

Statistical modelling of monthly mean sea level at coastal tide gauge stations along the Indian subcontinent

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This study investigates the suitability of statistical models for their predictive potential for the monthly mean sea level at different stations along the west and east coasts of the Indian subcontinent. Statistical modelling of the monthly mean sea level at 15 selected tide gauge stations (8 stations on the west and 7 stations on the east coast) along the coastline of the Indian subcontinent was attempted using autoregressive, sinusoidal and exponentially weighted moving average (EWMA) techniques. Statistics pertaining to the mean seasonal cycle as well as interannual variability are also presented. A strong domination of the annual cycle over the semi-annual cycle was seen at ten stations. The maximum seasonal sea level ranges were observed along the west coast at Bhavnagar (63 cm) and along the east coast at Sagar Island (48 cm). While the autoregressive and sinusoidal models were satisfactory, EWMA technique was found to be the best of all. Tuticorin on the east coast, and Mormugao on the west coast have shown minimum RMSEs for the corresponding coasts for all the three models, while Bhavnagar on west coast has shown very high RMSE values. The EWMA technique (which yields forecast with a lead time of only one month) gave the lowest root mean square errors relative to the verifying observations.

[Key words: Statistical modelling, monthly mean sea level, seasonal and interannual variability, oceanography, meteorology, Indian subcontinent]

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Introduction

The seasonal sea level variability results from oceanographic, meteorological and hydrological forcings¹. Monthly mean sea level changes reflect the variations in the parameters of oceanography (e.g. ocean heat content and circulation), meteorology (e.g. piling up of water due to local wind fields, changes in atmospheric surface pressure field), and hydrology (changes in river run-off regimes). It is also important to monitor seasonal sea level variability, as it is known to be important for marine life, anthropogenic effects and processes such as the erosion of beaches. The records of monthly mean sea level data show considerable interannual variability^{1,2}. The interannual variability contains useful information on how oceanic conditions vary from year to year, and their association with the oceanographic, meteorological and hydrological conditions.

With applications in the fields of oceanography, meteorology, and hydrology, modelling seasonal variability of sea level is very useful. Sea level can be studied using mathematical and statistical models. For any attempt on mathematical modelling, a detailed knowledge of the local oceanography and meteorology is required. When such data are not

available, there is room for statistical modelling of the monthly mean sea level time series. In statistical modelling, forecasting is done by taking into consideration the earlier values of the sea level time series, or making use of trigonometric functions, to account for the seasonal pattern of the data³. For multiregressive modelling of sea level, data at monthly intervals on related oceanographic, meteorological and hydrological parameters are utilised. However, for univariate models such as autoregressive, sinusoidal and exponentially weighted moving average ones, we require time series data at monthly intervals on the concerned parameter only (sea level, in the present case). The success of the model is measured by RMSE (Root Mean Square Error³). The model which gives minimum RMSE can be considered as better than the others.

Elsewhere, various statistical models for sea level modelling have been used earlier⁴⁻⁷. In the Indian context too, statistical techniques have been used for studying sea level variability⁸⁻¹⁰ and these have been attempted to understand mainly the interannual sea level variability. Shankar¹¹ used a one and half-layer dynamical reduced-gravity model for simulating the seasonal cycle of sea level at a few stations along the

Indian coastline. This model, however, failed to reproduce the winter peak along the east coast of India. As a result, the predicted sea level had a higher range along the west coast than along the east coast.

In a recent study on statistical modelling of met-ocean parameters in the Cochin estuarine system, Srinivas *et al.*¹² used the same models – autoregressive, sinusoidal and EWMA. They found that the models, especially EWMA, is particularly suitable for predicting the value of the parameter, one month ahead. Further, they reported that atmospheric pressure, SST, air temperature and sea level could be forecast with less than 10% error most of the time, whereas wind speed, relative density and rainfall could not be forecast with any acceptable degree of accuracy.

Some of the sea level stations along the Indian coastline are situated in estuaries and most of these estuarine systems are highly sensitive to changing climatic variables such as river discharge (water and sediments), temperature rise, rainfall, wind and wave climate¹³⁻¹⁵. Modelling the short and medium term seasonal variation of the sea level would be very useful in this context, as they are under severe anthropogenic effects ranging from dredging for navigation or to discharge of pollutants.

This study investigates the suitability of statistical models for their predictive potential for the monthly mean sea level at different stations along the west and east coasts of the Indian subcontinent. Three arbitrarily chosen models *viz.* autoregressive, least square sinusoidal and EWMA were tried for predicting the monthly mean sea level at fifteen stations along the coasts of the Indian subcontinent (Fig. 1).

The three models were tested for their ability to predict the monthly mean values of sea level at the selected stations, both short term (the months ahead) and medium term (three years ahead). The study was carried out to forecast the monthly mean sea level, up to three years in advance. These models need only continuous long time series data on sea level, at monthly intervals.

Materials and Methods

The monthly mean sea level data for 15 stations along the coastline of the Indian subcontinent were obtained from the archives of the Permanent Service for Mean Sea Level (PSMSL), UK, which compiles and archives monthly and annual mean sea level data received from different national organisations

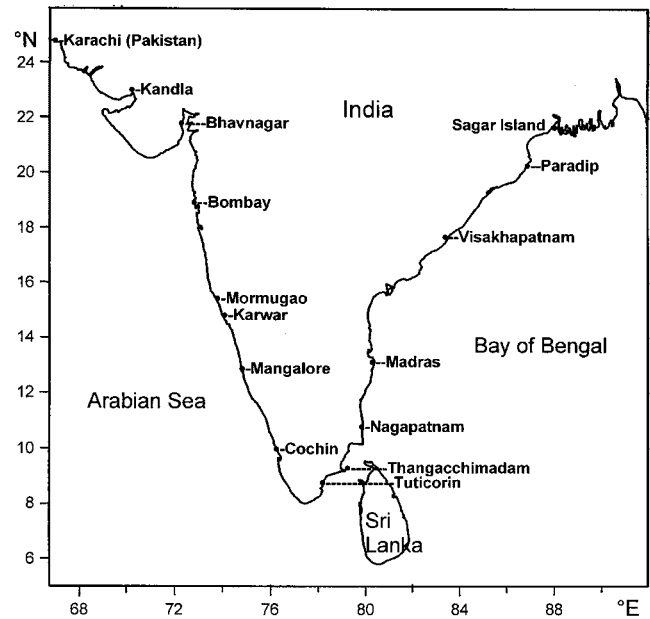


Fig. 1—Station location map

throughout the world¹⁶. The monthly mean sea level values are usually computed by averaging hourly values of the sea level for a particular month. At some of the older stations, the means of high and low waters have also been used. The Revised Local Reference (RLR) data of PSMSL, which are suitable for time series analysis, were utilised in this study. These data sets are regularly supplied to PSMSL by the Surveyor General of India for Indian stations and the Chief Hydrographer to the Pakistan Navy, for Karachi and are constantly updated. The latitudinal distance on the west coast between the southernmost and northernmost stations (Cochin and Karachi) is 1650 km, while on the east coast, it is 1430 km (between Tuticorin and Sagar Island).

