

## SEASONAL VARIATION IN MEAN-SEA LEVEL AT MORMUGAO, WEST COAST OF INDIA

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### ABSTRACT

Monthly mean-sea levels for a period of five years computed from the automatic tide-gauge records were analysed at ~~Mormugao~~. A seasonal trend in the mean-sea level with low values during the south-west monsoon and high values in the fair weather period were observed. An assessment of the factors responsible for these variations was made through an application of hydrodynamic equations. The predominant factors controlling the seasonal variation in the mean-sea level appeared to be coastal currents and water density. The direct effect of the wind appeared to be relatively insignificant from the analysis.

### INTRODUCTION

Variations in the sea level are mainly due to the changes in the resultant gravitational attraction of the moon and the sun on the earth. Oceanographic, meteorologic, hydrologic, geologic, seismologic and eustatic factors also contribute to the sea level variations. The first two factors are more important as compared to the others in studying the seasonal variations in the sea level. A knowledge of the fluctuations in the mean sea level finds an application in the prediction of storm surges, coast and harbour development and coastal zone management.

Considerable literature is available on the mean sea level and its seasonal and annual changes along many parts of the world's coasts. As far as the coast-line of India is concerned very few studies were carried out and these are mostly confined to the east coast. The works of Prasada Rao and Lafond (1954), Ramanadham and Varadarajulu (1964) and Varadarajulu and Dhanalakshmi (1975) pertain to cases on the east coast of the country and those of Ramaraju and Hariharan (1967) and Banse (1968) pertain to the west coast of India.

The present paper deals with the results of the studies carried out on the seasonal changes of the mean sea level based on the water levels recorded at Mormugao harbour, situated on the southern bank of the Mormugao Bay at the mouth of river Zuari (Fig. 1). In the study area, the tides are mixed semi-diurnal type with a range of about 2.0 m. The tide gauge is situated on the lee side of the existing shore-connected break water partly enclosing the main harbour.

The sea level undergoes seasonal changes. The influence of the various factors mentioned above were taken into consideration to provide explanations for the major features noticed in the sea level fluctuations.

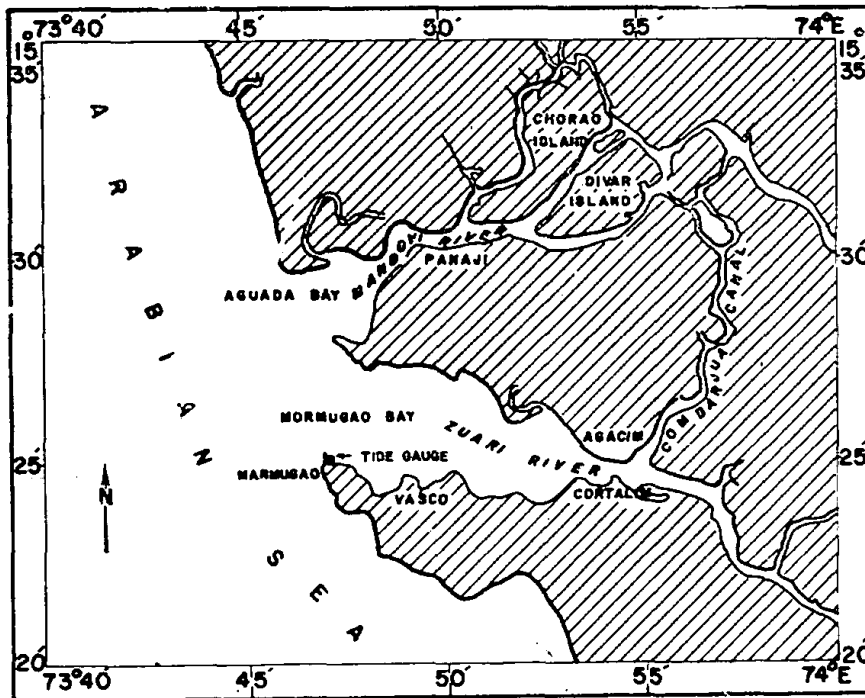


Fig. 1. Map of the study area and tide gauge position.

