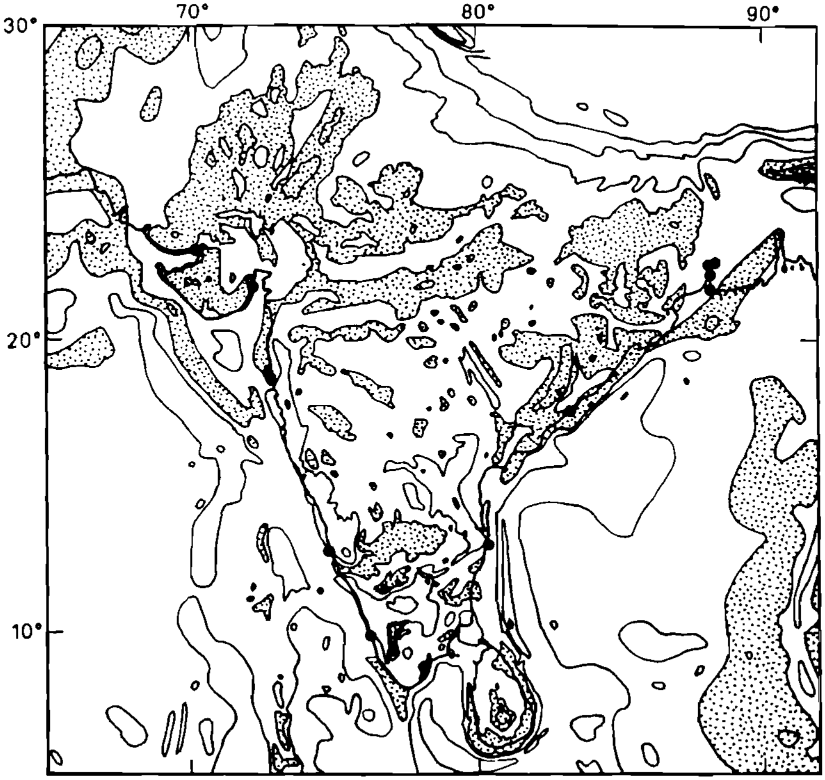


Figure 5. Map of free-air gravity anomalies of India and adjacent land and ocean floor. Contour interval is 50 mgal with areas of positive anomalies indicated by dotted pattern; blank areas have negative anomalies. Contours from BOWIN *et al.* (1982, sheets D9, D10, E9, and E10).

Indian Shield of Peninsular India south of the Indo-Gangetic Plain (Figure 6) is supported by the recording of only 14 earthquakes during 25 years; none exceeded magnitude 5.5. Most (nine) were near the coast, implying less stability there than farther inland. In contrast were more than 200 epicenters in Extra-Peninsular India and in bordering parts of the Indo-Gangetic Plain that were recorded during the same period. Depths of all earthquakes in Peninsular India were less than 70 km, and only five earthquakes farther north within Figure 6 were deeper (70 to 150 km). In the offshore area of Figure 6 earthquakes are only slightly related to topography. A cluster of epicenters lies just east of the Ninetyeast Ridge, but none are associated with the Laccadive Ridge or with the strait between India and Sri Lanka (Figure 4).

Marginal Sedimentary Basins

The Cenozoic sediments of Figure 4 are concentrated at depth within discontinuous basins beneath the coastal plain of the land, and they extend seaward beneath the continental shelves (Figure 7). Widest and probably thickest sediment fillings are those in the Bengal and Indus basins beneath the Ganges-Brahmaputra and Indus deltas. Farthest from the ocean are the several basins along the Indo-Gangetic Plain with their fillings of mainly terrestrial sediments.

Best studied are the basins from which petroleum is produced or ones that are believed to have best prospects for future production. Comparison of Figures 4 and 7 shows that most of these basins are in areas that have thick Cenozoic sediments, but several of them also