Calculation of the estimation constants was done utilising a part of the sea level data (*i.e.*, all the data excluding the last 36 months, for the station concerned) and the values were forecast for the subsequent months (last 36 months) to enable comparison of forecast values with the observed values. The stations considered and the years pertaining to which data were utilised for calculation of the constants and comparison are given in Table 1.

A good account of the three statistical models *viz.* autoregressive, least square sinusoidal and EWMA are given in Mendenhall & Reinmuth¹⁷, DeLurgio³, Cooper & Weekes¹⁸ and Emery & Thomson¹⁹.

The three models as applied in this study, are as follows

Table 1—Details of the sea level data used in the present study

Station	Start Year	End Year	Number of Years
West coast			
Karachi	1937	1947	11
Kandla	1950	1987	38
Bhavnagar	1937	1955	19
Bombay	1878	1988	111
Mormugao	1969	1980	12
Karwar	1970	1988	19
Mangalore	1961	1976	16
Cochin	1939	1988	50
East coast			
Sagar Island	1937	1988	52
Paradip	1966	1988	23
Visakhapatnam	1937	1988	52
Madras	1952	1988	37
Nagapatnam	1971	1988	18
Thangachimadam	1969	1983	15
Tuticorin	1964	1980	17

a) In the autoregressive model, the equation used is

$$z_{t+12} = a_0 + a_1 y_t + a_2 y_{t+3} + a_3 y_{t+6} + a_4 y_{t+9}$$

where z_{t+12} is the forecast value for the month $(t+12)$ and y 's are the observed mean sea level values of the concerned months. The constant a_0 , and the coefficients a_1 , a_2 , a_3 and a_4 were calculated using least square method¹⁹ by utilising past data, excluding the last three years of the record. The model implies, for instance, that the forecast of sea level for January of a particular year is done utilising sea level values of the months of January, April, July and October of the previous year. The model was initially tested with only the first two terms viz. $a_0 + a_1 y_t$, and subsequently other terms were added, one by one, noting how the accuracy of the technique improved by the addition of each term. Thus for Cochin, 47 years (1939-1985) data were utilised for computing a_0 , a_1 , a_2 , a_3 and a_4 and then the observed data for the subsequent 3 years (1986-'88) were compared with forecast values.

b) In the sinusoidal model, the forecast value z_t for the month 't' is given by

$$z_t = a_0 + a_1 t + a_2 \cos(360t/L) + a_3 \sin(360t/L) + a_4 t \cos(360t/L) + a_5 t \sin(360t/L)$$

If the predominant cycle has a period of one year i.e. twelve months, L is taken as 12 and consequently

360/L becomes 30°. If the predominant cycle is semi-annual (six month cycle), L is taken as 6 and 360/L becomes 60° and if the predominant cycle is ter-annual (four month cycle), L is taken as 4 and 360/L becomes 90°.

If L (the length of seasonal cycle) is 12, the above equation reduces to

$$z_t = a_0 + a_1 t + a_2 \cos(30t) + a_3 \sin(30t) + a_4 t \cos(30t) + a_5 t \sin(30t)$$

Estimation of a_0 , a_1 , a_2 , a_3 , a_4 and a_5 as well as comparison of observed values with forecast values of this model, were done as in the case of autoregressive model.

c) The Exponentially Weighted Moving Average (EWMA) model is a time series forecasting model based on a smoothing technique. In this model, the forecast value z_{t+1} , for $(t+1)$ th month is given by

$$z_{t+1} = (S_t + R_t) F_{t-1}$$

where S_t is referred to as "Smoothed average", R_t the "Trend gain" and F_t the "Seasonal factor". They are obtained as follows:

$$\text{Smoothed average } S_t = \alpha y_t / F_{t-L} + (1-\alpha) (S_{t-1} + R_{t-1})$$

$$\text{Trend gain } R_t = \beta (S_t - S_{t-1}) + (1-\beta) R_{t-1}$$

$$\text{Seasonal factor } F_t = \gamma (y_t / S_t) + (1-\gamma) F_{t-L}$$

where L is taken as 12 and α , β and γ are arbitrarily chosen values (between 0.0 and 1.0) which give best approximation to the observed values. The initial values of α , β and γ were chosen to be zero. As the formulae indicate, the values of S_t , R_t and F_t are mutually dependent and to obtain the forecast of any particular month, the values of the previous month are required. Thus, this process has to be repeated month after month, and the values of S_t , R_t and F_t are periodically revised. It should be particularly noted that the lead time of forecast for EWMA model is only one month - the model can be used to forecast the sea level only one month in advance (unlike the other two techniques). Comparison of forecast values with the observed ones were carried out as in the earlier two cases. This model is particularly suitable for predicting parameters that show sporadic variation e.g. rainfall.

Results and Discussion

Statistics of the time series

The standard deviation of the observed data and anomalies (de-seasonalised data) were generally found to be high along the east coast, as compared to the west coast, suggesting very energetic, seasonal as well as interannual, signals along the east coast (Table 2). The monthly anomalies were determined by subtracting the mean monthly sea level for each month from the corresponding month of the entire time series. Bhavnagar on the west coast appears to have the highest seasonal and interannual variations, probably due to the freshwater discharge of Narmada and a few other rivers, and also due to its unique location. Bhavnagar is also known for its very high tidal ranges. The seasonal sea level variances (%) contained in the entire time series for the various stations show higher values at stations along the east coast than those along the west coast. The seasonal cycle is strong along the east coast as compared to the west coast, in terms of year to year variability (Column 3, Table 2). At least six stations (out of seven) have a value of more than 64%, along the east

coast, whereas along the west coast only two (out of eight) have a value more than 64%. Along the west coast, the variance was maximum at Mormugao (70.5%) and minimum at Kandla (17.5%) whereas along the east coast, the variance was maximum at Nagapatnam (81.5%) and minimum at Tuticorin (37.6%).

