

AN EXAMINATION OF THE FACTORS THAT INFLUENCE THE MONTHLY-MEAN SEA LEVEL ALONG THE COAST OF INDIA

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ABSTRACT

Available data on monthly-mean sea levels at eight locations off India — Veraval, Bombay, Marmagao and Cochin on the west coast, and Nagappattinam, Madras, Vishakhapatnam and Calcutta on the east coast — have been used to determine the annual cycle of the sea level. Three other sets of data — atmospheric pressure, ship-drift estimates and rainfall — have been utilized to examine the factors that control the observed variations in the sea level.

In general, the effect of the atmospheric pressure variation on the monthly-mean sea level along the coast is significant; the amplitude of the effect is dependent on location and varies between 4-20 cm. The sea level at Calcutta shows no influence of large scale coastal circulation. Off Bombay the monthly-mean coastal currents are weak and do not show significant correlation with the sea level. Sea levels at Veraval, Marmagao, Cochin, Nagappattinam, Madras and Vishakhapatnam (corrected for atmospheric pressure effects) show good correlation with the longshore component of the coastal current. The sea level records at these locations could be a good tool for the long-term monitoring of the surface geostrophic currents along the coast.

INTRODUCTION

Studies during the last few decades have shown that monthly-mean sea level can be used to monitor the large scale, low frequency circulation of the oceans (e.g., WYRTKI, 1979). There is now a network of tide gauges in the Pacific Ocean to monitor sea surface topography, and similar networks have been proposed for the other oceans (see WYRTKI and PUGH, 1983). The North Indian Ocean component of such a network will have to rely on the data collected from tidal stations located within the territory of India. Some of the existing stations may be used towards this purpose.

The existing Indian tidal stations, however, were not set up to monitor the general ocean circulation, but rather to measure the tides in areas of interest to maritime activities. Hence, not all of the existing stations may be suitable for sea level monitoring. It is therefore necessary to identify the factors that control the monthly-mean sea level at the existing stations. Such an exercise would help to determine how the data already collected might be used to understand ocean circulation in the North Indian Ocean. Furthermore, it might become possible to select tidal stations that would be suitable for inclusion in a sea-level network.

With the above considerations in mind, we have examined available data on monthly-mean sea levels, together with other relevant information, from eight locations along the coast of India (Fig. 1). Four of these, Veraval, Bombay, Marmagao and Cochin, lie on the west coast. The others, Nagappattinam, Madras, Vishakhapatnam and Calcutta, are on the east coast. The next section is devoted to a preliminary discussion on the likely causes behind the monthly-mean sea level variations in coastal areas.

PRELIMINARY DISCUSSION

PATULLO, MUNK, REVELLE and STRONG (1955; hereafter referred to as PMRS) related the annual cycle for monthly-mean sea levels to effects from: (1) astronomic tides; (2) atmospheric pressure; and (3) "steric" fluctuations. Here it suffices to point out that the upper limit of the tidal contribution is around a centimeter, which is much less than the amplitude of the annual cycles we shall be dealing with. The contribution to the sea level change due to atmospheric pressure changes depends on the difference between the local pressure and the mean global sea surface pressure. The annual cycle of this contribution has been computed in the next section.

The most important finding of PMRS was that variations in the recorded monthly-mean sea level at a location generally agree closely with the "steric" departures (Z_α) in the vicinity of the location.

$$\text{Here, } Z_\alpha = \frac{1}{g} \int_{P_a}^{P_o} \Delta\alpha \, dP \quad (1)$$

$$\text{and, } \Delta\alpha = \frac{1}{\rho(T,S,P)} - \frac{1}{\rho(\bar{T},\bar{S},P)}$$

ρ is the density, T and S are the temperature and the salinity, \bar{T} and \bar{S} being their annual mean, g is the acceleration due to gravity, P_a is the atmospheric pressure, and P_o is the pressure at a depth where all seasonal effects are assumed to vanish. PMRS did not examine the implications of the above results to circulation in the vicinity of the tide gauge, even though the mass field (which determines Z_α), the sea surface topography, and the geostrophic velocity field are interrelated.

Consider the situation depicted in Figure 2. A coastal current flows southward along a north-south coastline. We assume that the motion is restricted up to a distance R from the coast, R being of the order of a Rossby radius of deformation (approximately 100 km) from the coast. Assuming that the pressure gradient normal to the coast is in geostrophic equilibrium with the velocity field, we get

$$fv_1^s = g \frac{\partial Z_s}{\partial x} \quad (2)$$

where f and g are the Coriolis parameter and the acceleration due to gravity, respectively. v_1^s is the longshore component of the surface geostrophic velocity, and $Z_s(x,y)$ is the topography of the ocean surface. Variations in Z_s near a coast can be determined from sea level data. We can write Z_s in terms of variations in dynamic height normal to the coast,

$$fv_1^s = \frac{\partial}{\partial x} \left[\int_{P_o}^{P_a} \delta dP \right], \quad (3)$$

where

$$\delta = \frac{1}{\rho(T,S,P)} - \frac{1}{\rho(0,35,P)}$$

is the specific volume anomaly. P_o is the pressure at the depth of no motion. The term in the square brackets is proportional to Z_α . The observation made by PMRS, that variations in Z_α closely match sea level changes, when viewed in isolation bears no particular implication to the dynamics of the currents in the vicinity of the tide-gauge. A static ocean, heated or cooled uniformly at the surface, will show variations in Z_α which match with the sea level variations. But when we look at the result from the point of view of the dynamics behind Equations (2) and (3), and impose the restriction that the changes in the mass field are mainly due to advection, the PMRS result becomes a tool to monitor coastal geostrophic currents. To see this we approximate Equation (2),

$$fv_1^s \approx \frac{g}{R} [Z_c - Z_o] \quad (4)$$

where Z_c is the sea level at the coast (point A in Figure 2), Z_o is the sea level at point B in Figure 2, at a distance R which is the offshore boundary of the coastal current. The variations in Z_α would be small in comparison to those in Z_c because point B is located in a regime which is quiescent in comparison to that A. Under these conditions variations in Z_α , Z_c , and v_1^s will match.

Our main concern in the present study is to see how well Equation (4) holds at the eight locations shown in Figure 1. One of the factors, other than tides and atmospheric pressure, which may introduce noise in the above relationship is the contribution to sea level from the accumulation of runoff due to rainfall in the vicinity of a tide gauge. This may be of special concern during the southwest monsoon season for gauges located at or near the mouth of a river. In the next section we assemble data to address these considerations.

DATA

The Permanent Service of Mean Sea Level (PSMSL) stores monthly and annual mean heights of sea level after collecting them from different national organizations (PSMSL, 1978). The monthly data used here have been supplied to the PSMSL by the Survey of India, Dehra Dun, India. These monthly mean values have been computed by averaging hourly values of a tidal record for a month (Table 1). We computed the normal monthly value for a month, say January, at a location by averaging the monthly values at that location for all Januaries of the data record. By averaging these normal monthly values we computed the annual mean at that location. The dashed curve in the top panel of Figures 3 to 10 gives the normal monthly values with the annual mean subtracted. The record of monthly mean sea level values shows considerable interannual variability, the extent of which can be seen from the standard deviations shown in Table 1. It should be noted that though the interannual variability may be a source of noise for the normal annual pattern considered here, this variability contains useful information on how the oceanic conditions vary from year to year.

