

## Tidal and non-tidal sea level variations at two adjacent ports on the southwest coast of India

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Analysis of sea level data collected at two adjacent ports (Cochin and Beypore) on the southwest coast of India has been made to understand tidal and non-tidal variations. Amplitudes of the tidal harmonic constituents showed that  $M_2$  is maximum, followed by  $K_1$ , for both the stations. A large spring-neap variation and monthly variation in the semi-diurnal forcing was seen at both the sites. The Form Numbers indicated that the tides are of a mixed and predominantly semi-diurnal type. Amplitudes of most of the tidal constituents are slightly larger at Beypore than at Cochin. The sea level variation is dominated by tidal signals at both the stations. Seasonal variation of the amplitudes of the most important harmonic constituents namely  $O_1$ ,  $K_1$ ,  $M_2$  and  $S_2$  are presented. The mean spring and neap tidal ranges exhibited a higher degree of variability (over the seasonal cycle) at Beypore than at Cochin. The annual cycles of non-tidal sea level at both the sites were similar, with most conspicuous changes during June and July at Beypore, caused by summer monsoonal river discharge. The annual cycles of atmospheric pressure at both the sites were remarkably similar. The atmospheric pressure is not an important controlling factor on sea level at both the sites. Analysis of the sea level series pertaining to the premonsoon season indicated that Cochin marginally leads Beypore, suggesting the propagation of coastal trapped waves from south to north. The cross-correlograms of the atmospheric pressure time series for the premonsoon and summer monsoon seasons between Cochin and Beypore suggest the mesoscale nature of the atmospheric pressure system.

[ **Key words:** Sea level, tidal and non-tidal variations, coastal trapped waves, Cochin, Beypore ]

In view of the need for carrying out site specific research, to understand the variability in sea levels of adjacent coastal systems for a range of purposes, a study pertaining to this aspect is attempted in this paper. For example, though worldwide, numerous studies are reported on coastal trapped waves, based mainly on sea level data<sup>1-5</sup>, this aspect has not been studied for the Indian coast. The investigation presents the analysis of simultaneous hourly sea level recorded at Cochin (9° 58'N; 76° 16'E) and Beypore (11° 10'N; 75° 48'E), the two adjacent estuarine ports located along the southwest coast of India (Fig. 1), to understand the tidal and non-tidal variability of sea level at these locations. The alongshore distance between the stations is about 200 km.

### Materials and Methods

Hourly sea level data obtained from the tide gauge at Cochin and the tide pole at Beypore from 0000 hr of 1 January to 2300 hr of 31 December, 1997 were used for the present analysis. Harmonic analysis of observed sea level provides the basis for the prediction of tides<sup>6,7</sup>. Tide filtering is necessary to study non-tidal signals, and harmonic analysis provides a

basis for computing the residuals. This is important as the tidal signal is strong in most of the coastal regions.

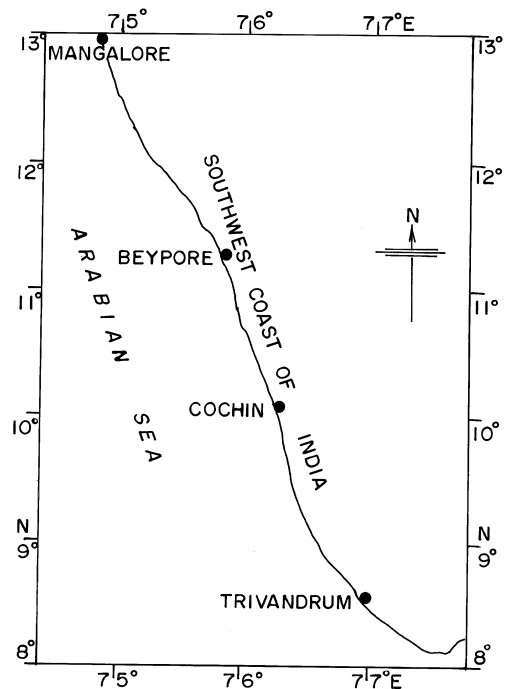


Fig. 1 — Location map

A new time series comprising of only tides (using the amplitudes and phases derived from harmonic analysis) can be constructed, and the original sea level time series can be de-tided by subtraction. The resultant time series can be used for studying the non-tidal sea level variations, which may have oceanographical, meteorological or hydrological signatures. It would thus be possible to study these forcings on sea level.

In the present study, 67 tidal constituents were resolved using the least squares method on hourly sea level data of 365 days. The periods for which the amplitudes were determined varied between 0.1294 days to 365.2728 days. For studying the seasonal march of the tidal constituents, the hourly sea level data for each month (28, 30 or 31 days) were subjected to the analysis and 29 harmonic constituents (0.1294 to 14.7653 days) were determined<sup>6</sup>.

#### Types of tides

The harmonic tidal constituents which enable us to recognise the characteristic features of tides at a particular location are  $M_2$ ,  $S_2$ ,  $N_2$ ,  $K_2$  and  $K_1$ ,  $O_1$ ,  $P_1$ .

The following are the four types of tides, which are of importance in the present context.

1. *Diurnal tide*—Only one high water occurs daily. At neap tide, when the moon has crossed the equatorial plane, two high waters may occur. The mean range of the spring tide is  $2(K_1 + O_1)$ .
2. *Mixed, predominantly diurnal tide*—At times only one high water occurs per day, after the extremes of the moon's declination. When the moon has passed over the equator, the two high waters per day show large inequalities in range and time. The mean range of the spring tide is  $2(K_1 + O_1)$ .
3. *Mixed, predominantly semi-diurnal tide*—Two high and two low waters occur daily with large inequalities in range and time. The maxima in inequalities occur whenever the moon's declination has passed its maximum values. The mean range of the spring tide is  $2(M_2 + S_2)$ .
4. *Semi-diurnal tide*—Two high and two low waters of nearly same height occur daily. The time of high water follows at approximately equal interval after transit of moon at that location. The mean range at spring tide is given by  $2(M_2 + S_2)$ .