The seasonal march of the mean sea level and that of the standard deviations (which indicates the month having maximum interannual variability) are presented in Fig. 2, for the west coast, and in Fig. 3, for the east coast. The seasonal cycle is complex and shows remarkable variability, even at closely spaced stations. This complexity seems to be more conspicuous along the west coast than on the east coast.

In earlier studies on seasonal variability of sea level along the coastline of the Indian subcontinent, a few stations showed highly significant relationship with coastal alongshore current^{2,11,20}. Reversals in the currents were clearly reflected in the sea level changes, thus suggesting that the sea level records at these stations would be useful for long term monitoring of the surface geostrophic flow along the

Table 2—Statistics of the sea level time series at various stations along the west and east coasts of the Indian subcontinent

	1	2	3	4	5	6	7
West coast							
Karachi	6.0	4.9	32.8	27.0	58.7	4.7	90.4
Kandla	12.0	10.9	17.5	85.3	8.2	1.9	95.4
Bhavnagar	26.8	15.1	68.2	98.3	1.0	0.4	99.7
Bombay	6.7	5.8	26.1	23.0	47.4	20.4	90.8
Mormugao	7.4	4.0	70.5	91.4	3.3	4.5	99.2
Karwar	9.0	5.8	58.2	82.4	13.6	1.0	97.0
Mangalore	8.5	6.1	49.2	1.8	41.6	44.8	88.2
Cochin	8.1	5.4	55.3	84.0	8.1	7.4	99.5
East coast							
Sagar Island	21.9	12.3	68.2	96.1	3.3	0.4	99.8
Paradip	16.9	7.4	81.1	91.5	7.0	0.5	99.0
Visakhapatnam	15.6	6.9	80.3	75.8	21.3	2.1	99.2
Madras	11.1	6.6	64.2	46.2	48.8	2.1	97.1
Nagapatnam	13.3	5.7	81.5	55.3	40.4	3.1	98.8
Thangacchimadam	17.5	8.1	78.3	83.4	12.5	3.5	99.4
Tuticorin	7.5	5.9	37.6	75.2	22.6	0.1	97.9

1 - Standard deviation of the entire sea level time series (cm)

2 - Standard deviation of the anomaly time series (cm)

3 - Seasonal variance (%) contained in the entire series given by:-
 $100 \times (1 - \text{Var}_{\text{res}} / \text{Var}_{\text{obs}})$, where Var_{res} is the variance of the residual time series (i.e. anomalies) and Var_{obs} is the variance of the original time series

4 - Contribution of the annual component to the total variance of the mean seasonal cycle (%)

5 - Contribution of the semi-annual component to the total variance of the mean seasonal cycle (%)

6 - Contribution of the ter-annual component to the total variance of the mean seasonal cycle (%)

7 - Sum of columns 4, 5 and 6 (%)

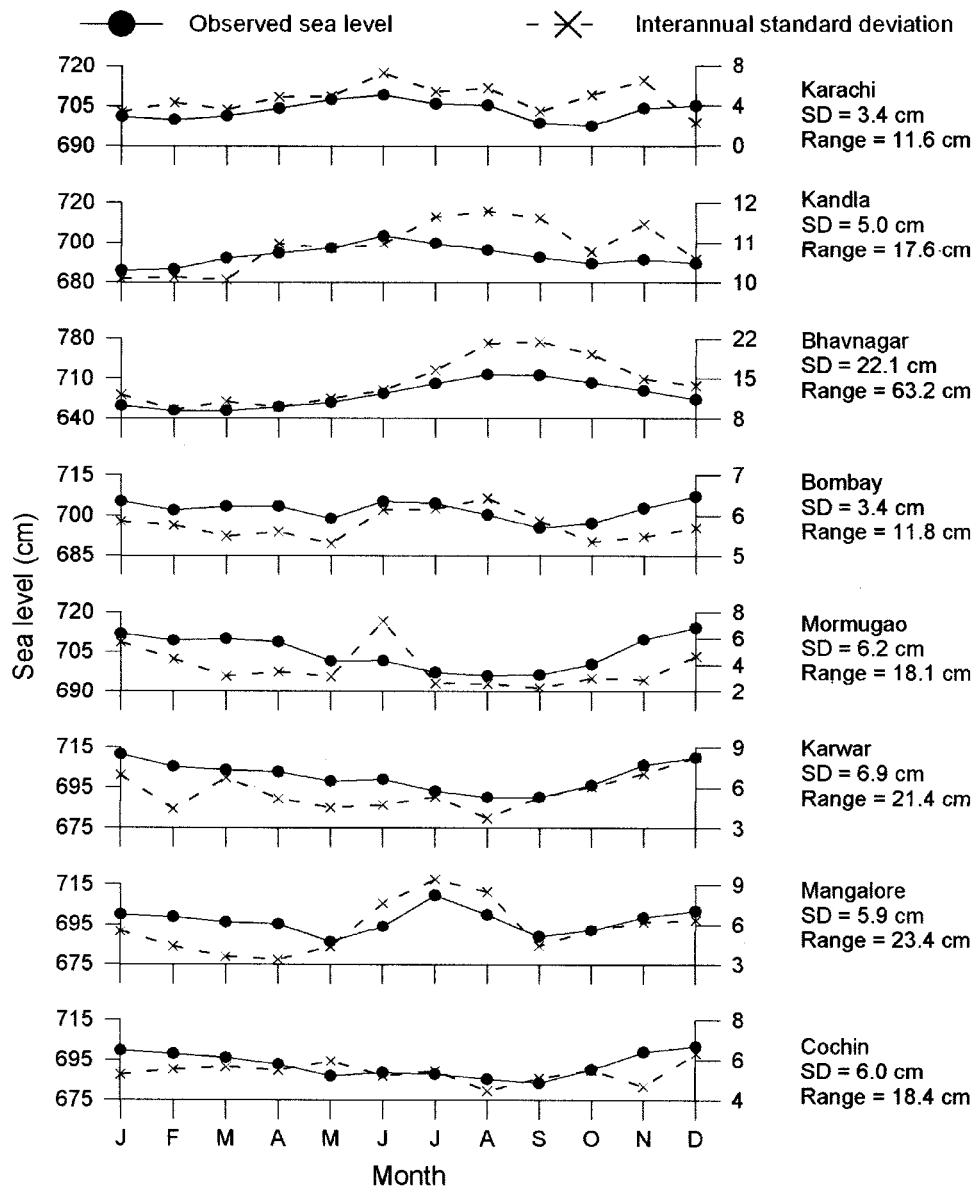


Fig. 2—Seasonal march of mean sea level and standard deviation of the sea level along the west coast of the Indian subcontinent. The y-axes scales are different. SD (cm) is the standard deviation of the mean seasonal cycle.

coastline of India. The relationship between observed sea level and coastal alongshore current is due mainly to the Coriolis force, which is responsible for deflecting the mass. Due to the action of the Coriolis force, a slope is created perpendicular to the direction of the currents and hence a change in sea level along the coast accompanies the change in coastal currents. When looking in the direction of flow in the northern hemisphere, the height of the sea level is greater on the right hand side and lower on the left hand side.