To compute the contribution of the atmospheric pressure variations to the changes in sea level we need the global and local monthly-mean atmospheric surface pressure. The data on surface pressure for Bombay, Marmagao, Vishakhapatnam and Calcutta have been taken from RAO (1981). The data for Veraval and Cochin have been taken from WEST COAST OF INDIA PILOT (1975), and those for Nagappattinam are taken from BAY OF BENGAL PILOT (1978). The global monthly mean surface atmospheric pressure has been given by PMRS, who have also defined a procedure for correcting the sea level for atmospheric pressure changes. The same procedure has been followed here. The corrected sea level is given by the solid curve in the top panel of Figures 3 to 10.

KNMI Atlas (1952) gives the monthly-mean ship drift estimates in the Indian Ocean on a $2^\circ \times 2^\circ$ grid. We have used these data to estimate the longshore component of the surface current (v_1^s). It is noted that though the use of ship-drift estimates as an indicator of surface currents has its own problems, no other source for estimating normal monthly surface currents along the coast of India is presently available. The longshore component has been determined by resolving the monthly-mean drift along a straight line tangential to the coast. The tangents and the 2° -squares for which the ship-drift data have been used are shown in Figure 1. The computed longshore components are shown in Figures 3 to 10. The following convention has been followed to determine the sign of these components. Along the west coast of India a component is taken as positive if the flow is northward. Along the east coast a component is taken as positive if the flow is southward. This choice was made to ensure that the sign of the sea level change and that of change in v_1^s would be the same if geostrophic balance as given in Equation (4) holds.

RESULTS AND DISCUSSION

The amplitude of the annual variation of the monthly-mean sea level at Veraval, Bombay, Marmagao and Cochin is around 20 cm. It is over 30 cm at Nagappattinam, Madras and Vishakhapatnam, and well over a meter at Calcutta. The magnitude of the correction due to atmospheric pressure is the highest, almost 10 cm, at Calcutta. It decreases towards the south. At Vishakhapatnam, Madras, Veraval and Bombay the maximum correction is around 7 cm. At Cochin it is less than 2 cm.

The circulation off the coast Nagappattinam, Madras and Vishakhapatnam is more energetic than that at the other locations. The longshore component off this coast is towards the north between February and August, the maximum magnitude of the component being around 40 cm s^{-1} . During September-January the longshore component is towards the south, its maximum magnitude being approximately 40 cm s^{-1} in November. At Cochin, Marmagao and Veraval the current is southward from March to October with a peak value of about 30 cm s^{-1} around July-August. During November-February the current is weak, less than 10 cm s^{-1} , and set towards the north. The monthly-mean circulation off Bombay remains weak with velocities less than 10 cm s^{-1} throughout the year, except during the month of July when a northward flow with magnitude of around 30 cm s^{-1} is noticed. The annual cycle of the longshore component off Calcutta, though similar to that at Vishakhapatnam, has an amplitude half of that at the latter.

Figure 3 to 10 reveal that at Veraval, Marmagao, Cochin, Nagappattinam, Madras and Vishakhapatnam the longshore current closely follows the pressure corrected sea level. Notice especially that the reversals in the currents are reflected in the sea level changes. The data that we have used here, particularly for currents, are not suitable for carrying out statistical significant tests. However, it is worthwhile to point out that the correlation coefficients between the atmospheric pressure-corrected sea level and the longshore current at Veraval, Marmagao, Cochin, Nagappattinam, Madras and Vishakhapatnam are 0.8, 0.7, 0.9, 0.9, 0.9 and 0.9 respectively. A scatter diagram of the pressure corrected sea level against the longshore current at the above six locations is given in Figure 11; the correlation coefficient for the 72 points plotted in the figure is 0.84. This value is high enough to conclude that the variation in the monthly-mean sea level at these locations is a good indicator of the longshore component of the coastal current. A least square linear fit through these points has a slope ($\Delta Z_s / \Delta v_1^s$) of 0.4 sec. We see that this figure is consistent with Equation (2) with g , f and R equal to 10^3 cm s^{-2} , $0.5 \times 10^{-4} \text{ s}^{-1}$, and 100 km respectively. This implies that a good physical basis exists to expect the high value of correlation seen above.

The sea level at Calcutta and Bombay does not fit in the above scheme. The Calcutta tide gauge is located on the River Hoogly about 60 km upstream from its mouth. It is likely that the dominant signal recorded by the gauge arises from the water level in the river. The coastal circulation off Bombay is weak. No clear signal arising from it is noticeable in the sea level data. Better quality data, particularly on the current distribution, are needed to examine the relationship between circulation and sea level.

The sea level at Veraval, Marmagao and Cochin decreases as the rainfall increases during the southwest monsoon (Figs. 3-6). This indicates that the contribution to the sea level change due to accumulation of rain runoff at these sites is small in comparison to that from large scale coastal

circulation. At Nagappattinam, Madras and Vishakhapatnam the variation in sea level follows a pattern similar to that of the rainfall variation, suggesting that the observed monthly-mean sea level variation during these months is, at least partially, a consequence of rain runoff. Though such a possibility cannot be unequivocally ruled out with the present data, a more interesting scenario, consistent with the conclusion that the monthly-mean sea level is predominantly related to the longshore current, does exist. Two of the forcing functions for the current of the east coast are the local wind stress and the curl of the wind stress over the Bay of Bengal. The longshore component of the wind stress is poleward from March to October, with a peak value of around 0.5 dyne cm^{-2} in June-July; from November to February the component is equatorward with a peak of 0.2 dyne cm^{-2} (SHETYE et al., 1985). The Sverdrup transport computed by using the field of curl of wind stress over the Bay of Bengal suggests a poleward coastal flow in January, and an equatorward flow in July. In addition to the above two, another forcing function may be operative. GOPALA KRISHNA and SASTRY (1985) have shown that during the southwest monsoon season a longshore density gradient arises along the east coast of India. The main cause of this gradient is the dilution produced by the runoff from the rivers which are fed by the rains over the Indian subcontinent. Coastal currents driven by longshore density gradient are believed to exist along the west coast of Australia (McCREARY et al., 1986) and along the west coast of India (SHETYE, 1984). The observed close relationship between the sea level and the coastal flow at Nagappattinam, Madras and Vishakhapatnam encourages us to suggest that the similarities between the rise in sea level and the increase in runoff during June-November are not due to accumulation of runoff. If the rainfall along the east coast has any contribution, it is probably because the runoff helps to set up a longshore density gradient which then enhances a southward flow, which in turn affects the sea level.

In summary, with regard to the factors that control the monthly-mean sea level at the eight locations studied here, we note the following:

(1) In general, the effect of atmospheric pressure variations on the monthly-mean sea level along the coast is significant. The amplitude of the effect, which varies between 4-20 cm, is dependent on location and decrease towards the south.