The relative importance of the diurnal and the semi-diurnal tidal constituents is expressed in terms of Form Number (F):

$$F = (HK_1 + HO_1)/(HM_2 + HS_2)$$

where  $HK_1$ ,  $HO_1$ ,  $HM_2$  and  $HS_2$  are the amplitudes of the  $K_1$ ,  $O_1$ ,  $M_2$  and  $S_2$  tides, respectively. With the aid of this Form Number, F, which describes the form of a tidal curve during one day, the tides may be broadly classified as follows:

- F = 0.00 - 0.25 : semi-diurnal tide
- F = 0.25 - 1.50 : mixed, mainly semi-diurnal tide
- F = 1.50 - 3.00 : mixed, mainly diurnal tide
- F > 3.00 : diurnal tide

The computations for understanding the spring-neap variation and monthly variation in the semi-diurnal forcing were performed following Beardsley *et al*<sup>8</sup>.

The standard techniques of time series analysis have been used to find evidence of waves-tidal as well as sub-tidal<sup>6,7</sup>. Daily means of sea levels were obtained using a two-step filtering procedure. Firstly, the dominant diurnal and semi-diurnal tidal components were removed from the hourly values. Secondly, a 119—point convolution filter centered on noon was applied to remove the remaining high frequency energy and to prevent aliasing when the data are computed to daily values<sup>9</sup>. The atmospheric pressure data (mean of 0830 and 1730 hrs) close to these sites were noted down from the Indian Daily Weather Reports (India Meteorological Department, Pune, India). The corrected sea level (corrected for local atmospheric pressure) was obtained by adding the daily mean atmospheric pressure (1 mb = 1 cm) to the daily mean sea level<sup>10</sup>. This procedure partially corrects for the inverse barometer effect, so that the remaining pressure fluctuations are primarily due to oceanic phenomena.

The presence of a travelling wave can be readily revealed by cross-correlation between the corrected sea level at both the stations, specifically by the maximum correlation occurring at some lagged time. The study envisaged the use of lag correlation (auto- and cross-correlation) for the different parameters *viz.* observed sea level, atmospheric pressure and corrected sea level at the two sites. The data were partitioned into two contrasting seasons (each of 120 days duration) namely premonsoon (February-May) and summer or southwest monsoon (June-September). The data were detrended by subtracting the straight line best-fit from the data segment to avoid “red noise” and were sine tapered<sup>11,12</sup>. The results of the auto- and cross-correlation analysis of the observed sea level, atmospheric pressure and corrected sea level time series for the two seasons are presented in this study.

**Results and Discussion**

The hourly sea levels at the two locations are presented in Fig. 2, along with the important lunar phases. The lunar phenomena having a superior effect on the tides are the perigee, new moon, full moon, maximum north and south declination.

**Annual analysis**

*Tidal constituents*

From the time series of hourly sea levels (Fig. 2), it is visually obvious that the tidal range is larger at Beypore than at Cochin. The amplitudes of the tidal constituents determined by harmonic analysis for the two sites are presented in Table 1. The  $M_2$  constituent showed the maximum amplitude, followed by  $K_1$ , for both the stations. Accuracy of the estimates of harmonic tidal constituents is highly dependent on the record length, total number of harmonic constituents sought and variance of the non-tidal signal in the record.

The average spring tidal range is the average difference between high and low waters during spring tides. When the phase of  $M_2$  and  $S_2$  tides are the same, the amplitudes of  $M_2$  and  $S_2$  tides are added, which

results in the range  $2(M_2+S_2)$ . This occurs during spring tide and the process repeats itself 14.77 days later. In the mean time, a moment occurs when the amplitudes of both tides result in  $(M_2-S_2)$ . This occurs during neap tide, giving a neap range of  $2(M_2 -S_2)$ . The amplitude of  $S_2$  thus determines the fortnightly inequality<sup>13</sup>.

At Cochin, the mean spring and neap tidal ranges were 55.1 cm and 25.0 cm, whereas at Beypore it was 76.3 cm and 35.9 cm, respectively. The Form Numbers indicated that the tide is of a mixed and predominantly semi-diurnal nature, having values of 0.92 and 0.80 for Cochin and Beypore, respectively. This result for Cochin, is in good agreement with those published<sup>14</sup>. In such regimes, two high and two low waters occur daily with large inequalities in range and time. The maxima of inequalities occur whenever the moon's declination has passed its maximum value. A large spring-neap variation and monthly variation in the semi-diurnal forcing at Cochin (2.20 and 3.89) and Beypore (2.13 and 3.50) was also seen.

The harmonic analysis also confirmed that most of the constituents are slightly larger at Beypore than those at Cochin (Table 1). The long period constitu-