The seasonal variance of coastal alongshore currents was found to be more on the east coast than on the west coast of India²⁰, indicating that the

alongshore currents are more energetic along the east coast as compared to the west coast. The western boundary currents are characteristically fast, deep and narrow while the eastern boundary currents are characteristically slow, shallow and wide. Currents driven by alongshore density differences could be stronger along the east coast as compared to the west coast, because of the substantial river discharge into the Bay of Bengal, which is more than four times that into the Arabian Sea. The stronger coastal currents along the east coast could be the reason for higher ranges in sea level seen along the east coast, as compared to the west coast. The interannual

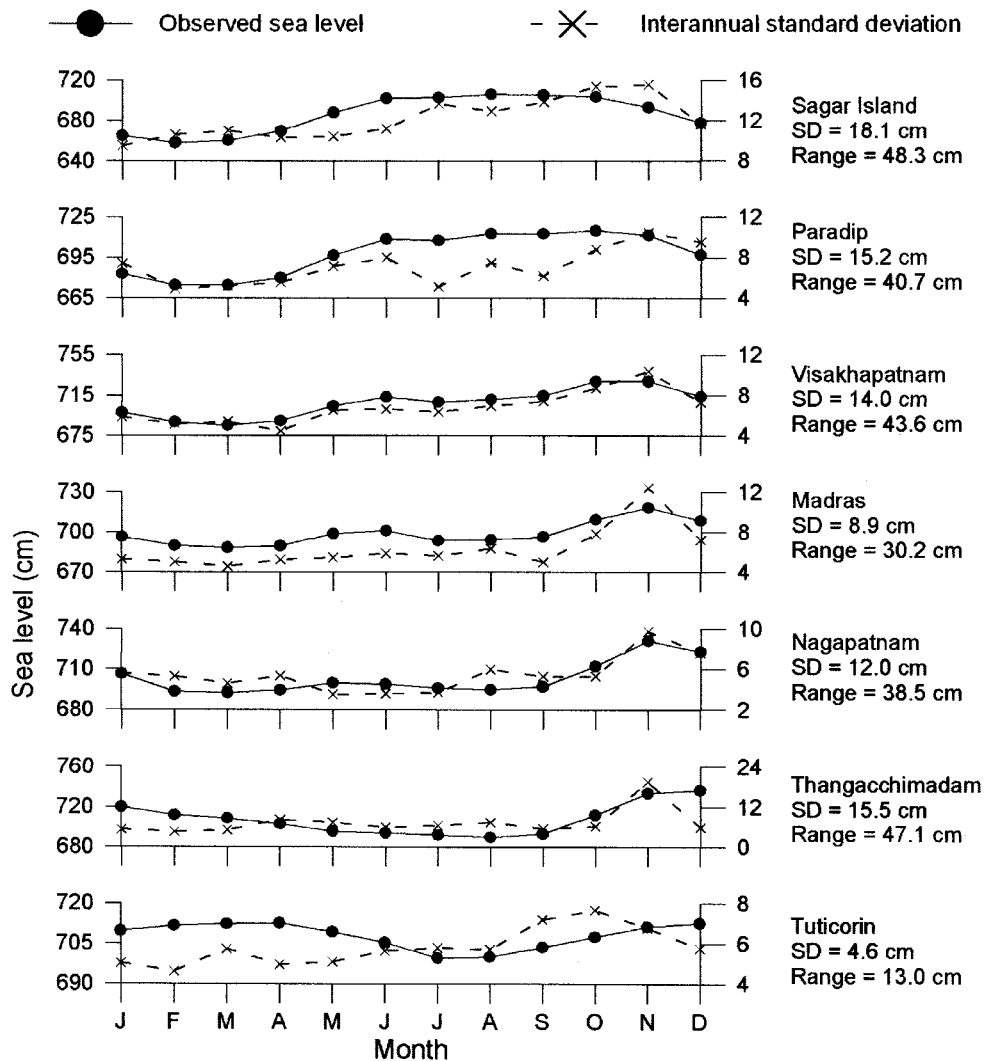


Fig. 3—Seasonal march of mean sea level and standard deviation of the sea level along the east coast of the Indian subcontinent. The y-axis scales are different. SD (cm) is the standard deviation of the mean seasonal cycle.

variability in sea level also shows a complex nature along the west coast, whereas along the east coast, the maximum was consistently seen during November, probably due to the interannual variation in rainfall over the Indian subcontinent and associated river discharge, during that month. The annual maximum in rainfall is seen during that month for some of the stations²⁰.

The percentage variances explained by the annual, semi-annual and ter-annual components of the climatological mean seasonal cycle of sea level, which were determined by harmonic analysis, are also presented in Table 2. These are presented to appreciate the dominance of the particular component (annual/semi-annual or in some cases ter-annual). The three components together generally explain more than 88 % of the seasonal variance for all the stations.

The least square fits, using the three cycles were found to explain a high percentage of variability along the east coast as compared to the west coast. A domination of the annual over the semi-annual cycle was seen at five out of eight stations along the west coast whereas it was six out of seven stations, along the east coast. Further, out of the fifteen stations, a strong domination of the annual over the semi-annual cycle was seen at ten stations. In general, the annual component dominated the semi-annual component, for all the stations, except for Karachi, Bombay, Mangalore and Madras. At Mangalore, the ter-annual component was the most dominant one, while the contribution by the annual component was hardly 2%. In an earlier study on statistical modelling of met-ocean parameters in the Cochin estuarine system, Srinivas *et al.*¹² reported that air temperature is

dominated by a strong semi-annual cycle whereas other parameters (sea surface temperature, atmospheric pressure, wind speed, rainfall, relative density and sea level) by a strong annual cycle.