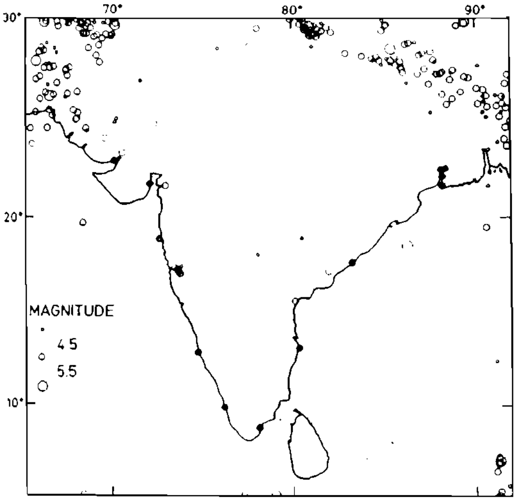
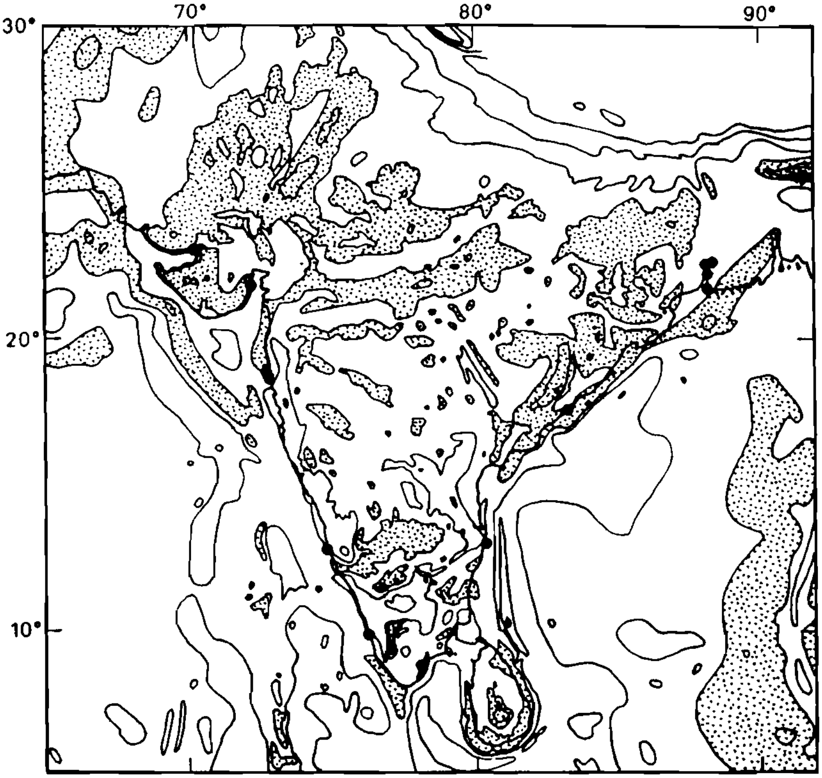


Figure 6. Earthquake epicenters for India and vicinity from National Oceanographic and Atmospheric Administration data in files of Woods Hole Oceanographic Institution for the period 1961 to 1985?. The pattern is similar to that indicated on a world-scale chart compiled by ESPINOSA *et al.* (1982). Smallest circles indicate magnitudes less than 4.5; largest circles indicate magnitudes greater than 5.5; intermediate circles indicate intermediate magnitudes.

include older strata (such as in the Pranhita-Godavari Basin of the Godavari Graben) that also may also contain prospective reservoirs in weathered rocks. Probably deepest is the Bengal Basin where near the front of the Ganges Delta sediments have buried the Pre-Cambrian basement to a depth of about 12 km, of which about half is Cenozoic in age (SENGUPTA, 1966). A "hingeline" beneath the basin (Figure 4: SENGUPTA, 1966; CURRAY, 1984) may mark the edge of continental crust. Thick sediments continue southward beneath the Ganges Cone (Figure 7). Considerable study also has been made of the Bombay and Cambay basins that underlie the Indus Delta and they probably are limited on the west by a northerly subsurface extension of the Laccadive Ridge (Figure 4). Complex folds on the floors of these two basins are the sites of petroleum accumulations from which most of the oil used by India is produced, the rest being mostly from the Assam Basin at the far northeast (SOEPARJADI *et al.*, 1987). As knowledge of offshore basins increases because of continuing seismic exploration and drilling, oil production from them probably will increase (ORASIANU, 1986).

The basins beneath the coastal plain are made discontinuous by basement ridges transverse to the coast. For example, the Kutch and Cambay basins are separated by the Saurashtra Ridge (a southwesterly extension of the Pre-Cambrian shield of the broad peninsula between Kandla and Bhavnagar, Figure 1). Similarly, the Bombay and Karnataka basins are separated by the Panjim Ridge and the Karnataka and Kerala basins by a change from carbonate to clastic sediments off Calicut (RAMASWAMY and RAO, 1980). Other transverse ridges separate the basins beneath the eastern coast of India. These basins, each having several kilometers of Late Cretaceous and Cenozoic sediments, are segmented by secondary ridges (SASTRI *et al.*, 1973; SAHNI 1982; CURRAY, 1984) similar to those of the Bombay and Cambay basins. The southern part of the Cauvary Basin occupies a failed rift between India and Sri Lanka that now may be opening slowly to further separate these pieces of continental crust. The northern part of the basin is atop continental crust that slowly subsided from Early Cretaceous through Paleogene. Drill-hole stratigraphy (CURRAY, 1984) shows subsidence increasing from Early Neogene to the present—at an overall rate of 0.04 mm/year. Oldest sediments in basins of both coasts are Late Jurassic or Early Cretaceous in age, indicating marginal subsidence of the Pre-Cambrian shield before impact of India with Asia. The weight of the thick Mesozoic and Cenozoic sediments in each coastal basin must have produced local subsidence of the crust that made room for additional sediments, with probably less subsidence above the transverse ridges that separate basins.