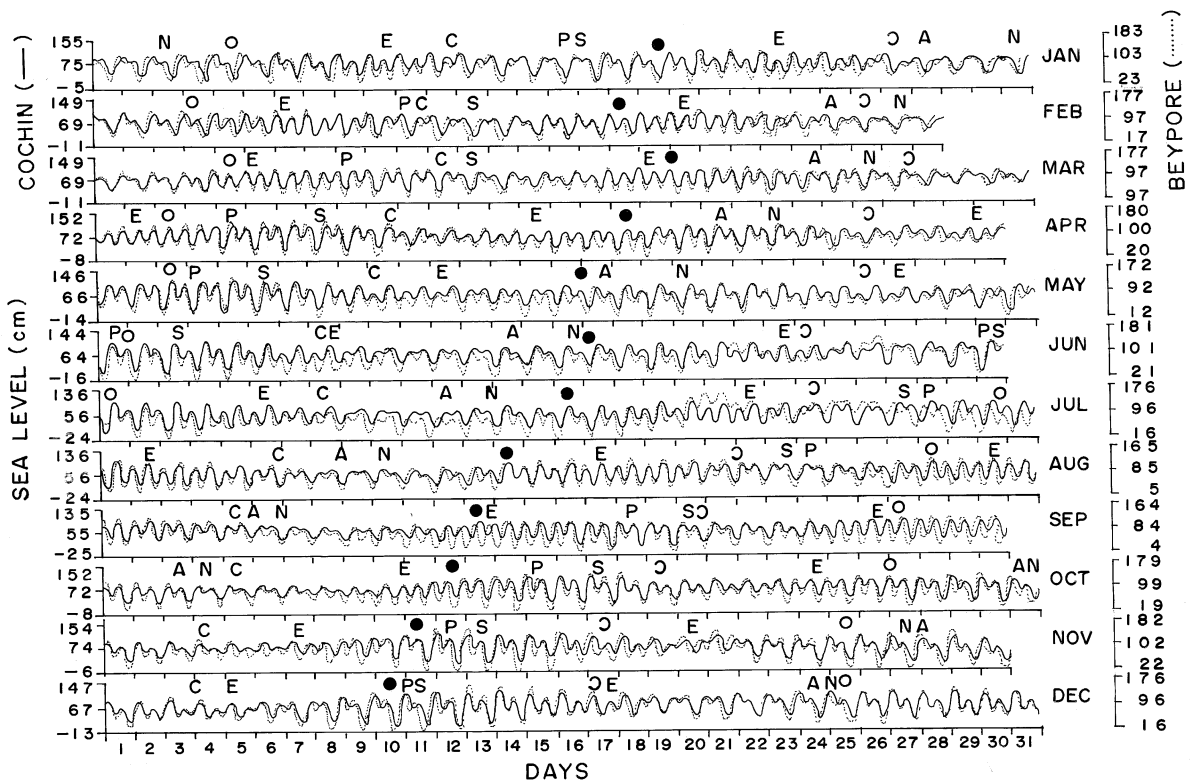


Fig. 2—Hourly sea level at Cochin and Beypore. P = PERIGEE; A = Apogee; ● = NEW MOON; ☾ = First Quarter; ○ = FULL MOON; ☽ (= Last Quarter; E = Moon on Equator; N = MAXIMUM NORTH DECLINATION; S = MAXIMUM SOUTH DECLINATION; Lunar phenomena having a superior effect on the tides are printed in CAPITALS.

ents ( $S_a$ ,  $S_{sa}$ ,  $M_{sf}$ ,  $M_f$ ) are usually small, and depend largely upon regional meteorological conditions during the time when these observations were made<sup>15</sup>. From the amplitudes of  $M_m$ ,  $M_{sf}$  and  $M_f$  for Cochin and Beypore, we find that non-linear contribution of semi-diurnal tides is comparatively higher at Beypore than at Cochin.

In the case of mixed tides, the magnitude of the diurnal tides is similar to that of semi-diurnal tides. In this tidal regime, the relative importance of the semi-diurnal and diurnal components keep changing throughout the month. The diurnal tides have large magnitudes when the moon's declination is greatest

but reduce to low values when the moon is passing through the equatorial plane. Semi-diurnal tides are most important after full and new moon and are only partly reduced during the period of neap tides. Dronkers<sup>14</sup> also brought out the variation of the daily inequality with the moon's declination as well as the variation in range with the phases of the moon, for Cochin. In a mixed tide with very large diurnal inequality, the higher low water (or lower high water) frequently becomes indistinct (or vanishes) at the time of extreme declinations. During these periods, the diurnal tide has such overriding dominance that the semi-diurnal, although still present, cannot be seen on

Table 1—Amplitudes of the 67 harmonic tidal constituents at Cochin and Beypore

Number	Constituent	Period (h)	Amplitude (cm)		Number	Constituent	Period (h)	Amplitude (cm)	
			Cochin	Beypore				Cochin	Beypore
1	$S_a$	8766.5470	7.6042	4.4090	35	$M_2$	12.4206	20.0336	28.0495
2	$S_{sa}$	4382.8890	3.8452	3.5351	36	$H_2$	12.4030	0.2650	1.0379
3	$M_{sm}$	763.4869	1.5674	1.5241	37	$MKS_2$	12.3855	0.0697	1.3246
4	$M_m$	661.3101	1.3690	3.4185	38	$LDA_2$	12.2218	0.3483	0.3461
5	$M_{sf}$	354.3674	0.4220	1.5463	39	$L_2$	12.1916	0.6917	1.1764
6	$M_f$	327.8592	1.2402	2.3442	40	$T_2$	12.0165	0.4524	1.6321
7	$ALP_1$	29.0727	0.0607	0.1184	41	$S_2$	12.0000	7.5078	10.0997
8	$2Q_1$	28.0062	0.3525	0.3718	42	$R_2$	11.9836	0.1532	1.1479
9	$SIG_1$	27.8484	0.2200	0.6601	43	$K_2$	11.9672	1.7574	2.4902
10	$Q_1$	26.8684	2.2245	1.9761	44	$MSN_2$	11.7861	0.0802	0.4675
11	$RHO_1$	26.7231	0.4532	0.4739	45	$ETA_2$	11.7545	0.1354	0.2197
12	$O_1$	25.8193	8.7552	10.0544	46	$MO_3$	8.3863	0.0603	0.9151
13	$TAU_1$	25.6681	0.2778	0.0333	47	$M_3$	8.2804	0.1819	0.4066
14	$BET_1$	24.9748	0.0599	0.6036	48	$SO_3$	8.1924	0.3715	0.5043
15	$NO_1$	24.8332	1.5432	0.2221	49	$MK_3$	8.1771	0.3492	0.7416
16	$CHI_1$	24.7091	0.2389	0.5977	50	$SK_3$	7.9927	0.0429	0.2888
17	$PI_1$	24.1321	0.1822	1.0149	51	$MN_4$	6.2692	0.2286	0.1441
18	$P_1$	24.0659	4.5441	5.3678	52	$M_4$	6.2103	0.6662	0.2314
19	$S_1$	24.0000	0.9546	2.9597	53	$SN_4$	6.1602	0.0406	0.1287
20	$K_1$	23.9345	16.5641	20.3245	54	$MS_4$	6.1033	0.5655	0.1240
21	$PSI_1$	23.8693	0.5366	0.0555	55	$MK_4$	6.0949	0.0897	0.1550
22	$PHI_1$	23.8045	0.5023	0.4845	56	$S_4$	6.0000	0.1344	0.1927
23	$THE_1$	23.2070	0.2051	0.5377	57	$SK_4$	5.9918	0.0544	0.1111
24	$J_1$	23.0985	1.0287	1.0057	58	$2MK_5$	4.9309	0.2754	0.2955
25	$SO_1$	22.4202	0.2046	0.2867	59	$2SK_5$	4.7974	0.0526	0.0123
26	$OO_1$	22.3061	0.4585	0.5342	60	$2MN_6$	4.1663	0.1069	0.2314
27	$UPS_1$	21.5782	0.2493	0.4267	61	$M_6$	4.1402	0.1825	0.2683
28	$OQ_2$	13.1622	0.1273	0.3801	62	$2MS_6$	4.0924	0.4017	0.1974
29	$EPS_2$	13.1273	0.0590	0.2302	63	$2MK_6$	4.0886	0.1207	0.1353
30	$2N_2$	12.9054	0.7144	0.9544	64	$2SM_6$	4.0457	0.1083	0.1484
31	$MU_2$	12.8718	0.2879	0.0800	65	$MSK_6$	4.0419	0.0390	0.0470
32	$N_2$	12.6584	4.3321	5.4741	66	$3MK_7$	3.5296	0.0091	0.0991
33	$NU_2$	12.6260	0.7979	1.5557	67	$M_8$	3.1052	0.1162	0.0862
34	$H_1$	12.4382	0.2517	1.8812					

the tidal curve. This condition is often referred to as the vanishing tide. This is seen during January 3-4, at both the stations (Fig. 2).