#### DATA AND ANALYSIS

The data on hourly variations in the water level recorded at Mormugao (by a recording type tide gauge) were collected for the years 1966 to 1970 from the Mormugao Port Trust. The relevant meteorological data reported from the Mormugao Weather Observatory, were collected from the India Meteorological Department.

The daily mean sea level heights were computed by taking an arithmetic mean of the hourly readings for twentyfour hours. Monthly mean heights were then determined by averaging the daily mean values. This method is adequate to eliminate the effect of short period tidal constituents (Patullo, Munk, Revelle and Strong, 1955).

#### RESULTS

Mean monthly and annual sea level heights are presented for the period 1966 to 1970 in Table I. The table shows that sea level varies from month to month and year to year. Also during the course of each year the sea level is subject to consistent seasonal changes attaining a low value during the south-west monsoon and high value during the fair weather months. The distribution of the monthly mean sea level heights (Fig. 2) shows a cyclic feature. The monthly heights of the mean sea level show in general a lowering trend from January to September after which the trend reverses. Banse (1968) reported almost similar features for some other stations on the west coast of India. The annual maximum is observed in December/January and minimum in August/September. The annual (average) range of mean sea level fluctuations is about 18 cm.

Table 1. Monthly and annual mean sea level at Mormugao in cm.

Year	Jan	Feb	March	April	May	June	July
1966	125.20	121.20	121.50	118.70	110.60	122.00	118.10
1967	140.12	135.60	136.40	139.20	124.10	128.00	120.80
1968	131.39	130.29	137.09	131.41	121.07	122.54	116.64
1969	134.86	132.70	134.10	132.95	127.28	115.83	120.91
1970	133.68	134.45	133.34	134.17	128.34	129.26	129.14
mean monthly	133.05	130.85	132.49	131.30	122.28	123.53	121.12

	Aug	Sept	Oct	Nov	Dec	Annual Mean
	117.20	123.80	131.20	130.40	142.14	123.50
	119.90	113.70	125.10	134.91	130.20	129.00
	114.93	115.74	127.58	132.88	139.37	126.74
	123.99	119.35	128.12	136.38	137.50	128.66
	120.71	121.76	128.40	137.64	136.94	130.67
mean monthly	119.35	118.87	128.08	134.44	137.23	

DISCUSSION

The dynamic nature of the sea level is the result of many external and internal forces which act upon the sea level singly and/or in combination. The extent to which these forces contribute to the changes observed in the sea level could be assessed by the basic hydrodynamic equations dealing with the motion in the sea.

The equations of motion in two dimensional form, neglecting the nonlinear terms and bottom friction, along with the equation of continuity for the computation of sea surface elevation caused by the different driving forces, are expressed as :

$$\frac{\partial u}{\partial t} + g \frac{\partial s}{\partial x} + \frac{\partial P_a}{\partial x} \frac{1}{\rho_w} - \frac{\tau_x}{\rho_w(D+s)} - f_v = 0 \quad \dots (1)$$

$$\frac{\partial v}{\partial t} + g \frac{\partial s}{\partial y} + \frac{\partial P_a}{\partial y} \frac{1}{\rho_w} - \frac{\tau_y}{\rho_w(D+s)} + f_u = 0 \quad \dots (2)$$

$$\frac{\partial s}{\partial t} + \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \quad \dots (3)$$

where  $x$  and  $y$  are the horizontal coordinates,  $u$  and  $v$  are the corresponding depth-mean velocity components,  $f$  is the coriolis parameter,  $g$  is the acceleration due to gravity,  $D$  is the depth,  $s$  is the elevation of the sea surface,  $\rho_w$  is the density of seawater,  $P_a$  is the atmospheric pressure and  $\tau_x$  and  $\tau_y$  are the components of wind stress in  $x$  and  $y$  directions.