(2) At Calcutta the gauge data show no influence of the large scale coastal circulation. It appears that the gauge here is predominantly under the influence of the level of the River Hoogly. The monthly-mean coastal circulation off Bombay is weak. No significant correlation between the longshore component of the current and the monthly-mean sea level is noticed.

(3) The sea level corrected for atmospheric pressure effects at Veraval, Marmagao, Cochin, Nagappattinam, Madras and Vishakhapatnam shows a good correlation with the longshore component of the coastal current. The sea level records at these stations would be a good tool for the long term monitoring of the surface geostrophic currents along the coast.

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Table 1.

(1)	(2)	(3)	(4)
Veraval	1959-64	17	25
Bombay	1957-63	3	23
Marmagao	1969-78	8	14
Cochin	1958-78	13	11
Nagappattinam	1971-77	15	21
Madras	1957-77	28	15
Vishakhapatnam	1957-78	28	17
Calcutta	1957-63	0	46

(1): Location

(2): Years covered in the data

(3): Number of months missing in the record

(4): Mean standard deviation (mm) of the normal monthly-mean value (standard deviation of the

$$\text{normal} = \sqrt{\frac{n \sum x_i^2 - (\sum x_i)^2}{n^2 (n - 1)}} \text{ where } x_i \text{'s are monthly-mean values for a given month,}$$

and **n** is the number of values used to compute the normal).

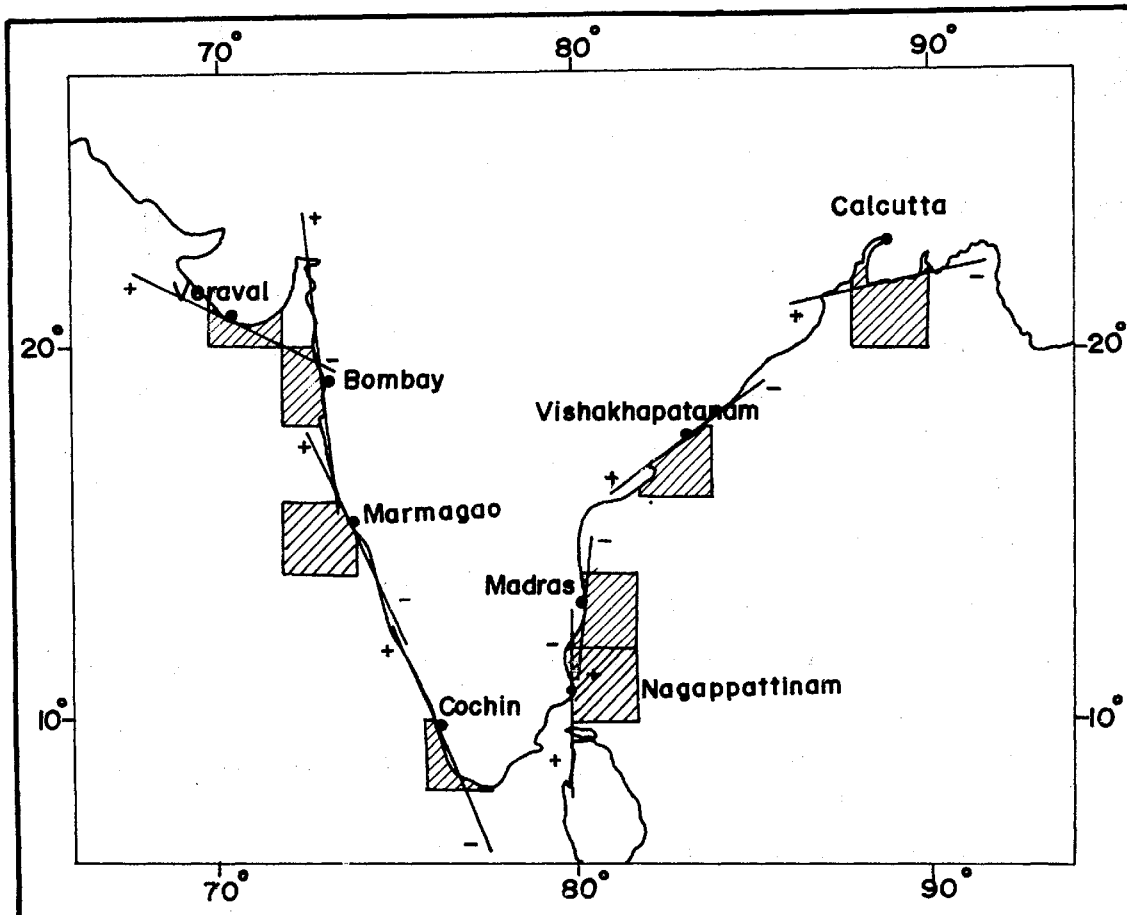


Figure 1. Area of interest, showing the locations of the eight stations where monthly mean sea levels have been documented. The hatched two-degree squares show the areas from where ship-drift values have been used to estimate coastal currents. The tangent to the coast used to compute the longshore component is shown at each location. The convention used to define the sign of the component is also shown.

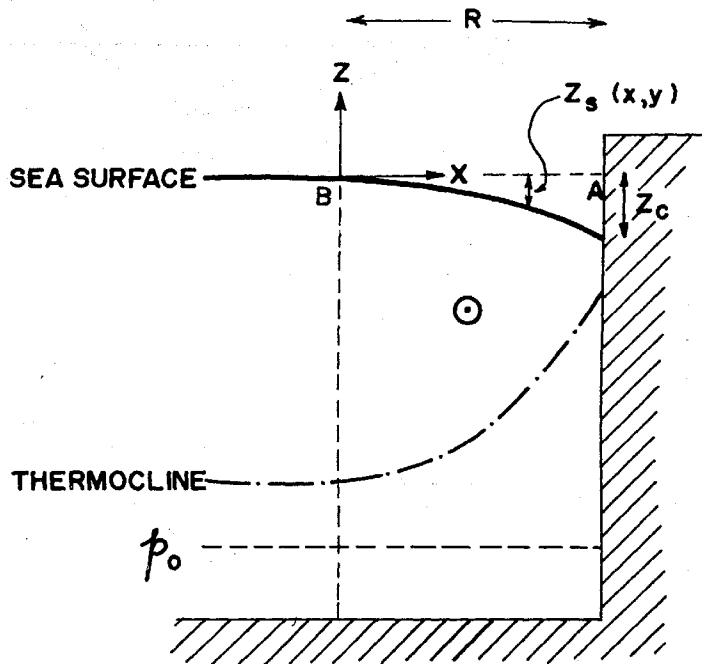


Figure 2. An idealized coastal current. The coastline stretches along the north-south direction. The current is southward, and the motion extends up to a distance R from the coast. $Z_s(x,y)$ is the sea surface. X , Y and Z are the eastward, northward and upward axes respectively. The sea surface tilts down by Z_c at the coast. The thermocline tilts upward towards the coast. P_0 is the pressure at the level of no motion.