In addition to the astronomical forcing, there are few harmonic constituents which are primarily due to periodic meteorological forcing - annual ( $S_a$ ), semi-annual ( $S_{sa}$ ) and the diurnal tide,  $S_1$ . The radiational tides (often referred as meteorological tides) have their origin in daily or seasonal variations in the weather conditions which usually occur with some degree of periodicity. They are called radiational tides due to their association with the cycles of solar radiation and are strongly enhanced by seasonal climatic variations.  $S_a$  and  $S_{sa}$  have much higher amplitudes than  $S_1$ . In the present study, the  $S_a$  constituent contributed the maximum followed by  $S_{sa}$ , and the least by  $S_1$  constituent, for both the stations (Table 1). The amplitudes of  $S_a$  and  $S_{sa}$  tides were found to be higher at Cochin as compared to Beypore.

The amplitudes of the annual and semi-annual equilibrium tides at Cochin are 0.14 cm and 0.91 cm, respectively. These are very small compared to the amplitudes of the annual (7.60 cm) and semi-annual (3.85 cm) components of the sea level (Table 1). At Beypore, the amplitudes of the annual and semi-annual components of sea level were 4.41 and 3.54 cm, whereas the amplitudes of the annual and semi-annual equilibrium tides were 0.13 and 0.89 cm, respectively. It is thus evident that the annual and semi-annual components in the observed sea level are almost entirely due to non-tidal influences, as indicated by the high ratio of observed to equilibrium tidal amplitudes. The annual solar cycle produces a weak astronomical tide, but generates the major climatic cycles such as those exhibited by seasonal atmospheric pressure, wind, rainfall, evaporation and sea surface temperature<sup>15-17</sup>.

Tidal ranges on relatively shallow continental shelves are usually larger than those in the open ocean. The shallow water tidal constituents arise from the distortion of the main constituent tidal oscillations<sup>6,18</sup>. The shallow water constituents included in the present study are derived only from the largest main constituents, namely  $M_2$ ,  $S_2$ ,  $N_2$ ,  $K_2$ ,  $K_1$  and  $O_1$ , using the lowest type of interactions (Table 1). At Beypore, shallow depth, irregular coastal geometry, bottom topography and high river discharge could be responsible for the higher amplitudes of shallow water components.

#### *Meteorological residuals*

The regular and predictable tidal movements of the sea are continuously modified by the effects of the

weather. Exchange of energy between the ocean and atmosphere occurs over a wide range of space and time scales. The relative importance of tidal and non-tidal movements depends on the time of the year and the local bathymetry. The meteorological residual (non-tidal residual, set-up, or non-tidal component) is the difference between observed sea level and predicted tides. The standard deviation of the meteorological residual varies from values of a few centimeters at tropical oceanic islands, to tens of centimeters in areas of extensive shallow water subjected to stormy weather. Even though tidal variations can be removed in the analysis, there could be energy in the tidal frequencies because of small timing errors in the gauge and weak interaction between the tides and the surges.

The meteorological residuals (Fig. 3) are more noisy at Beypore due to nonlinear influence from the shallow depth, interaction with Chaliyar river, irregular coastal geometry and bottom topography on the tides. The periodic fluctuations are caused by the ineffectiveness of the tidal predictions to resolve all the nonlinear harmonics in the tides. These fluctuations are particularly prominent during heavy discharge periods, as is seen for Beypore during June and July. The meteorological residuals for Cochin, however, did not reveal any such conspicuous feature. In this regard, it is worth mentioning that the discharge into the Cochin backwater region is largely controlled by the hydroelectric projects situated upstream of the rivers, causing minimum riverine influence on the sea level. In the case of Beypore, probably because of the absence of such hydroelectric projects upstream of the river Chaliyar, considerable riverine influence on the sea levels near the mouth could be observed, particularly during summer monsoon months. The non-tidal circulation is very much influenced by the highly variable river discharge at Beypore. Tide gauge timing errors can also cause a periodic component to be present in the meteorological residuals. The standard deviations of the hourly observed sea level were 21.7 cm and 28.9 cm for Cochin and Beypore whereas that of the meteorological residuals were 5.5 cm and 9.5 cm, revealing that tides are responsible for about 93.7% and 89.2% of the variance of the observed sea level at the two stations.

#### **Seasonal variation**

When presenting the results of a tidal analysis, it is usual to refer to tidal "constituents" rather than tidal "constants", the reason being that the constituents may

have slight changes if a different period of data is analysed for the same place. Analysis of individual months of the sea level data for the same place invariably show small variations in the tidal constituents about some mean value<sup>6</sup>. Reasons for the variability include inconsistencies in the measuring instruments, analysis limitations due to non-tidal energy at tidal frequencies and real oceanographic modulations of the tidal behaviour. Pugh<sup>6</sup> opined that for monthly analyses, there remains a real oceanographic signal, which is not due to variations in the astronomical forcing functions, as these variations persist no matter how fully the forces are represented.

We are not aware of studies concentrating on the seasonal march of tides at stations along the Indian coastline, but the same has been reported elsewhere<sup>19,20</sup>. Detailed discussion on some of these aspects are presented below.

*Principal tidal constituents*

The seasonal variation in the amplitude of the most important harmonic constituents namely O<sub>1</sub>, K<sub>1</sub>, M<sub>2</sub> and S<sub>2</sub>, are presented in Fig. 4 A-D. O<sub>1</sub> component showed very little variation whereas K<sub>1</sub> showed com-

paratively higher variation. The seasonal cycle of K<sub>1</sub> is more or less the mirror image of that of S<sub>2</sub> with the maxima of K<sub>1</sub> corresponding with the minima of S<sub>2</sub> and *vice-versa*. The contribution of the K<sub>1</sub> component is conspicuously more during June and December and less during March and September whereas it is exactly opposite for S<sub>2</sub>. Further, K<sub>1</sub> and S<sub>2</sub> amplitudes showed a similar seasonal march at both the sites, which was seen to be lacking for O<sub>1</sub> and M<sub>2</sub> constituents. To appreciate these aspects better, statistics of the amplitudes are presented in Table 2. It is evident that the mean and standard deviation, over the seasonal cycle, are higher at Beypore than at Cochin.