Welander (1961) provided the necessary justification for the assumption made on the hydrostatic approximation and for neglecting the non-linear acceleration terms. The equations were obtained by integrating the basic hydrodynamic equations from the bottom to the surface. As the elevation of the sea surface 's' is assumed to be negligibly small in comparison to the depth D,  $(D+s)$  could be treated as equivalent to 'D' for all practical purposes. Bottom friction was disregarded assuming it as negligible.

### Atmospheric pressure

Atmospheric pressure affects the sea level directly. Applying the statical law of the barometric influence in which the sea surface acts as an inverted barometer (rising approximately 1 cm for a decrease in air pressure of 1 mb and vice-versa), the mean-sea level corrected for atmospheric pressure is presented in Fig. 2.

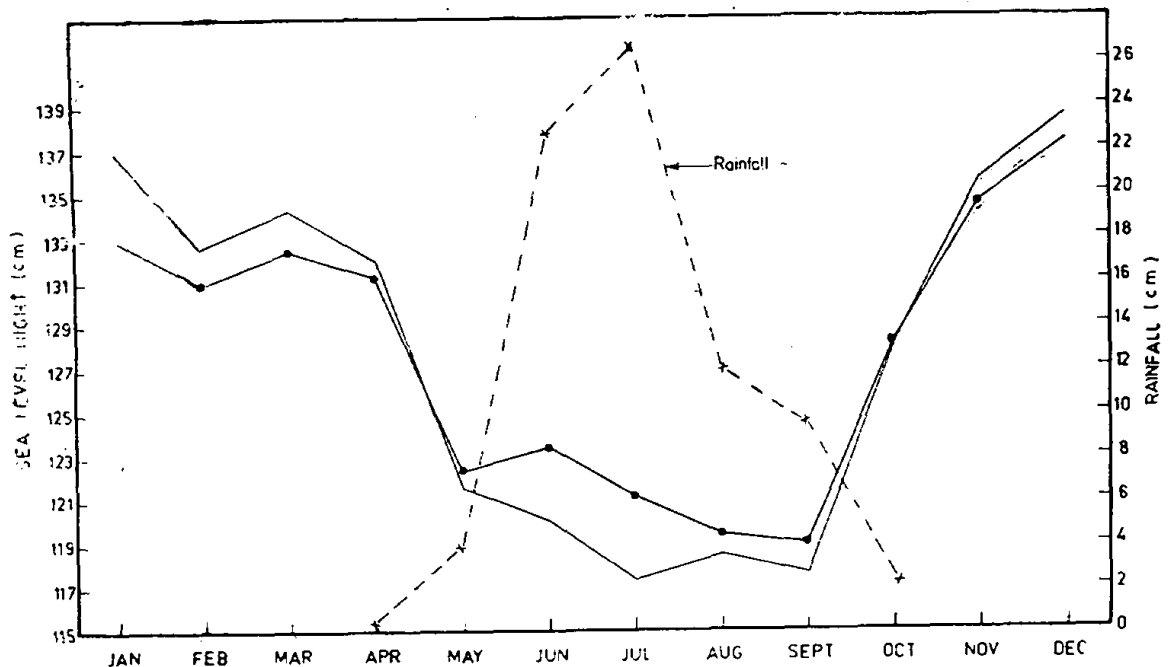


Fig. 2. Mean monthly sea level heights: observed (closed circles) and corrected for atmospheric pressure (continuous line) and monthly rainfall (crosses and broken line).

Fig. 3 shows the deviations of monthly mean-sea level and atmospheric pressure from the normal (mean of five years). It could be inferred from Figs. 2 and 3, that the effect of atmospheric pressure is insignificant as there is no regular inverse correspondence noticeable between the deviations of the mean-sea level and atmospheric pressure. In this connection it is worthwhile to note that the barometric effect is less pronounced in low latitudes than in higher latitudes (see Lisitzin, 1963).

### Wind

Wind acts directly and indirectly on the sea surface producing changes in the sea level. In shallow waters the surface drift caused by the wind is nearly in the direction of the wind. This direct effect of the wind is such that steady on-shore and

Table II. Monthly mean wind direction and speed (recorded at Mormugao).