STATION : VERAVAL

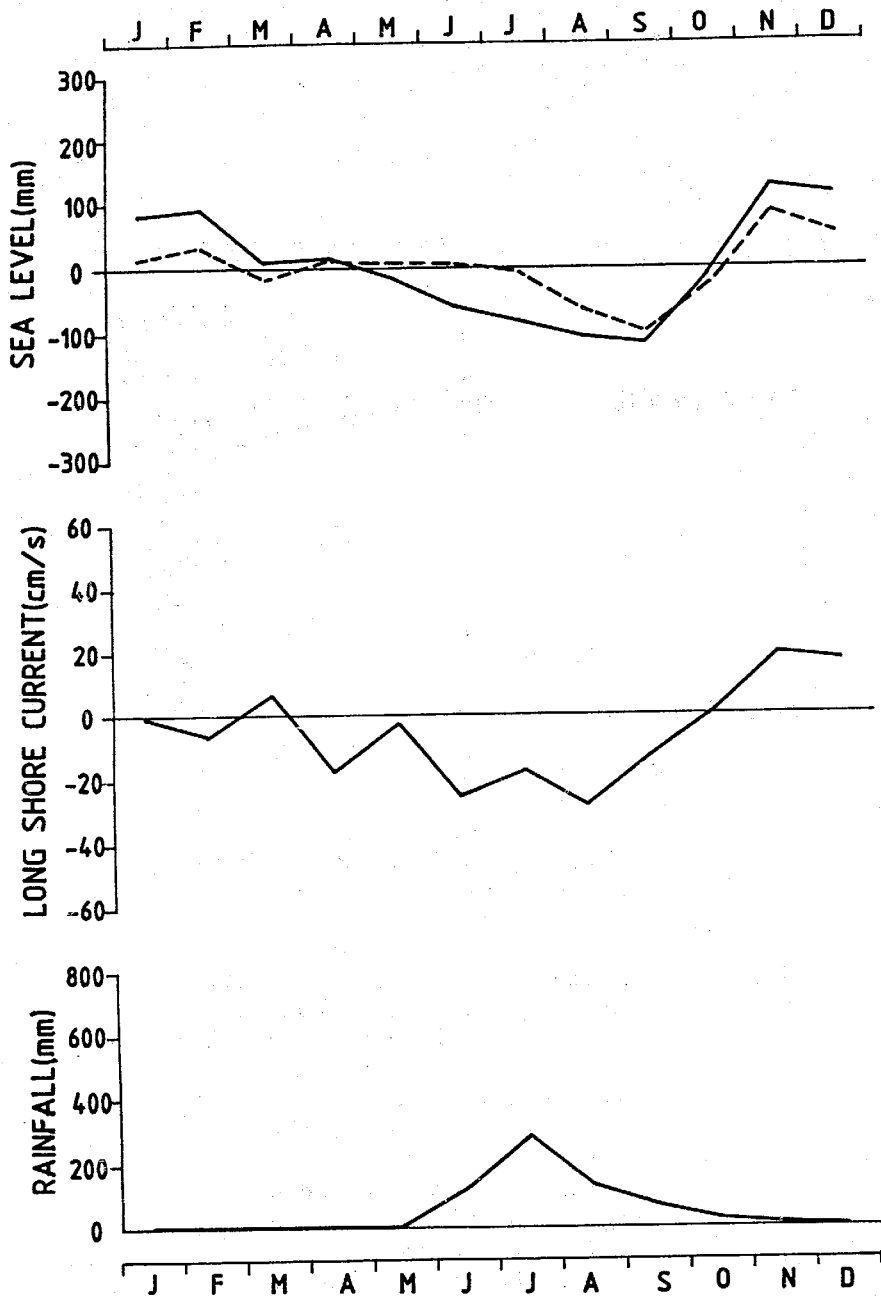


Figure 3. Normal monthly data for VERAVAL. The dashed line in the top panel gives the recorded monthly-mean sea level (mm). The sea level corrected for variations in atmospheric pressure is shown by the solid line in the same panel. The second panel shows the longshore component of the coastal current (cm sec^{-1}) based on the ship-drift values. The third panel gives the monthly mean rainfall in mm. The horizontal axis defines the month. Sources of data are given in the text.

STATION : BOMBAY

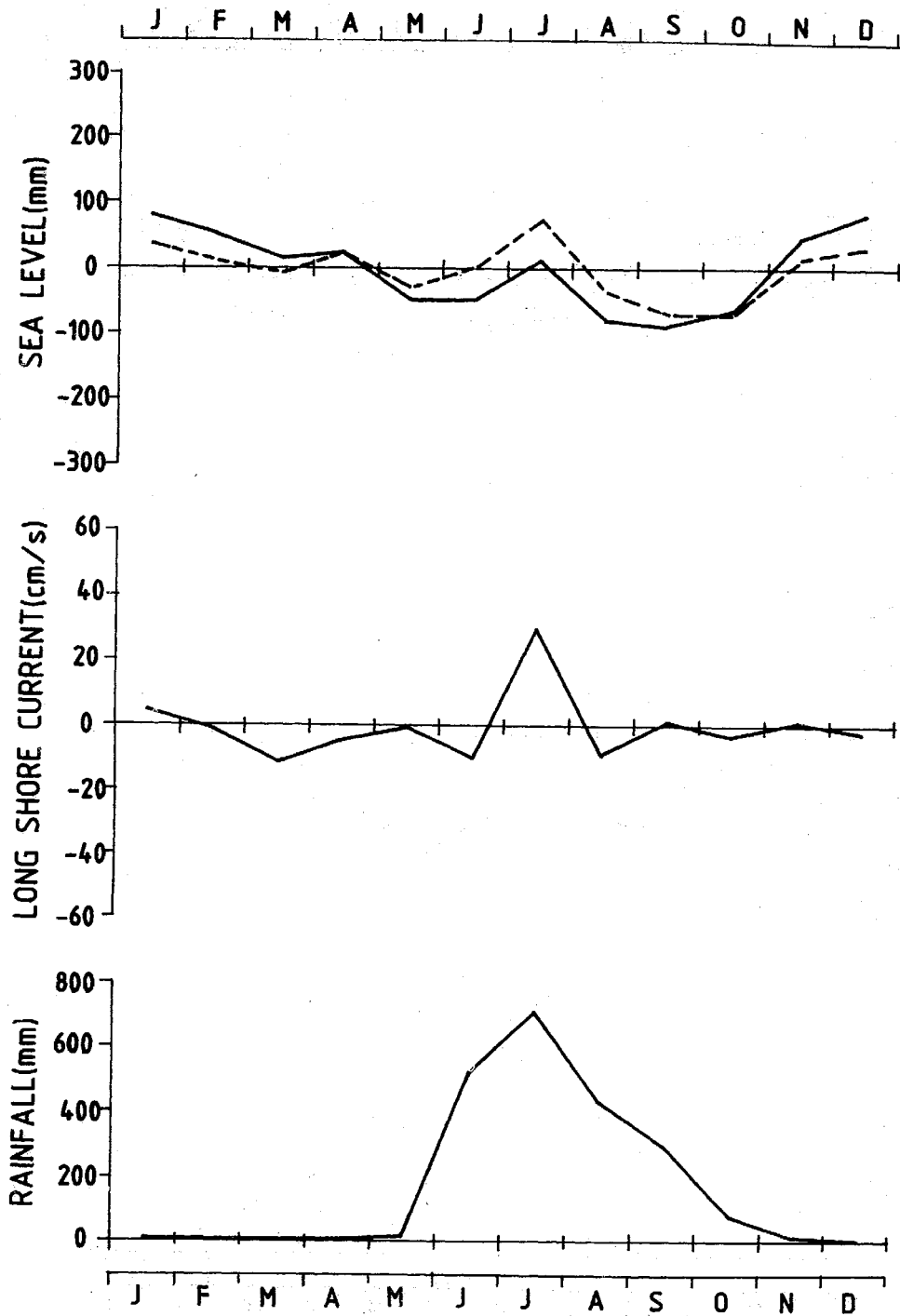


Figure 4. Same as in 3, but for Bombay (Apollo Bandar).