Pugh<sup>6</sup> discussed the monthly variability of the tidal constituents, and showed that usually there exists a consistent regional pattern in these variations. The irregular variations are likely to be caused by shallow-water interactions between tides and surges, as a result of more energy being lost from tides and surges travelling together<sup>21</sup>. It is reported that there is a seasonal modulation of the M<sub>2</sub> constituent amplitude which varies between 1% and 2% in the North Sea<sup>22</sup>. A part of such modulations is directly due to astronomical effects such as the influence of the sun on the

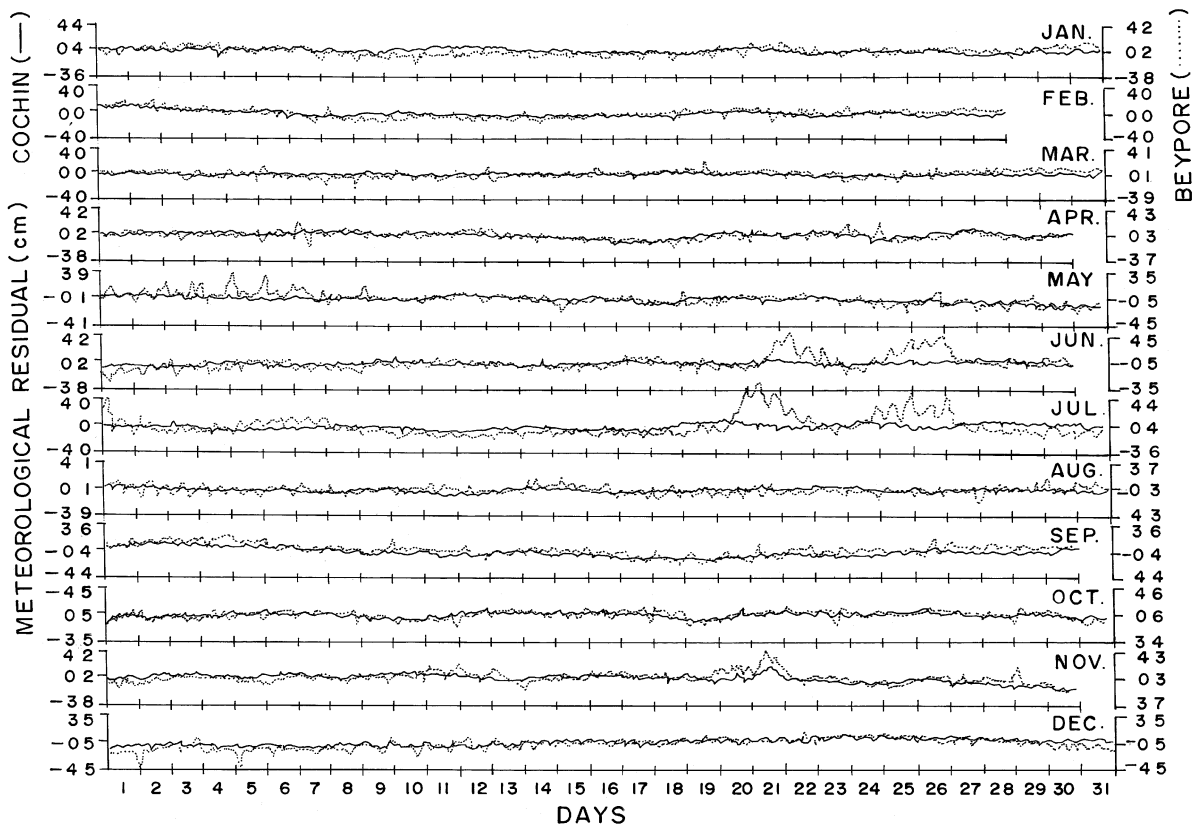


Fig. 3—Hourly meteorological residuals at Cochin and Beypore

lunar orbit, but the rest of the variability could probably be due to tide-surge interaction.

The amplitudes of  $O_1$ ,  $K_1$ ,  $M_2$  and  $S_2$  constituents displayed very little variability as seen for the annual (Table 1) as well as seasonal analysis (Table 2), pointing out remarkable stability of these constituents, at both the locations. The amplitudes based on the annual analysis showed a change, which was less than 5% of its seasonal mean value.

### Spring and neap tidal ranges

The monthly march of the mean spring and mean neap tidal ranges are presented in Fig. 4E,F. The mean spring and neap tidal ranges exhibited a higher degree of variability (over the seasonal cycle) at Beypore as compared to that at Cochin (Table 2). The mean spring tidal range was found to be more than twice the mean neap tidal range at both the sites. However, the tidal regime experienced throughout the year is a micro-tidal one, with the range being less than 1 m, at both the locations.

### Form numbers

The Form Numbers, computed using monthly data on the amplitudes of  $O_1$ ,  $K_1$ ,  $M_2$  and  $S_2$  constituents were generated to get a clear seasonal picture of the diurnal and semi-diurnal forcings (Fig. 4G). The Form Numbers varied from 0.69 to 1.14 at Cochin and 0.55 to 1.07 at Beypore indicating that the tide is of a mixed, predominantly semi-diurnal type, at both the sites, throughout the year. The seasonal means are 0.93 and 0.81 at Cochin and Beypore, respectively (Table 2). These values agree well with that obtained using the annual analysis (0.92 and 0.80). However, relatively higher diurnal contribution during June and December, and higher semi-diurnal contribution during March and September is seen. This is in agreement with observations reported elsewhere<sup>6,23</sup>. The solar declination plays a very important role in this regard. The solar declination varies seasonally from  $23.5^\circ$  N in June to  $23.5^\circ$  S in December. During March and September, the solar declination is zero and hence the total amplitude of the diurnal forcing is the least.