Autoregressive model

The values of a_0 , a_1 , etc. used in the autoregressive models as well as the RMSEs are given in Table 3, for the west and the east coasts. The coefficient a_1 is higher compared to a_2 , a_3 , a_4 and a_5 . a_1 is the coefficient for the observed value one year earlier to the forecast month, and is of the order of 0.34-0.79, indicating that the forecast value for any given month depends on 34-79% of the value recorded twelve months ago. Thus, this method brings out the importance of seasonal factor in the forecasting procedure. From Table 3, it is evident that increasing the number of terms need not necessarily reduce the RMSE. Along the west coast, four stations (Karachi, Kandla, Mormugao and Karwar) required just one term, i.e., a_1 (excluding the a_0 term), for the least RMSE. Similarly, at Tuticorin, on the east coast, the model with only two terms performed better than that containing five terms, suggesting that increasing the number of terms has not reduced the RMSE to any significant level. However, at other stations along the east coast, more terms were required for bringing down the RMSE. The forecasts for the last 36 months of the data using the autoregressive technique are presented in Fig. 4A for the west coast and in Fig. 4B for the east coast.

Sinusoidal model

At Karachi, Bombay and Madras, the predominant seasonal cycle is semi-annual, therefore, (360/L) is taken as 60° in the sinusoidal model. At most of the remaining stations, the predominant cycle is annual and hence (360/L) is taken as 30° . Interestingly, Mangalore is the only station that showed a dominance of the ter-annual cycle over the semi-annual as well as annual cycle, most probably caused by the effects of freshwater discharge of Netravathi and Gurupur rivers during summer monsoon season. The sea level at this station shows a high peak during the summer monsoon season, not seen so conspicuously at other stations. The numerical values are highest for a_2 and a_3 (Table 4). They are multiplication factors for the first two terms of the trigonometric functions and can be taken to be responsible for the cyclic variation in the parameter (Fig. 5).

EWMA model

The values of α , β and γ chosen for the EWMA models as well as the RMSEs are presented in Table 5. The value chosen for β is practically nil throughout. This is the factor responsible for trend suggesting that there is no conspicuous change due to trend in the value of the sea level. As the lead period of estimate under this model is only one month, this is as expected. The constants α and γ , which are connected to the seasonal factor appear to be the main influencing constants. Combining the above three

Table 3—Coefficients of the best autoregressive model (a_0 , a_1 , a_2 , a_3 , a_4). RMSE is the root mean square error (cm).

Station	a_0	a_1	a_2	a_3	a_4	RMSE
West coast						
Karachi	461.7833	0.342786	---	---	---	5.966
Kandla	182.4525	0.737683	---	---	---	6.615
Bhavnagar	134.2782	0.685728	0.170554	-0.272820	0.220671	17.255
Bombay	209.2782	0.462422	0.005448	0.158633	0.075372	5.751
Mormugao	200.3524	0.715786	---	---	---	4.408
Karwar	240.8331	0.655935	---	---	---	5.815
Mangalore	434.8822	0.473864	-0.122760	0.024222	---	6.734
Cochin	177.9880	0.668542	0.073140	-0.127220	0.128384	6.230
East coast						
Sagar Island	87.2554	0.767005	0.108828	-0.14992	0.146961	13.428
Paradip	412.7158	0.673638	-0.033490	-0.23156	---	11.119
Visakhapatnam	438.9237	0.716976	-0.120760	-0.14591	-0.071130	9.742
Madras	419.0718	0.592181	-0.192260	---	---	11.511
Nagapatnam	329.2153	0.785988	-0.095110	-0.07166	-0.087630	8.394
Thangachhimadam	444.8406	0.725461	-0.097970	-0.17546	-0.080460	9.035
Tuticorin	362.6249	0.488036	---	---	---	4.945