STATION : MARMAGAO

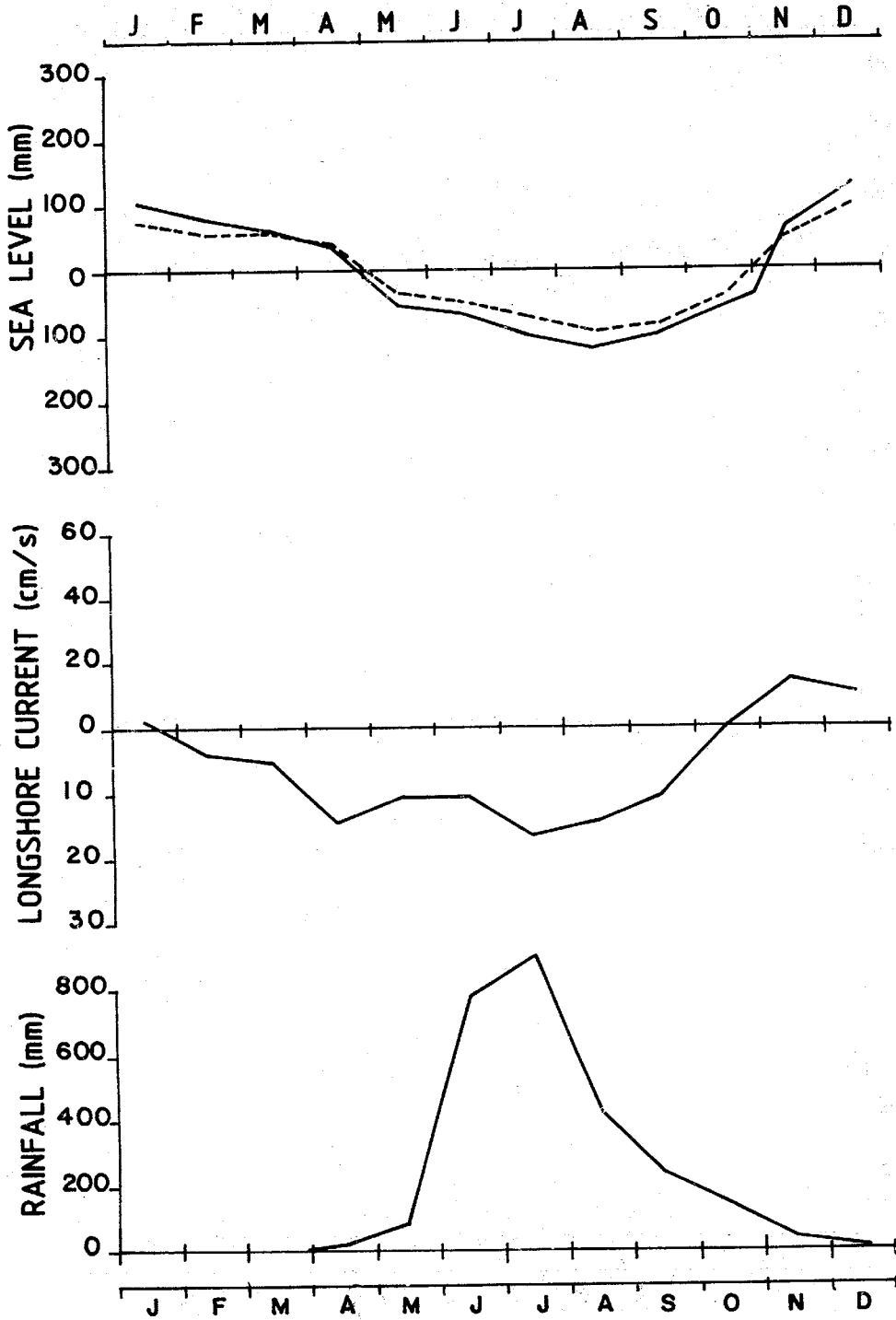


Figure 5. Same as in 3, but for Marmagao.