### Tidal signal vs meteorological signal

The seasonal cycle of the tidal signal (variance in percentage, accounted by the tides to that of the observed sea level) for Cochin and Beypore, are presented in Fig. 4H. Excluding the months of June and July at Beypore, both the stations showed a tidal

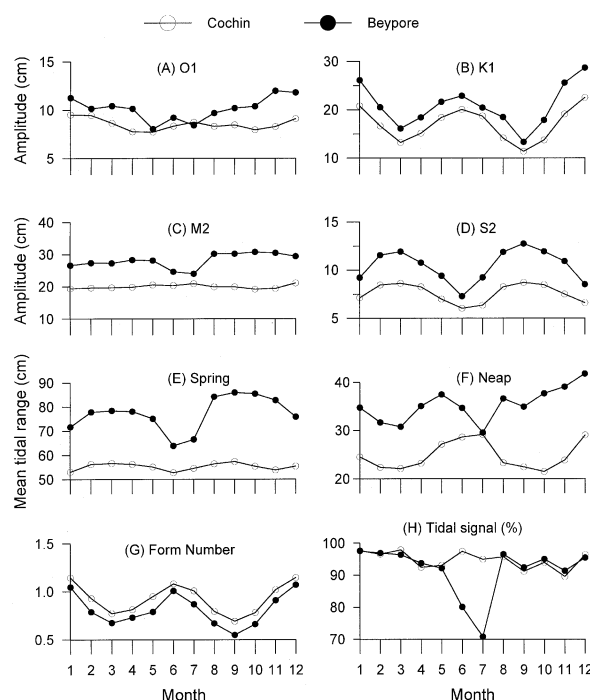


Fig. 4—Seasonal march of (A) amplitude of  $O_1$  (B) amplitude of  $K_1$  (C) amplitude of  $M_2$  (D) amplitude of  $S_2$  (E) mean spring tidal range (F) mean neap tidal range (G) Form Number and (H) tidal signal

Table 2—Tidal statistics based on monthly data

Parameter	Cochin		Beypore	
	Mean	SD	Mean	SD
$O_1$ (cm)	8.53	0.60	10.15	1.21
$K_1$ (cm)	17.00	3.47	20.85	4.44
$M_2$ (cm)	20.00	0.61	28.11	2.25
$S_2$ (cm)	7.62	0.97	10.45	1.68
Mean spring tidal range (cm)	55.25	1.44	77.12	7.11
Mean neap tidal range (cm)	24.77	2.89	35.32	3.52
Form Number	0.93	0.15	0.81	0.17
Tidal signal (%)	94.68	2.72	91.50	8.01

signal component greater than 90%. The tidal signal components at Beypore during June and July were 80% and 70%, respectively, which may be due to overwhelming effect of river discharge on water level, which overrides the tidal signal. Excepting for this period, the seasonal march was similar at both the locations, indicating strong tidal forcing, even though the tidal range is small. The seasonal variability was more at Beypore as compared to that at Cochin, because of the above reasons (Table 2).

### Annual cycles of sea level and atmospheric pressure

The time series of daily sea level and atmospheric pressure are presented in Fig 5A,B. The overall mean

for each time series has been subtracted and the daily data are presented as departures from the annual mean. The annual cycles of sea level at both the sites were more or less similar. The most conspicuous changes were, however, observed during June and July at Beypore, caused by sporadic river discharge. The annual cycles of atmospheric pressure at both sites were remarkably similar. The percentage variance explained by the relationship between the two stations were 44% and 95%, in the case of sea level and atmospheric pressure, respectively. In general, the annual cycles of sea level and atmospheric pressure, at both the sites showed a similar pattern, with low values during summer monsoon (June-September) season, and high values during the premonsoon (February-May) and postmonsoon (October-January) seasons.

#### Barometric factor

From hydrostatic considerations, the sea level is expected to be depressed by 1 cm, for every 1 mb rise in atmospheric pressure<sup>6</sup>. The observed inverse barometric factor (or "isostatic" factor - ratio of sea level change to atmospheric pressure change) is usually close to the theoretical value of  $-1.01$  cm/mb. It is computed by linear regression from uncorrected sea level and atmospheric pressure. During earlier investigations along the Australian coast, it was seen that the sea level did not respond isostatically to atmospheric pressure<sup>24,25</sup>. Hamon<sup>25</sup> in his study, found that changes in sea level followed changes in sea level pressure with up to 2 days lag.

In the present study, the variance of the observed sea level time series during premonsoon period, is less than that for the summer monsoon period at Cochin, whereas the summer monsoon time series shows a variance roughly six times that of the premonsoon period at Beypore (Table 3). In the case of Beypore, the marked increase in the variance, during summer monsoon season is because of the sporadic river discharge during June-July. The premonsoon time series of the atmospheric pressure shows a variance which is marginally less than that of the summer monsoon time series, both at Cochin and Beypore (Table 3). Because of the mesoscale nature of the atmospheric pressure systems, similar signatures are seen at both the locations.

The premonsoon series of the observed sea level at Cochin and Beypore show a marginally smaller variance than that of the corrected sea level series (Table 3). On the other hand, during the summer monsoon sea-

son, the observed sea level series show a marginally higher variance than that of the corrected sea level series. Castro & Lee<sup>5</sup> in their study, reported that the atmospheric pressure adjustment process did not significantly change the variance of the original sea level time series. The march of sea level and atmospheric pressure is similar at both the sites, suggesting that atmospheric pressure is not an important controlling factor on sea level at the two sites (Fig 5A,B).

#### Coastal trapped waves

##### Auto-correlation

The auto-correlograms for Cochin and Beypore for the premonsoon and summer monsoon seasons in respect of daily observed sea level, atmospheric pressure and pressure corrected sea level are presented in Fig. 6. There is clear evidence of the presence of a wave of about 9 to 10 day period in the observed sea level at Cochin and Beypore during premonsoon season (Fig. 6A). For the summer monsoon season, there is an indication of waves of 7 day period in the series for Cochin, and 4 day period in that for Beypore (Fig. 6B). The peaks, however, are not very prominent. Waves of approximately 8 day period can be seen in the series of the atmospheric pressure at Cochin and Beypore during premonsoon season (Fig. 6C). The atmospheric pressure series during the summer monsoon season, on the other hand, displayed periods of approximately 5 to 6 days (Fig. 6D). The peaks for both the seasons and at both the places are not marked. Both the stations showed strikingly similar auto-correlograms, for both the premonsoon and summer monsoon series of atmospheric pressure.

With the application of the pressure corrections, the premonsoon series of sea level showed a marked peak at 9 day lag (Fig. 6E), which was sharper and more distinct than that presented for the observed sea level (Fig. 6A). The summer monsoon series of corrected sea level also displayed a period of approximately 7 to 8 days at Cochin, and 5 days at Beypore (Fig. 6F).