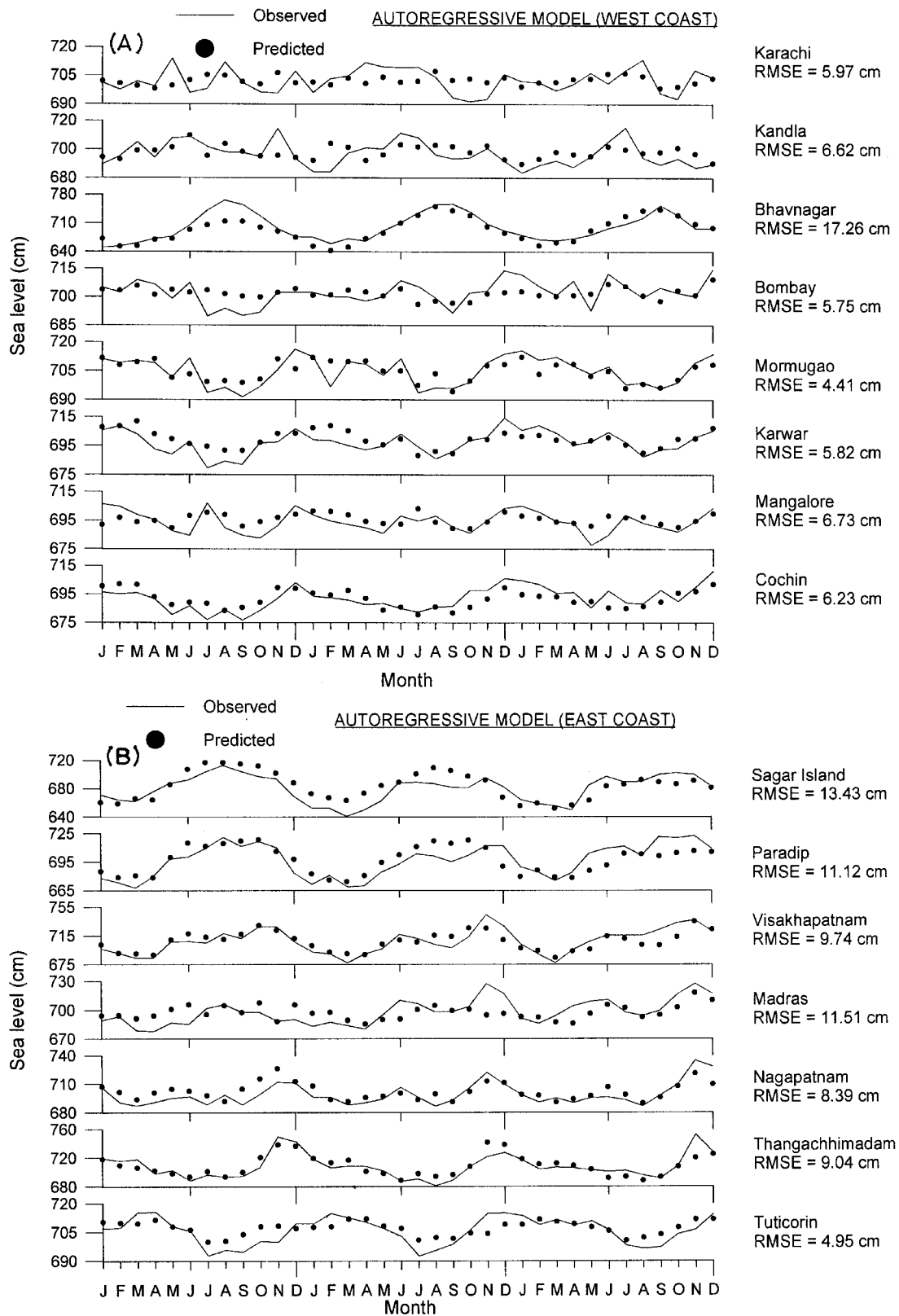


Fig. 4—Observed and modelled data on monthly mean sea level at different stations along the A) west coast and B) East coast of the Indian subcontinent. The y-axes scales are different. Root mean square error (RMSE) is in cm. The last 36 months of the data for each station are predicted with autoregressive model.

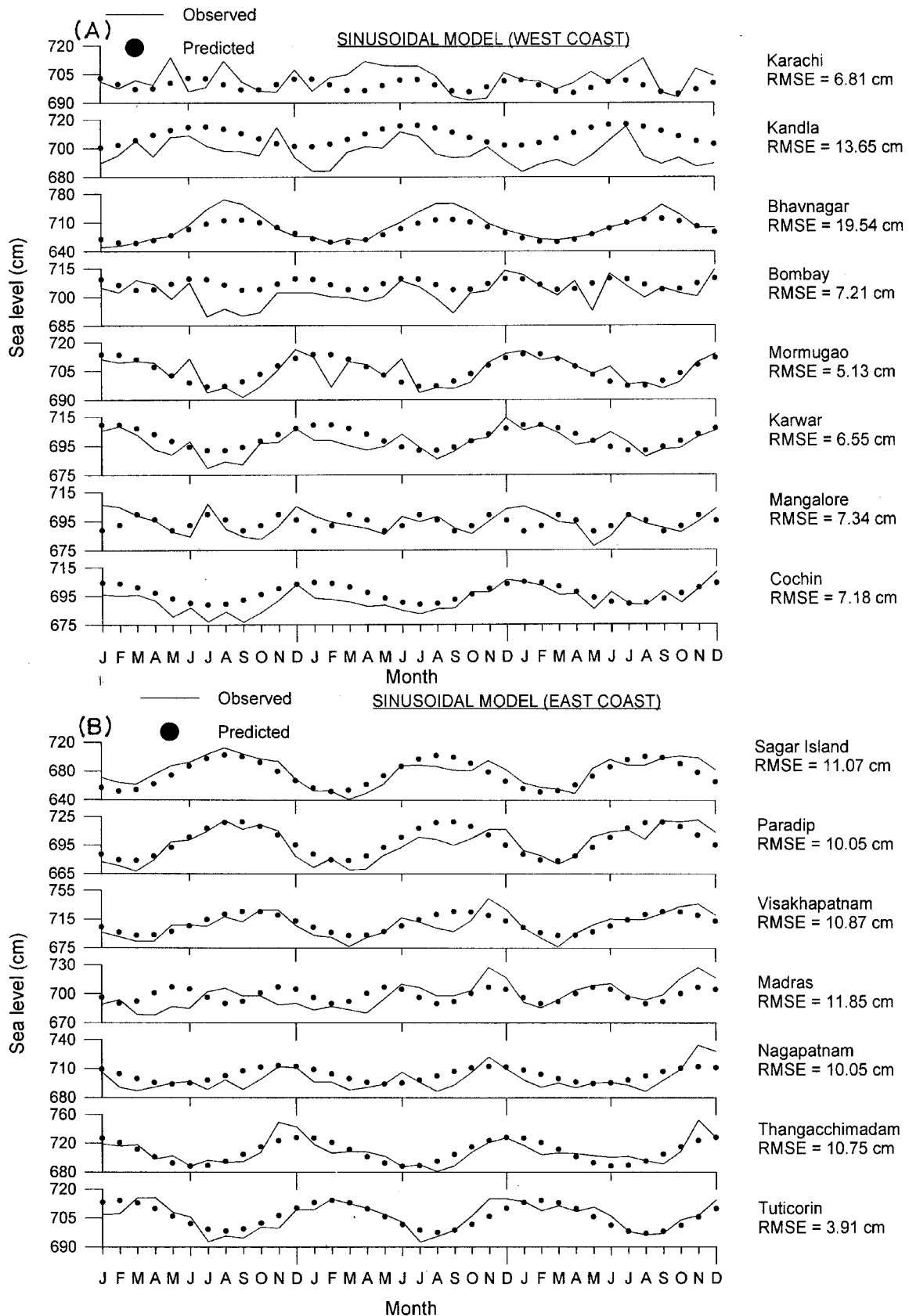


Fig. 5—Same as Fig. 4, but the model used is sinusoidal

Table 4—Coefficients of the best sinusoidal model ($a_0, a_1, a_2, a_3, a_4, a_5$). RMSE is the root mean square error (cm).

Station	a_0	a_1	a_2	a_3	a_4	a_5	RMSE
West coast							
Karachi	706.6644	-0.065641	4.775010	-2.762819	-0.017705	0.040724	6.809
Kandla	678.0316	0.069989	-5.987590	0.205560	-0.002186	-0.005563	13.650
Bhavnagar	667.3136	0.107437	-5.337965	-27.679550	---	---	19.542
Bombay	697.3638	0.007132	3.075348	1.593978	-0.000115	-0.000263	7.208
Mormugao	704.0197	0.010990	6.313179	5.814422	---	---	5.128
Karwar	701.3674	-0.003542	6.419958	6.452600	---	---	6.551
Mangalore	700.1225	-0.036912	1.889178	-5.556296	---	---	7.344
Cochin	688.5977	0.013923	6.468410	4.390012	---	---	7.184
East coast							
Sagar Island	695.3464	-0.030490	-10.385840	-23.105590	---	---	11.071
Paradip	696.7863	0.010057	-4.158060	-20.332050	---	---	10.054
Visakhapatnam	704.8042	0.007319	3.382060	-16.718990	---	---	10.865
Madras	698.8624	-0.000510	6.121483	-6.487490	0.000306	0.000503	11.851
Nagapatnam	704.5244	-0.004270	14.662670	-6.975190	-0.031600	0.015459	10.053
Thangacchimadam	706.0295	0.013383	19.871440	3.520890	---	---	10.746
Tuticorin	710.5997	-0.025380	2.800276	1.272249	0.007746	0.030811	3.911

Table 5—Details of the EWMA model. RMSE is the root mean square error (cm).