STATION : COCHIN

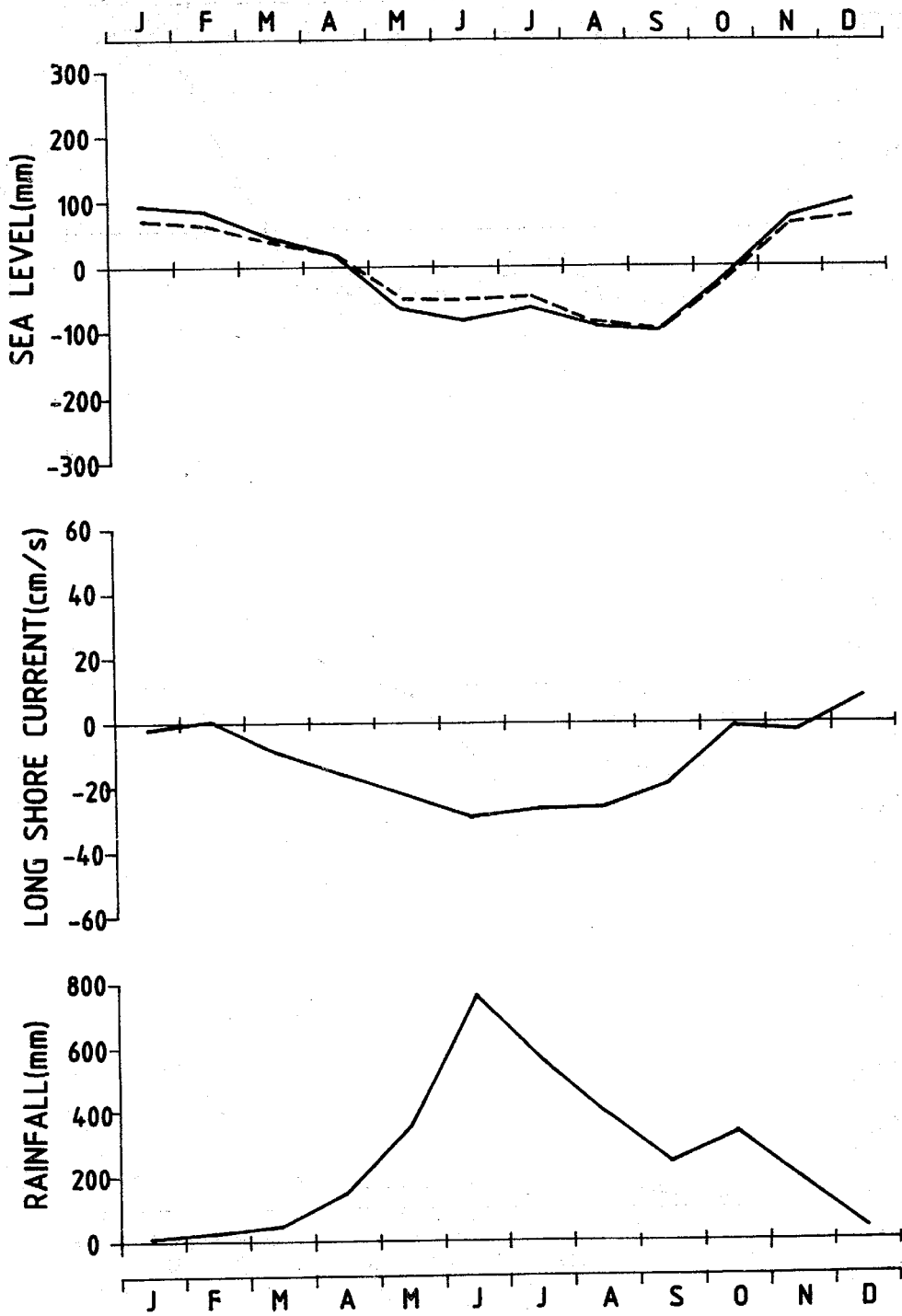


Figure 6. Same as in 3, but for Cochin.

STATION : NAGAPATTINAM

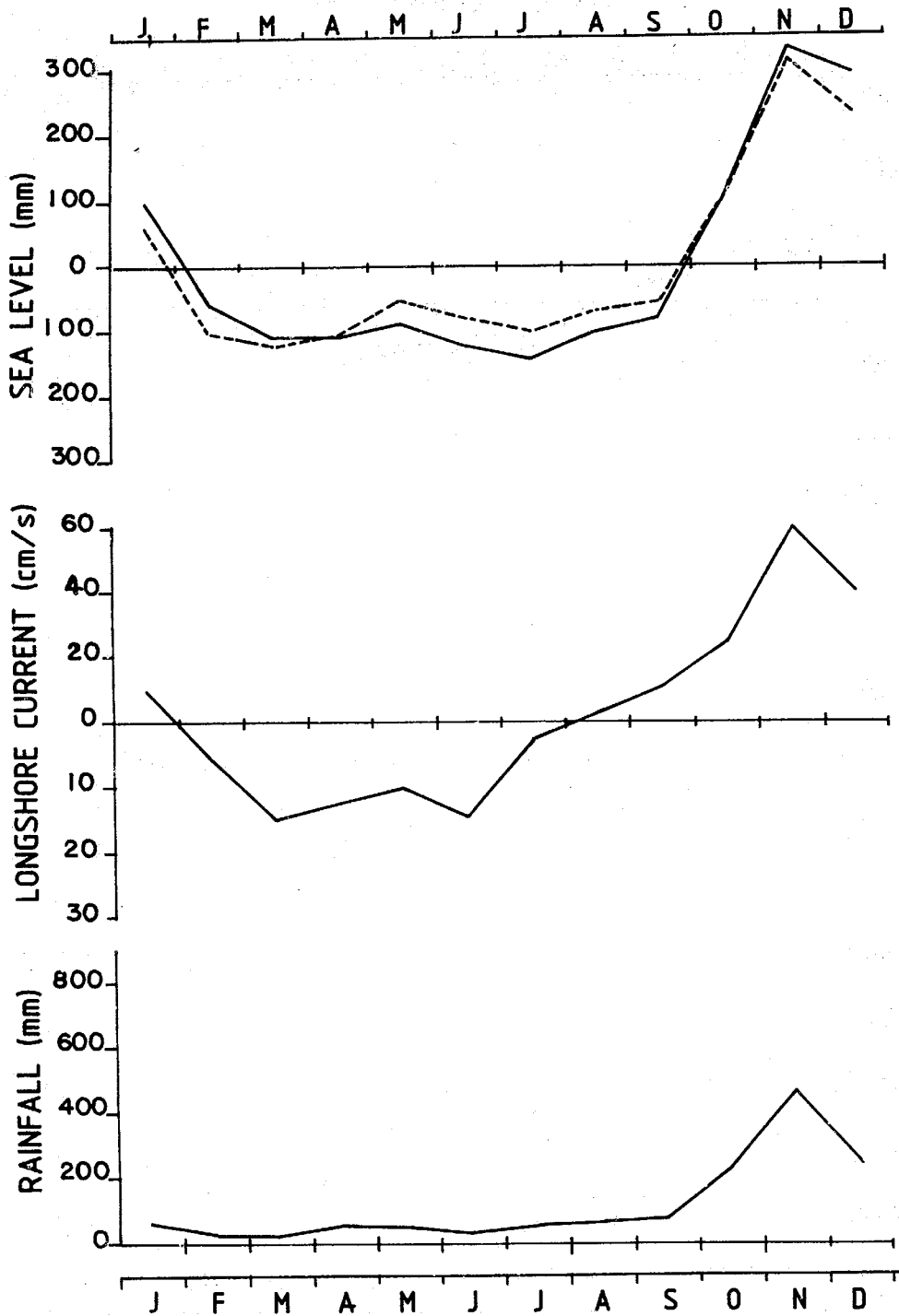


Figure 7. Same as in 3, but for Nagappattinam.