Table 3—Variance of the observed sea level, atmospheric pressure and corrected sea level at Cochin and Beypore

Parameter	Premonsoon (February-May)		Summer monsoon (June-September)	
	Cochin	Beypore	Cochin	Beypore
Observed sea level (cm <sup>2</sup> )	8.7	7.9	13.2	58.3
Atmospheric pressure (mb <sup>2</sup> )	1.4	1.2	1.5	1.4
Corrected sea level (cm <sup>2</sup> )	9.1	9.9	11.8	56.8



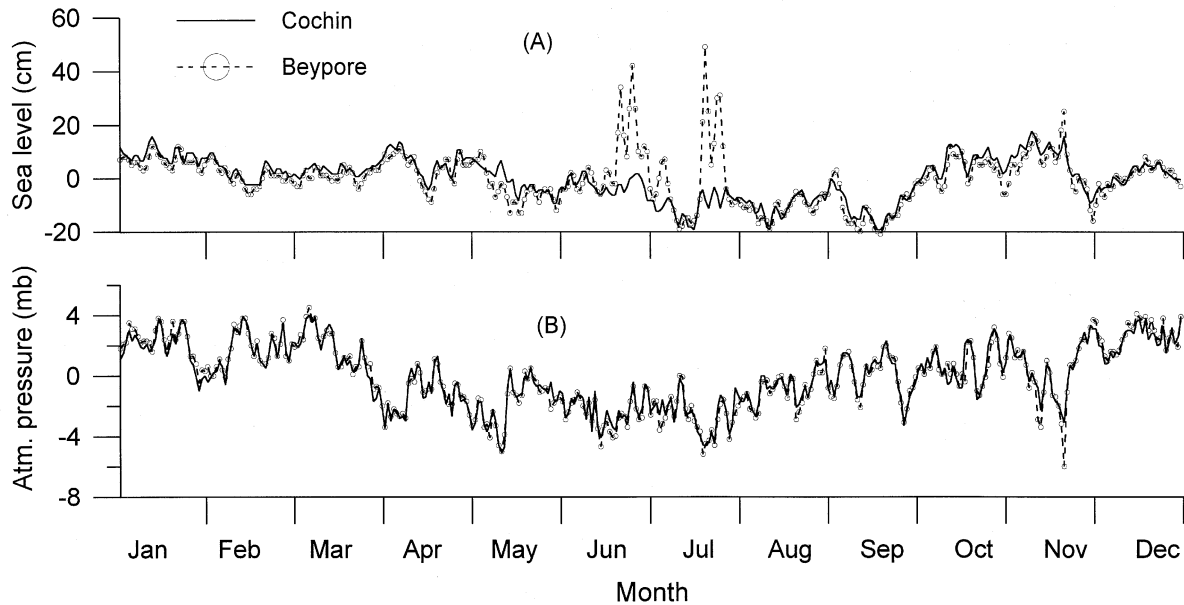


Fig. 5—Daily march of (A) sea level and (B) atmospheric pressure at Cochin and Beypore

The peaks displayed for the corrected sea levels during the summer monsoon season were more marked than those displayed for the observed sea levels (Fig. 6B). If atmospheric pressure is the main excitation and this excitation is transmitted hydrostatically, the auto-correlograms of the observed and pressure corrected sea level series would have differed to a much greater extent. From the above, it appears that waves at subtidal frequencies of around 5-10 days period, may be present in the sea level series. Similar results have been reported elsewhere. For example, Yuce & Alpar<sup>26</sup> found that dominant sea level fluctuations occurred at time scales greater than 10 days, as also shorter period fluctuations occurred between 3-8 days in the Sea of Marmara.

#### Cross-correlation

The cross-correlograms between Cochin and Beypore for the observed and corrected sea levels for the premonsoon season are presented in Fig. 7A. Maximum cross-correlation occurs slightly to the right of zero lag, which shows that Cochin marginally leads Beypore, for both observed and corrected sea levels. Waves with a period of about 9 to 10 days were also observed in the premonsoon series. The correlogram is more or less symmetric with respect to zero lag. The time lags could be more readily observed between corrected sea levels. Usually maximum correlations are slightly higher, and lags more definite, for the corrected sea levels. Time lags between sea levels at adjacent ports imply the existence of time lags between sea level

and atmospheric pressure, at least at some stations, because the pressures are nearly in phase<sup>24</sup>.

The cross-correlograms between Cochin and Beypore for the observed and corrected sea levels for the summer monsoon season are presented in Fig. 7B. Cochin marginally leads Beypore by about a day, during the summer monsoon season, for both the observed and corrected sea levels. It is also evident that the cross-correlogram is not symmetrical with respect to zero lag and also that Beypore may be leading Cochin at higher lags (these could be artifacts, caused by the effect of river discharge on sea level, during summer monsoon season at Beypore). The cross-correlograms for both the corrected and observed sea levels did not vary greatly as reported elsewhere<sup>24</sup>.

Remarkable coherence of simultaneous non-tidal residuals was obtained in the South Australian waters spanning a distance of 700 km<sup>27</sup>. This was attributed to progressive coastal long waves (height of nearly 1 m and period in the range 5-20 days) influenced by the presence of the shelf and its ability to act as a wave guide. As part of a study on the meteorologically induced flushing of three estuaries in USA<sup>28</sup>, it was observed that the filtered sea level records at Chesapeake Bay and Naragansett Bay were strongly coherent, having similar amplitudes, despite a separation of 600 km. A time lag of one day between sea levels at Sydney and Coff's harbour has been reported<sup>24</sup>. Osmer & Huyer<sup>11</sup> observed that the sea level at Crescent City leads the sea level at Tofino (British Columbia, a distance of 820 km) by about a day.