Month	Jan	Feb	March	April	May	June	July	Aug	Sept	Oct	Nov	Dec
Direction	NE	NW	NW	NW	NW	SW	SW	SW	SW	NE	NE	NE
Speed m/sec.	3.0	3.5	3.5	4.0	4.0	5.5	6.5	5.5	3.5	3.0	3.0	3.0

off-shore winds cause a rise and fall in the sea level respectively, at the coast. Table II gives the mean monthly wind direction and speed. During the fair weather months, the wind pattern is found (from daily weather reports) to comprise of land and sea

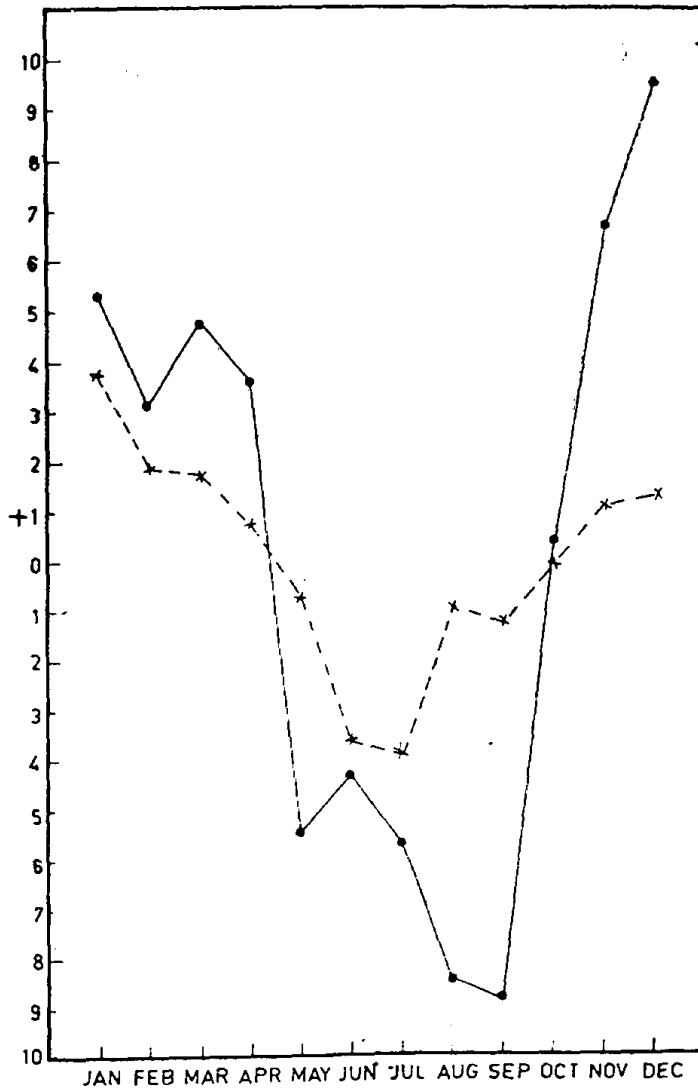


Fig. 3. Deviations in monthly mean sea level (closed circles) and atmospheric pressure (crosses and broken line) from the normal.

breezes, unlike the south-west monsoon when steady and relatively strong on-shore wind prevails over the region. The extent to which the steady on-shore winds influence the sea level by way of wind set-up at the coast could be understood from the following example.

Considering a one dimensional case, the slope of the sea surface produced by the wind stress can be computed from

$$\frac{\partial s}{\partial x} = \frac{\tau_x}{\rho_a g D} \quad \dots \quad \dots \quad (4)$$

equating the second and fourth terms in eqn. 1, where  $\tau_x = k \rho_a W_a^2$ ,  $k$  is the drag coefficient,  $\rho_a$  the density of air and  $W_a$ , the wind speed. Assuming the edge of the continental shelf as the nodal point, and taking the average depth of the continental shelf off Goa as 60 m and width as 60 km (Nair, 1975),  $k = 2.4 \times 10^{-3}$ ,  $\rho_a = 1.3 \times 10^{-2}$  g/cm<sup>3</sup> and  $g = 980$  cm/sec<sup>2</sup>, the change in the height of the sea level is obtained as,  $\Delta s = 2$  cm, for a wind speed of 8 m/sec. Although 8 m/sec is greater than the highest mean monthly wind speed (July) shown in Table II it has been chosen for convenience of computation. The computed wind stress compares very well with Hidaka's (1958) computed value of the wind stress for the five degree square grid which also includes the region under discussion in this paper.