Long-term support for the land subsidence is provided by the discovery of temples and other structures submerged 5 to 6 m beyond the tip of the peninsula southwest of Kandla (submerged probably in the 14th century B.C.; RAO, 1987). Other known sites of submerged ports are off Bombay, Mangalore, the coast just north of Sri Lanka, and Vishakhapatnam. Further submarine archaeological exploration may considerably expand the knowledge of locales of subsidence. A later submergence near Kandla occurred when 5000 km^2 of the western side of the Gulf of Kutch suddenly submerged 4 to 5 m in 1819, and a nearby area a third that size emerged about 1 m, according to WADIA (1963,



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Indian Shield of Peninsular India south of the Indo-Gangetic Plain (Figure 6) is supported by the recording of only 14 earthquakes during 25 years; none exceeded magnitude 5.5. Most (nine) were near the coast, implying less stability there than farther inland. In contrast were more than 200 epicenters in Extra-Peninsular India and in bordering parts of the Indo-Gangetic Plain that were recorded during the same period. Depths of all earthquakes in Peninsular India were less than 70 km, and only five earthquakes farther north within Figure 6 were deeper (70 to 150 km). In the offshore area of Figure 6 earthquakes are only slightly related to topography. A cluster of epicenters lies just east of the Ninetyeast Ridge, but none are associated with the Laccadive Ridge or with the strait between India and Sri Lanka (Figure 4).

Marginal Sedimentary Basins

The Cenozoic sediments of Figure 4 are concentrated at depth within discontinuous basins beneath the coastal plain of the land, and they extend seaward beneath the continental shelves (Figure 7). Widest and probably thickest sediment fillings are those in the Bengal and Indus basins beneath the Ganges-Brahmaputra and Indus deltas. Farthest from the ocean are the several basins along the Indo-Gangetic Plain with their fillings of mainly terrestrial sediments.

Best studied are the basins from which petroleum is produced or ones that are believed to have best prospects for future production. Comparison of Figures 4 and 7 shows that most of these basins are in areas that have thick Cenozoic sediments, but several of them also

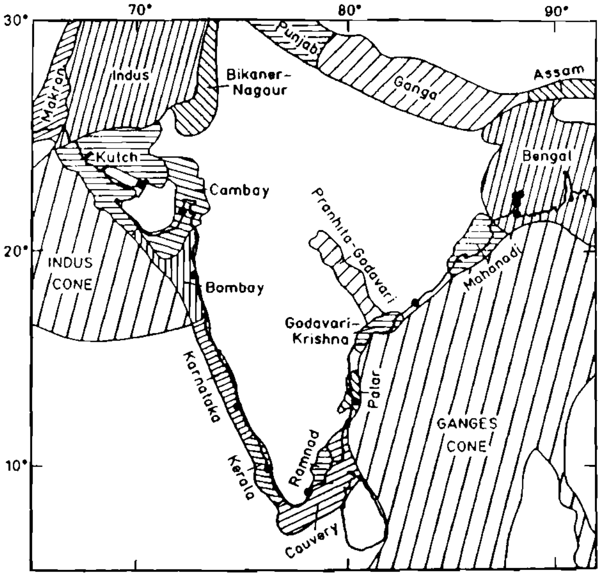

Figure 7. Somewhat diagrammatic outlines of basins containing mainly thick Cenozoic sediments that have some prospect of petroleum potential. From COURY and HENDRICKS (1978) updated from RAMASWAMY and RAO (1980) and ORASIANU (1986).

p. 47). Wadia provided additional information about subsidence from observations of a submerged forest off Bombay and submerged peats near and south of Madras and in the Ganges Delta. Similarly, many raised marine terraces occur along the coasts of India, but most studies of them appear to be so local as to yield little available information about crustal deformation possibly associated with the distributions of coastal basins and their intervening ridges.