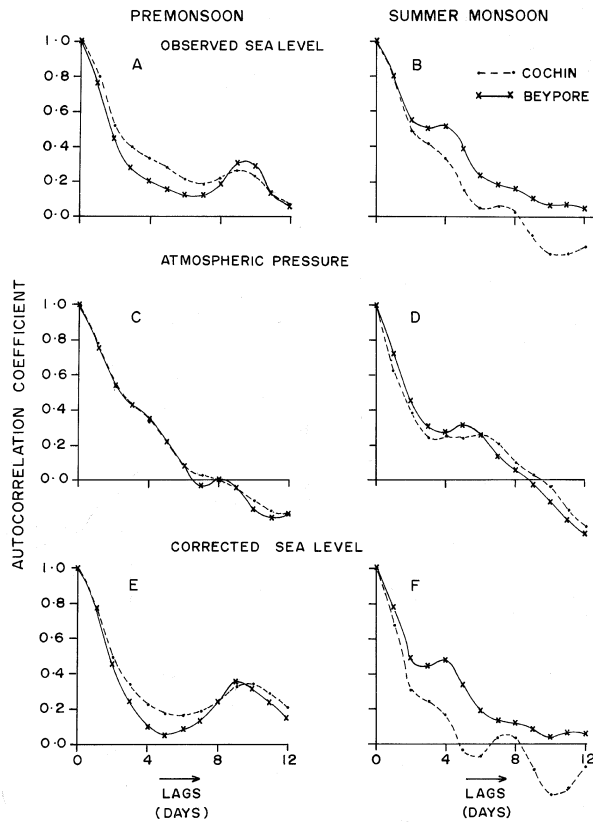


Fig. 6—Auto-correlograms for Cochin and Beypore for daily data on (A) premonsoon observed sea level (B) summer monsoon observed sea level (C) premonsoon atmospheric pressure (D) summer monsoon atmospheric pressure (E) premonsoon corrected sea level (F) summer monsoon corrected sea level

Continental shelf waves were found to exist at all times on the east and west coasts of Australia and it has been suggested that these waves are probably energized by atmospheric pressure variations<sup>25</sup>. The propagating events in the coastal wave guide, such as Kelvin waves, topographic or shelf waves, and hybrid waves (where both stratification and topography are important) are all expected to travel poleward<sup>10,29</sup>.

Goodrich<sup>28</sup> suggested that strong coherence in sea level at periods greater than 10 days may be due to the presence of coastal trapped waves, the wavelength of which is of the order of hundreds of kilometers. He also opined that at shorter periods, the sea level records are found to be much less coherent with the independent oscillations driven by local meteorological and hydrological forcings.

The cross-correlograms of the atmospheric pressure time series for the premonsoon and summer monsoon seasons between Cochin and Beypore show that the correlation is maximum at zero lag (Fig. 7C). The cross-correlograms are also symmetrical with

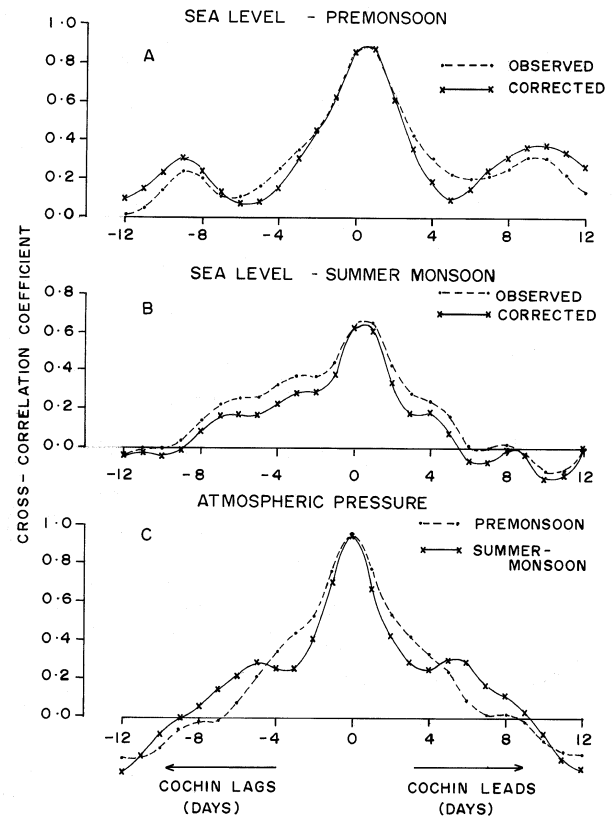


Fig. 7—Cross-correlograms between Cochin and Beypore for daily data on (A) premonsoon sea level (observed and corrected) (B) summer monsoon sea level (observed and corrected) (C) atmospheric pressure (premonsoon and summer monsoon)

respect to zero lag. The premonsoon period shows a weak 8 day wave and the summer monsoon period shows a 5 day wave. Elsewhere, strong alongshore correlation of atmospheric pressures over 500 km station separation has been reported<sup>30</sup>. Ramp *et al.*<sup>10</sup> also reported the large coherence scales of the atmospheric pressure fields.

From the above account, it can be concluded that during the premonsoon season, Cochin leads Beypore marginally, for the sea level series (both observed and corrected), suggesting propagation of coastal trapped waves from south to north (as to be expected for the northern hemisphere). This northward propagation was, however, not clearly seen for the summer monsoon season, which could be an artifact created by the predominantly freshwater dependent sea level series at Beypore (in the summer monsoon season nearly 75% of the annual rainfall occurs).

Estuary-shelf exchanges can be tidal or non-tidal in nature, and this distinction is important. Semi-diurnal and diurnal tidal exchanges are continuous and predictable as they are periodic and hence, they consti-

tute a reliable baseline for flushing. Meteorological forcing in shelf and estuarine waters provide a relatively important supplement to tidal processes<sup>31</sup>. In regions with low tidal ranges and strong winds, energy density spectra (computed from time series of water level or current data) may exhibit dominant concentrations of energy at subtidal frequencies. Variability over time scales of the order of several days is generally attributed to meteorological forcing<sup>32</sup>. The topography - depth, length and orientation, will exert a substantial influence on estuarine response to local meteorological forcing.

The tidal amplitudes are larger at Beypore than at Cochin, with the  $M_2$  constituent showing maximum amplitude, followed by  $K_1$ . The tides are of mixed, predominantly semi-diurnal nature, at both locations. Tidal energy was responsible for 93.7% and 89.2% of the variance in the observed sea level at Cochin and Beypore, respectively. Cross-correlograms indicated that Cochin marginally leads Beypore for the sea levels (observed as well as corrected) during the premonsoon season. This suggests northward propagation of coastal trapped waves of approximately 10 day period during premonsoon season, while such a phenomenon was not clearly seen during summer monsoon season. To have a deeper insight into coastal trapped phenomena and propagation of upwelling signals along the southwest coast of India, detailed studies using sea level, currents and associated met-ocean data using moored instruments, at a number of stations is required.

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