#### *Rainfall and river discharge*

Mean monthly rainfall is shown in Fig. 2 and the river discharge for the year 1966 is shown in Fig. 4. Rainfall is maximum during the months June to August and so also is the run off.

#### *Currents*

Due to the action of coriolis force, a slope is created perpendicular to the direction of the currents and hence a change in the sea level along the coast accompany the currents parallel to the coast.

As steady state condition is assumed, and the  $x$ -axis is aligned in the direction of the current, the second and the last terms in the eqn. 2 reach a balance. Hence the deviation in the height of the sea level can be determined as

$$\Delta s = - \frac{2u\omega \sin \phi \cdot l}{g} \quad \dots \quad \dots \quad (5)$$

where  $l$  is the distance across the current. Taking  $l = 60$  km,  $u = 50$  cm/sec (the current attains this strength in the SW monsoon),  $\omega = 7.29 \times 10^{-5}$  sec<sup>-1</sup> and  $\phi = 15^\circ N$ , from the eqn. 5, we get,  $\Delta s = 12$  cm. In the northern hemisphere, the height of the sea level is greater on the right hand side and lower on the left hand side of the currents.

The currents prevailing along the coast of Goa from October to January is either northerly or north westerly. In February it reverses in its direction and a

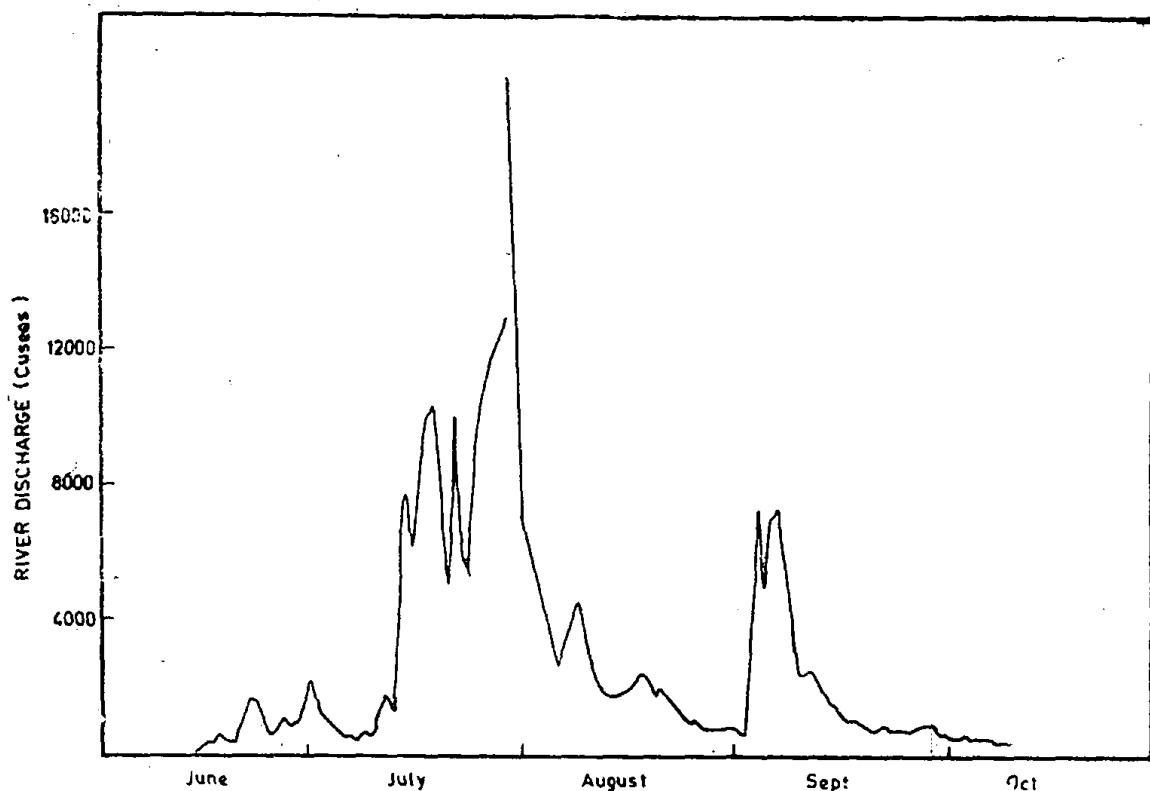


Fig. 4. River discharge for the year 1966.

southerly flow begins and persists upto September, with an intensification during the peak south-west monsoon period (Varadachari and Sharma, 1964 and K.N.M. I., 1952).

#### *Effect of change in water density*

Patullo (1960) and several other investigators (see Lisitzin, 1963) proved that the mean sea level variations in low latitudes are controlled to a very large extent by the steric effect. Lafond (1939) (see Lisitzin, 1963) concluded in a study along the Pacific coast that the changes in density of coastal waters are mainly explained by the variations in the current system.

Various oceanographic studies provide evidence on the occurrence of upwelling and sinking along the west coast of India (Varadachari and Sharma, 1964; Ramamirtham and Patil, 1965; Ramamirtham and Rao, 1973; Banse, 1968; Rao, Cherian, Varma and Varadachari, 1974). The occurrence of this phenomenon is largely based on the sloping of isolines of different hydrographic parameters such as temperature, salinity and density. Varadachari and Sharma (1964) and Sastry and D'Souza (1972) suggested that the upwelling is due to the divergence in the field of motion. Generally, sinking occurs along the coast when the current direction is northerly and upwelling occurs when the current direction is southerly.