CONCLUSIONS

All tide-gauge records of India are in Peninsula India. The most acceptable ones have confidence levels of 1.00 or 0.99 for their linear least squares time-elevation regression curves spanning 24 to 105 years. Not included are records from Kandla, Veraval, Bhavnagar, Marmagao, Tuticorin, Haldia, and Tribeni (Table 1) that have student-t confidence levels only between 0.71 and 0.58; most also have too short time spans. Four others (Saugor, Diamond Harbor, Kidderpore, and Calcutta) also are omitted even though their confidence levels are good (0.99 to 0.97), because they appear to have been influenced greatly by cyclonic storm surges, floods, or datum shifts (Figure 3). Omission of these eleven tide-gauge records leaves five (Bombay, Mangalore, Cochin, Madras, and Vishakhapatnam) that are considered reliable indicators of changed relative sea level during the overall period of their recording—1878 to 1982. The average of these five station records reveals a range of relative land-level changes between + 1.3 and − 2.1 mm/year with an average of −0.5 mm/year and a median of −0.8 mm/year. This small range could indicate either slow marginal subsidence of Peninsular India or slow rise of actual area level. These results are similar to those obtained by AUBREY and EMERY (1986) for Australia, where eight acceptable station records average 2.2 mm/year of land subsidence or sea-level rise. Other coastal regions of the world (coasts of North America, Japan, northern Europe, South America, the Caribbean Sea, and the Mediterranean Sea) exhibit more erratic and local changes that are ascribable to tectonics associated with folding, faulting, melting of ice caps, volcanic activity, and delta growth, few of which (other than delta growth) can be important along the western and southeastern coasts of Peninsular India and of Australia.

The similarity of tide-gauge records in Peninsular India and Australia is striking in view of the fact that Australia has long been known for its tectonic stability and India for its nearness to a belt of tectonic instability that formed the Earth's most spectacular mountain range—the Himalayas. However, the two regions have similar Pre-Cambrian crusts and both were part of the same land mass adjoining Antarctica, even though India separated about 127 myr BP. and Australia only about 50 myr BP. Can it be that these two regions are the best indicators of present relative sea-level change, and that differences between station records along the coasts of each crust merely reflect increments of submergence or emergence caused by local tectonics, delta building, or basin filling?

Choice between eustatic rise of sea level and coastal subsidence may be provided by evidence from repeated precise leveling surveys across India. If the surveys reveal tilting or downward warping of the coastal margins of the crust with respect to the central inland region, subsidence of the land is indicated. If no warp is evident, we must appeal to continuing post-glacial rise of sea level. If the latter turns out to be the more important, it is probable that India and Bangladesh will experience accelerating ocean invasion in future decades because of increased melt caused by rise of temperature (the greenhouse effect) produced by carbon dioxide from burning of fossil fuels and from other trace gases. Higher air temperature likely will increase the return of meltwater from remaining glaciers, and higher seawater temperature must expand the volume of ocean water. Quantification of these alternatives is so important for the coastal populations of India and Bangladesh that efforts to distinguish between them must be made. The most evident method is that of analysis of repeated precision leveling surveys. If data for existing past surveys are unavailable outside India, the study must be completed by Indian government engineers and geologists. Use of Very Long Baseline Interferometry and Differential Global Positioning Surveys (CARTER and ROBERTSON, 1986) may enhance our ability to separate land-level from sea-level changes.

ACKNOWLEDGEMENTS

This work was funded by the National Science Foundation under Grant number OCE-8501174, and by the Coastal Research Center of the Woods Hole Oceanographic Institution. Supplies and services were supported in part by the Ocean Industry Program. The manuscript was reviewed by E. Uchupi, J. D. Milliman, C. D. Hollister, P. A. Pirazzoli, and T. R. Healy, who provided useful additional information and comments. Appreciation is expressed to C. O. Bowin for the information or earthquakes and to D. T. Pugh of the Permanent Service for Mean Sea Level for magnetic tapes containing updated information on tide-gauge records. MSL data for Indian ports has been supplied by Number 68 (Tidal) Party, Geodetic and Research Branch, Survey of India, with the permission of the Surveyor General of India.

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☐ RESUMEN ☐

India tiene la mayoria de las estaciones de medida de mareas del Norte del Océano Indico a partir de las cuales se puede estimar a largo plazo el movimiento relativo del nivel medio del mar. Sin embargo, dos tienen registros muy cortos, cino tienen probre valor estadistico y cuatro parecen estar muy influenciadas por episodios de altos niveles del mar causados por tormentas ciclónicas o illuvias monzónicas, o alternativamente por pobres registros de mareas. Las cino estaciones de registro restantes que aparecen útiles (tres en la costa Oeste y dos en la costa Este) revelan cambios entre + 1.3 y − 2.1 mm/año de cambio del nivel relativo de la tierra al nivel del mar con un promedio de menos de 0.7 mm/año, indicando un relativo hundimiento de la tierra.