Station	Best Model			RMSE
	α	β	γ	
West coast				
Karachi	0.1	0.0	0.3	5.825
Kandla	0.1	0.2	0.1	6.051
Bhavnagar	0.8	0.0	0.6	10.434
Bombay	0.2	0.0	0.1	4.880
Mormugao	0.0	0.1	0.5	3.922
Karwar	0.2	0.0	1.0	5.173
Mangalore	0.4	0.0	0.3	5.359
Cochin	0.3	0.0	0.1	4.581
East coast				
Sagar Island	0.8	0.0	0.4	8.108
Paradip	0.3	0.0	0.1	8.281
Visakhapatnam	0.2	0.0	0.1	7.310
Madras	0.9	0.0	1.0	9.327
Nagapatnam	0.4	0.0	0.3	5.809
Thangacchimadam	0.0	0.0	0.2	8.081
Tuticorin	0.0	0.0	0.3	3.816

factors, we can conclude that trend is not an important consideration in predicting sea level under this model, while cyclical and seasonal variations are important factors. The forecast values are highly sensitive to the values of α , β and γ . To bring out the best combinations of α , β and γ , the model was run with their values varying from 0.0 to 1.0 i.e., a total of 1331 combinations. The models that gave the least RMSE are presented in Table 5. Small change in α , β and γ values was seen to drastically change the RMSE. The forecasts using the EWMA technique are presented in Fig. 6.

In conclusion, it can be seen that the highs and lows of the modelled monthly data on sea level generated using the three techniques, coincided with those of the observed values for most of the stations, as is evident from the figures (Figs 4-6). However, the observed and modelled values at highs and lows differed and the models were not suitable for certain specific months, while satisfactory for other months. The RMSE for EWMA model is smaller than those for autoregressive and sinusoidal models (Tables 3-5), indicating that EWMA model is the most suitable one for forecasting sea level. Of the remaining two, the autoregressive model presented lower RMSE than the sinusoidal model, for most of the stations. For the sinusoidal model, the estimated values are cyclical in nature without sharp kinks, and the crests and troughs are also relatively smooth. This is in contrast to the estimated values by autoregressive and EWMA models. Further, it can be seen that RMSE for west coast stations, in general, are lower than those for east coast, thereby indicating that the forecasting models can be applied with better accuracy along the west coast than along the east coast. Tuticorin on the east coast, and Mormugao on the west coast have shown minimum RMSEs for the corresponding coasts for all the three models, while Bhavnagar on west coast has shown very high RMSE values. The deviations of the forecasts were quite high at particular months, in respect of all the three models, for Bhavnagar. The RMSE has been normalized by the range of mean sea level at each station, in order to make better comparison of the performance of the models, as

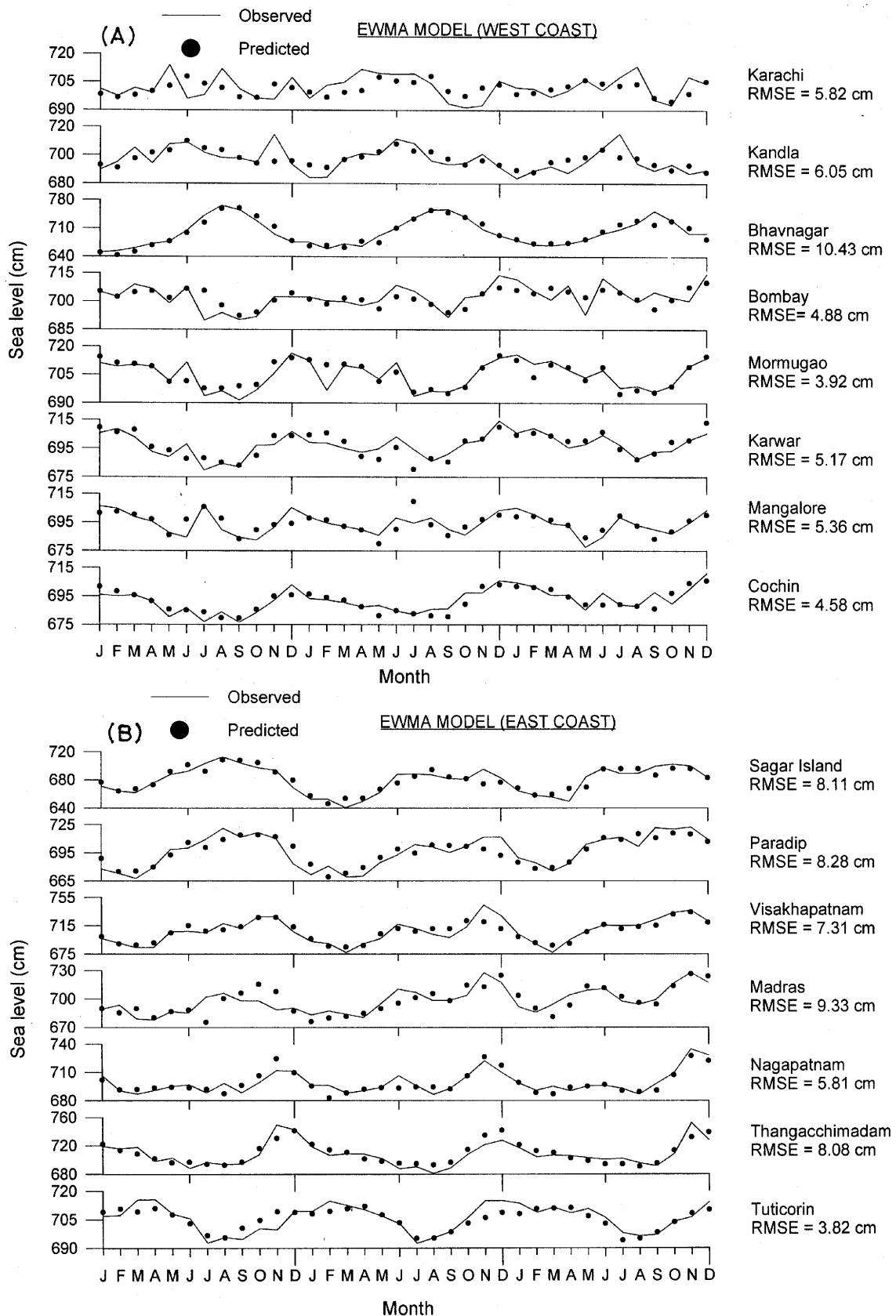


Fig. 6—Same as Fig. 4, but the model used is EWMA

Table 6—Normalized RMSE in respect of autoregressive, sinusoidal and EWMA models.