As a consequence of these processes, a change in the density structure of water takes place along the coast. A relationship between the density change and the sea

level is assumed as a change of 1 unit in  $\sigma_t = 4$  cm change in sea level approximately (arbitrarily taken from Striem and Rosenan, 1972). The seasonal change in mean density ( $\sigma_t$ ) of the water column would be of the order of 2 to 3 units greater during the south-west monsoon period than during the fair weather season (Ramamirtham, 1965, 1973 & Rao, Cherian, Varma and Varadachari, 1974). Unfortunately, accurate steric sea level could not be computed due to the non-availability of continuous observations on temperature and salinity throughout the year.

Based on these results the following conclusions can be drawn :

The effect of atmospheric pressure changes cannot be considered as a factor contributing significantly towards the cyclic pattern observed in the mean monthly sea level fluctuations. The wind pattern seems to have relatively very little direct effect on the sea level as is evident from the estimations made on wind set-up. The rainfall and the associated freshwater discharge contribute to changes in the density of the coastal waters. However, owing to the mixing following the transverse circulation in the coastal waters, there could be a reduction in the effect of the river discharge on the sea level. The transverse circulation which takes place for the reasons of continuity probably aids the process of upwelling and causes shoreward movement of dense bottom water and offshore movement of surface water. As a result of these processes, the effect of rainfall and run off may be nullified and further obliterated by the effect of coastal current. The high mean sea level noticed during the period of northerly currents and the low mean sea level during the period of southerly currents and the magnitude of their effect obtained from the calculations, strongly suggest that the changes in the mean sea level are principally caused by the current system augmented by the processes of sinking and upwelling which bring about the changes in the distribution of density. As a supporting evidence, it may be added that the transitional periods in the current reversal nearly coincide with those of the monthly mean-sea levels. Banse (1968) also indicated that the trend in the mean sea level on the west coast of India from April to October agrees well with the waxing and waning of the coastal currents.

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