No está muy claro si estos registros dan un hundimiento real de la tierra o un ascenso del nivel del mar.

Independientemente de esta causa, un aumento de hundimiento puede ser esperado en las próximas décadas debido al aumento de temperaturas (efecto invernadero de la combustón en el mundo de los combustibles fósiles) que han aumentado el volumen de las aguas del océano asi como el dehielo glacial.

La realización y estudio de precisas y repetidas medidas del nivel en tierra, combinadas con la información obtenida de la avanzada tecnologia geodésica servirán para cuantificar la importancia relativa del hundimiento de las franjas costeras relativo a áreas de estuario (hundimiento de costas) frente al crecimiento del volumen de agua del océano causando la intrusión de éste.—*Department of Water Sciences, University of Cantabria, Santander, Spain.*

☐ ZUSAMMENFASSUNG ☐

Indien unterhält die meisten Gezeiten-Meßstationen des nördlichen Indischen Ozeans, aus denen durchschnittliche jährliche Meeresspiegel berechnet werden können, um Langzeitveränderungen abzuschätzen. Allerdings sind zwei Meßreihen zu kurz, fünf haben nur eine geringe statistische Verläßlichkeit und vier weitere scheinen stark von episodisch hohen Meeresspiegelständen beeinflußt zu sein, die von zyklonalen Sturmwellen beziehungsweise monsunalen Fluten verursacht wurden oder aber durch schlechte Gezeitenmessungen bedingt sind. Es bleiben fünf Meßstationen übrig, deren Meßreihen brauchbar erscheinen (drei an der west- und zwei an der Ostküste). Sie zeigen Tendenzen zur Veränderung des Landniveaus relativ zum Meeresspiegel, die zwischen + 1,3 und − 2,1 mm pro Jahr (mit einem jährlichen Durchschnitt von −0,7 mm) liegen. Das deutet auf eine relative Senkung des Landes hin. Es ist unklar, ob sich in diesen Meßreihen eine absolute Landsenkung oder ein tatsächlicher eustatischer Meeresspiegelanstieg dokumentiert. Auch unabhängig von der gegenwärtigen Ursache ist mit vermehrter Absenkung in den kommenden Jahrzehnten aufgrund erhöhter Temperaturen zu rechnen (Treibhaus-Effekt wegen des weltweiten Verbrennens von fossilen Brennstoffen), was zur Vergrößerung des Meerwasservolumens wie auch zur Zunahme an glazialem Schmelzwassers führen kann. Wiederholte präzise Nivellements an Land zusammen mit Information aufgrund der modernen geodätischen Technologie können die Relationen zwischen absinkenden Küstenzonen und landeiwärtigen Gebieten einerseits und zunehmendem Meerwasservolumen und dadurch bedingten Meeresspiegelanstieg andererseits quantifizieren.—*Helmut Brüchner, Geographisches Institut, Universität Düsseldorf, F.R.G.*

☐ RÉSUMÉ ☐

L'Inde possède la plupart des stations marégraphiques du nord de l'Océan Indien, à partir desquelles est calculée la moyenne annuelle des niveaux relatifs de la mer servant à l'estimation des tendances à long terme. Tous ces enregistrements ne sont pas d'égale qualité, deux couvrent une trop courte période, cinq ont une faible pertinence statistique, et quatre autres paraissent très influencés par les hausses du niveau de la mer causées par les typhones et les moussons, ou sont altérés par l'enregistrement de très faibles marées. Les données des cinq stations qui semblent satisfaisantes (trois sur la côte ouest, deux sur la côte est) laissent apparaitre une variation de niveau relatif située entre +1,3 et −2,1 mm/ an avec une moyenne de 0,7 mm/an, donc une tendance á la subsidence du continent. On ne peut dire si cela correspond vraiment à une subsidence du continent ou à une montée eustatique du niveau de la mer. De toutes manières, ont peut s'attendre à une augmentation de la submersion dans les décennies à venir à cause de l'élévation des températures (effet de serre provoqué par la consummation des fuels marins fossiles) qui peut augmeter le volume des eaux océaniques tandis qu'augmente celui des eaux glacielles. Seules des campagnes de nivellements précis et répétés sur le continent, combinées aux informations de la technologie géodésique avancée, peuvent mesurer la part de la subsidence côtière dans l'augmentation du volume des eaux océaniques causant une ingression de l'océan.—*Catherine Bressolier, E.P.H.E., Montrouge, France.*