STATION : MADRAS

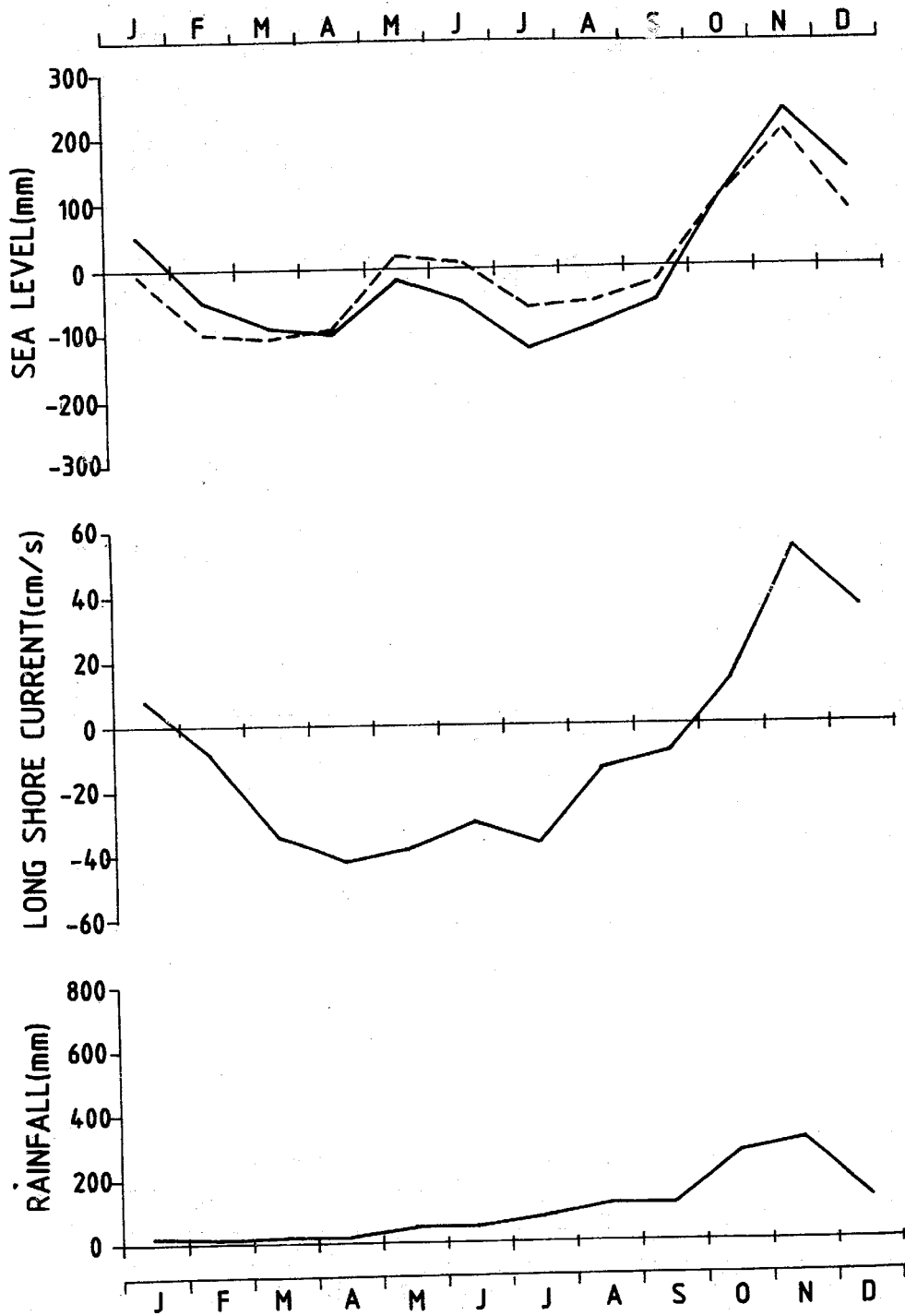


Figure 8. Same as in 3, but for Madras.

STATION : VISHAKHAPATANAM

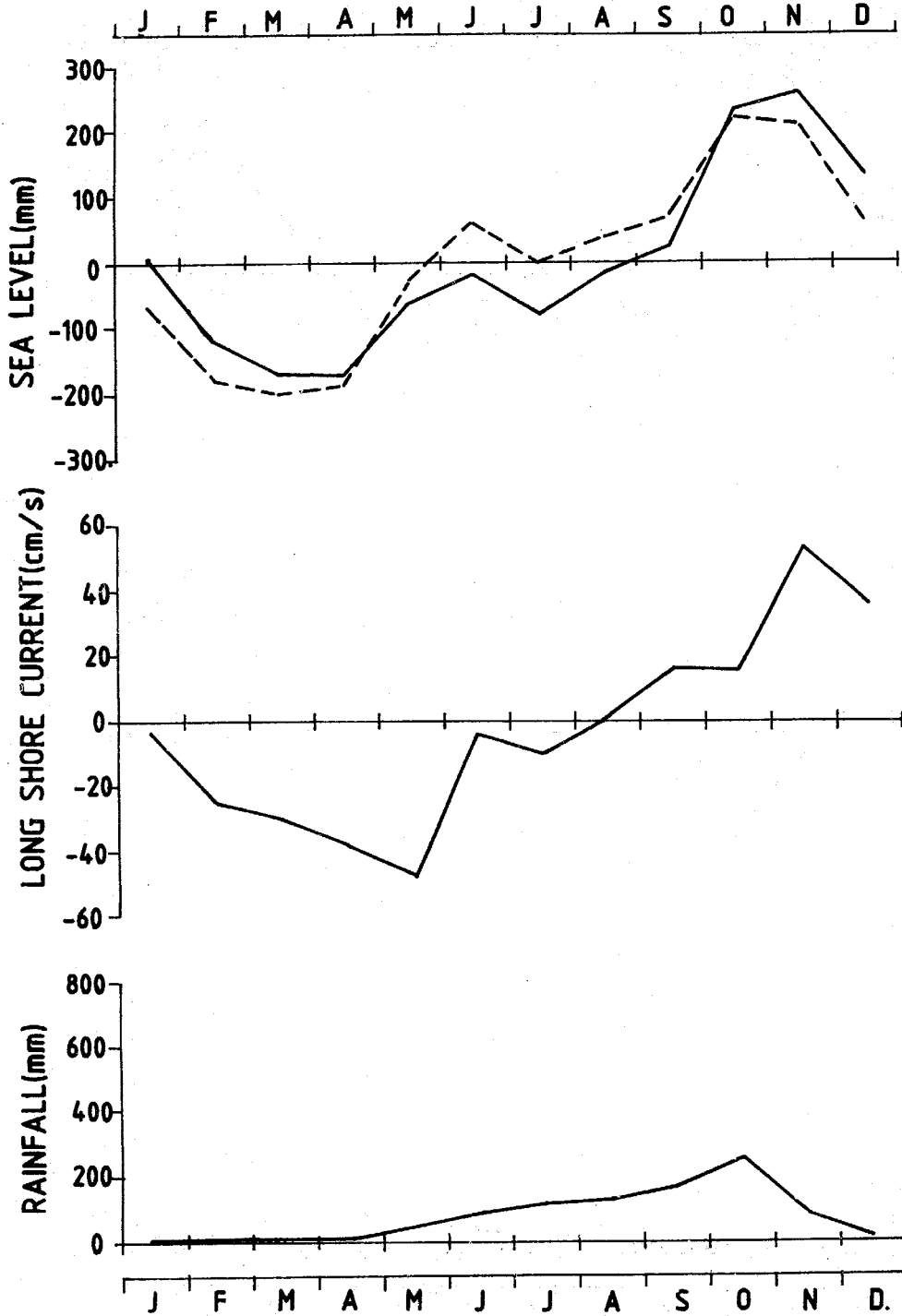


Figure 9. Same as in 3, but for Vishakhapatnam.