Station	Autoregressive	Sinusoidal	EWMA
West coast			
Karachi	0.514	0.587	0.502
Kandla	0.376	0.776	0.344
Bhavnagar	0.273	0.309	0.165
Bombay	0.487	0.611	0.414
Mormugao	0.244	0.283	0.217
Karwar	0.272	0.306	0.242
Mangalore	0.288	0.314	0.229
Cochin	0.339	0.390	0.249
East coast			
Sagar Island	0.278	0.229	0.168
Paradip	0.273	0.247	0.203
Visakhapatnam	0.223	0.249	0.168
Madras	0.381	0.392	0.309
Nagapatnam	0.218	0.261	0.151
Thangacchimadam	0.192	0.228	0.172
Tuticorin	0.380	0.301	0.294

RMSE alone is likely to exaggerate the errors for stations such as Bhavnagar, with a higher seasonal variability. These normalized RMS values (Table 6) show that the models are fairly accurate even for stations such as Bhavnagar, where the seasonal variability is quite high. Eventhough the performance of the three models is satisfactory, it would be worthwhile to investigate alternate models *e.g.* AutoRegressive, Integrated and Moving Average (ARIMA) model, which is an accurate and very versatile model, for better predictions³.

Conclusion

Three forecasting models *viz.* autoregressive, sinusoidal and EWMA were used to forecast monthly mean sea level at 15 stations along the coastline of the Indian subcontinent (8 on the west coast and 7 on the east coast). Statistics pertaining to the mean seasonal cycle as well as interannual variability are also presented. A strong domination of the annual cycle over the semi-annual cycle was seen at ten stations. Autoregressive model has shown that the value of the corresponding month of the previous year has a dominating influence on the estimate. For the sinusoidal model, the estimated values are cyclical in nature without sharp kinks, and the crests and troughs are also relatively smooth. EWMA model is highly sensitive to small changes in α , β and γ values and these can drastically change the RMSE. All the three models have shown that the seasonal signal is very important. Forecasts for the west coast gave better

accuracy than those for the east coast. Tuticorin on the east coast and Mormugao on the west coast have shown minimum RMSEs for the corresponding coasts for all the three models, while Bhavnagar on west coast has shown very high RMSE values. EWMA model yielding estimates with a lead of only one month, turned out to be better than the remaining two models with low RMS values. Autoregressive and sinusoidal models come next in that order.

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References

- 1 Tsimplis M N & Woodworth P L, The global distribution of the seasonal sea level cycle calculated from coastal tide gauge data, *J. Geophys. Res.*, 99 (1994) 16,031-16,039.
- 2 Shetye S R & Almeida A M, An examination of the factors that influence the monthly-mean sea level along the coast of India, in *Proceedings of the IOC - Unesco Workshop on Regional Co-operation in Marine Science in the Central Indian Ocean and Adjacent Seas and Gulfs. IOC Workshop Report 37 (supplement)*, (Unesco, Paris), (1985) pp. 87-104.
- 3 DeLurgio S A, *Forecasting principles and applications*, (Irwin McGraw-Hill, Boston) 1998, pp. 802.
- 4 Brundrit G B, Trends of Southern African sea level: Statistical Analysis and Interpretation, *South African J. Mar. Sci.*, 16 (1995) 9-17.
- 5 Sultan S A R, Moamar M O, El-Ghribi N M & Williams R, Sea level changes along the Saudi coast of the Arabian Gulf, *Indian J. Mar. Sci.*, 29 (2000) 191-200.
- 6 Sultan S A R & Ahmad F, Annual and semi-annual variations of sea level at Jeddah, central coastal station of the Red Sea, *Indian J. Mar. Sci.*, 29 (2000) 201-205.
- 7 Sultan S A R & Elghribi N M, Sea level changes in the central part of the Red Sea, *Indian J. Mar. Sci.*, 32 (2003) 114-122.
- 8 Das P K & Radhakrishna M, An analysis of Indian tide-gauge records, *Proc Indian Acad Sci (Earth Planet Sci)*, 100 (1991) 177-194.
- 9 Das P K & Radhakrishna M, Trends and the pole tide in Indian tide gauge records, *Proc Indian Acad Sci (Earth Planet Sci)*, 102 (1993) 175-183.
- 10 Indira N K, Singh R N & Yajnik K S, Fractal analysis of sea level variations in coastal regions of India, *Curr Sci*, 70 (1996) 719-723.
- 11 Shankar D, Seasonal cycle of sea level and currents along the coast of India, *Curr Sci*, 78 (2000) 279-288.
- 12 Srinivas K, Revichandran C & Dinesh Kumar P K, Statistical forecasting of met-ocean parameters in the Cochin estuarine system, southwest coast of India, *Indian J. Mar. Sci.*, 32 (2003) 285-293.

- 13 Dyer K R, Response of estuaries to climate change, in *Climate change: Impact on coastal habitation*, edited by D. Eisma, (Lewis Publishers, London) 1995, pp. 85-110.
- 14 Psuty N P, Estuarine dynamics and global change, in *Coastal ocean space utilization III*, edited by N D Croce, S Connell & R Abel, (Chapman and Hall, London) 1995, pp. 213-222.
- 15 Houghton J T, Ding Y, Griggs D J, Noguer M, Van der Linden P J, Dai X, Maskell K & Johnson C A, *Climate Change 2001: The scientific basis* (Cambridge University Press, Cambridge) 2001, pp. 881.
- 16 Woodworth P L & Player R, The permanent service for mean sea level: an update to the 21st century, *J. Coastal Res.*, 19 (2003) 287-295.
- 17 Mendenhall W & Reinmuth J E, *Statistics for management and economics*, (Duxbury Press, Massachusetts) 1978, pp. 789.
- 18 Cooper R A & Weekes A J, *Data, models and statistical analysis*, (Heritage Publishers, New Delhi) 1988, pp. 400.
- 19 Emery W J & Thomson R E, *Data analysis methods in physical oceanography*, (Pergamon Press, London) 1998, pp. 634.
- 20 Srinivas K, Seasonal and interannual variability of sea level and associated surface meteorological parameters at Cochin, Ph.D. thesis, Cochin University of Science and Technology, India, 1999.