STATION : CALCUTTA

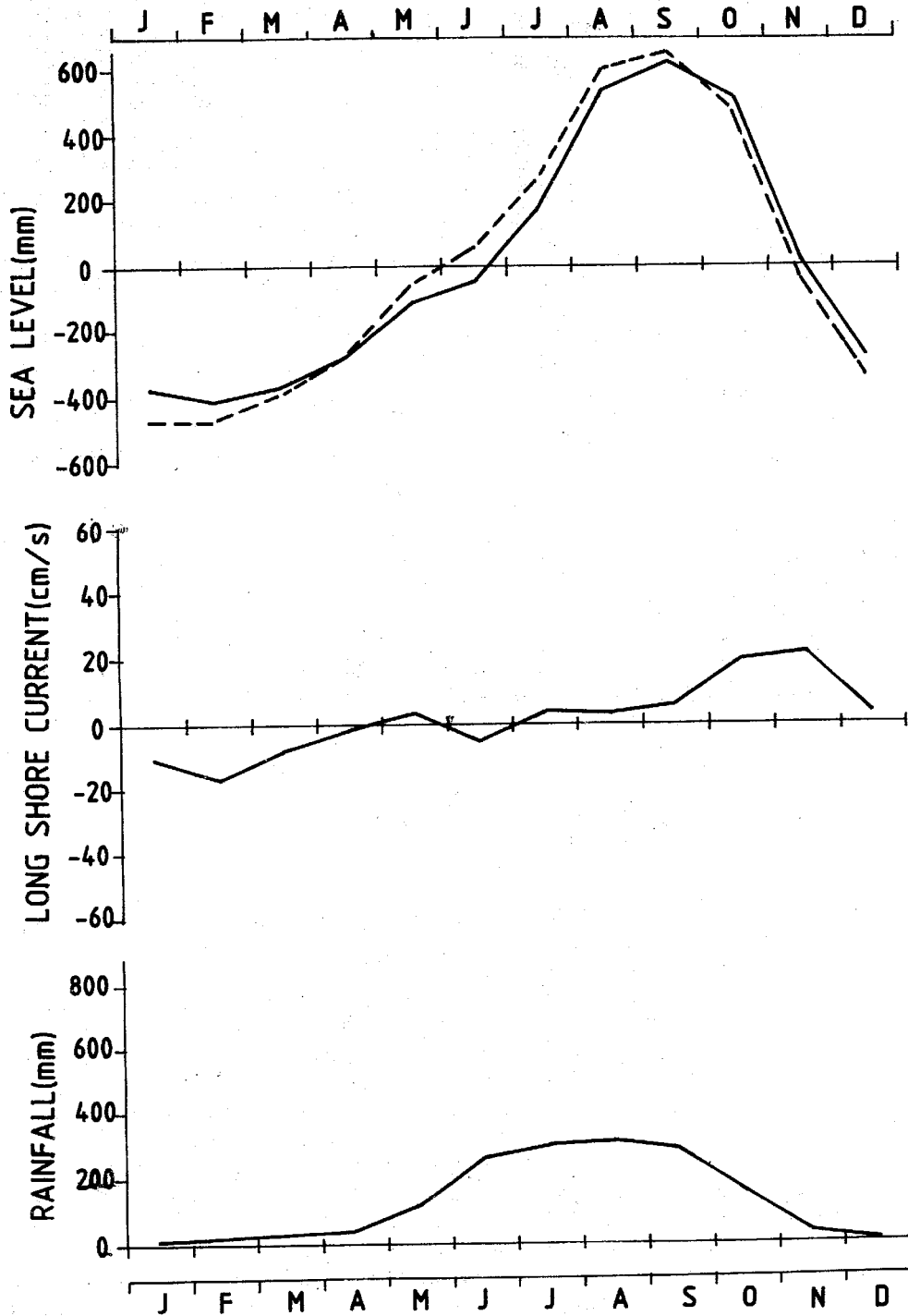


Figure 10. Same as in 3, but for Calcutta.

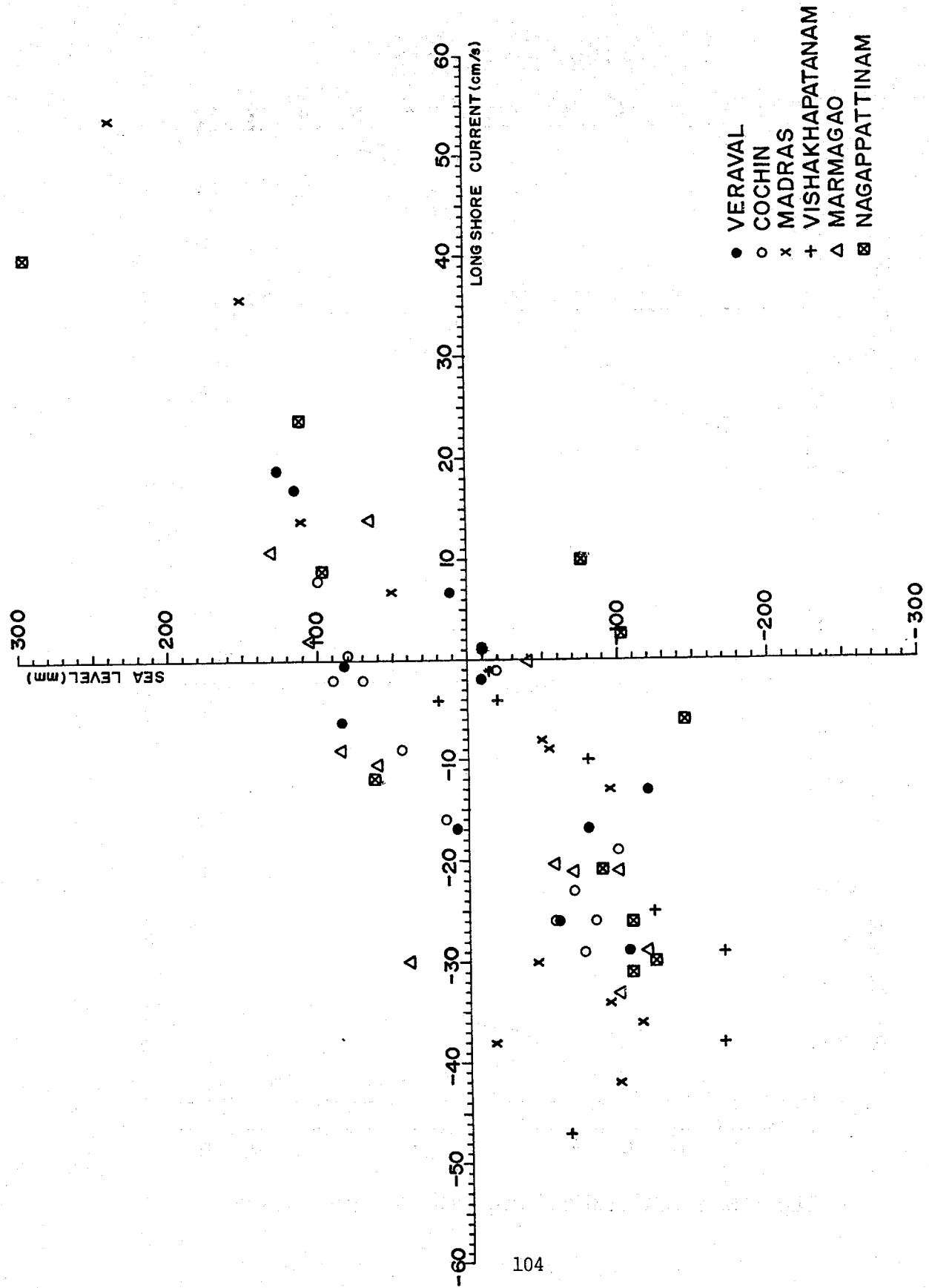


Figure 11. Scatter diagram of sea level against longshore current at Veraval, Marmagao, Cochin, Nagappattinam, Madras and Vishakhapatnam.