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Coherence between interannual variability of sea level with some surface met-ocean parameters at Cochin, southwest coast of India

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The interannual coherence of some surface met-ocean parameters (viz. SST, air temperature, atmospheric pressure, scalar wind speed, cross-shore and along-shore wind stress, rainfall and relative density) with observed sea level has been studied for Cochin (southwest coast of India) using long term time series data. Among the parameters, SST, relative density and sea level showed statistically significant long term trends. All the parameters, when smoothed, showed statistically significant correlations with the observed sea level. Forty percent of the variance in the sea level was accounted for by the along-shore wind stress.

[**Key words**: Sea level, coherence, interannual variability, Cochin]

Induced by a number of factors - meteorological, oceanographic, hydrological, astronomical and geological, the sea level demonstrates considerable variability on different time scales. Meteorological, oceanographic and hydrological processes produce a large fraction of the seasonal and interannual variability in sea level records. For some stations, the seasonal and interannual effects of winds on sea level may be more significant than the direct atmospheric pressure effect. In estuarine regions, the annual and interannual cycles of sea level may be significantly affected by fresh-water flow. Monitoring of interannual sea level changes can be used to describe ocean dynamics.

The seasonal variability of sea level and the associated surface met-ocean parameters at Cochin were studied earlier[1]. The seasonal variance (%) contained in the entire series was SST (71.3), air temperature (82.8), atmospheric pressure (75.4), scalar wind (40.6), cross-shore wind (33.7), along-shore wind (62.1), rainfall (72.7), relative density (83.5) and observed sea level (64.4). The same series have been used in the present study also. The interannual variability was maximum in the case of winds (cross-shore, scalar and along-shore winds) followed by sea level.

The aim of the present study is to highlight the interannual coherence of sea level and associated oceanographic and surface meteorological parameters, using long term time series observations collected at Cochin, southwest coast of India (Fig. 1). This is to determine the important met-ocean parameters that drive the interannual sea level at this station. The long term trends of the met-ocean parameters are also discussed.

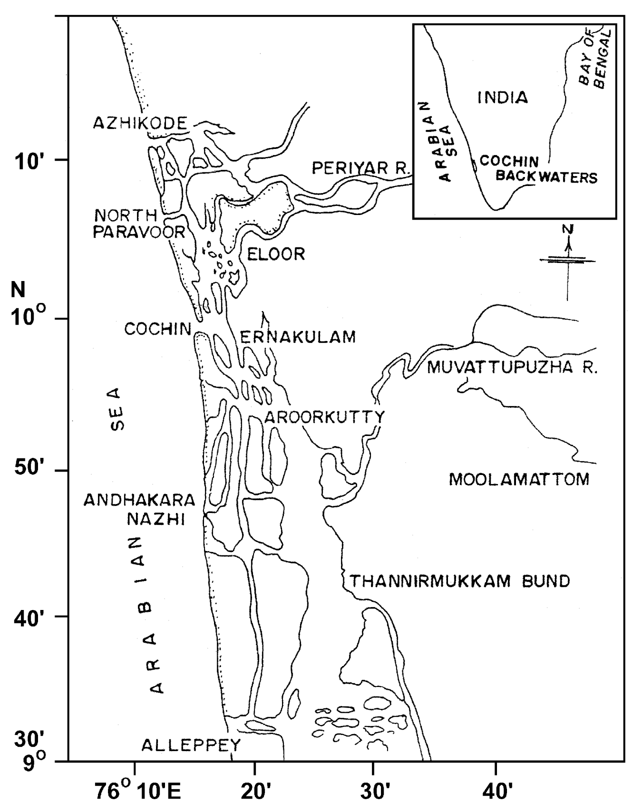

Fig. 1 — Location map

Materials and Methods

The meteorological and oceanographic data used for the present study are presented in Table 1. The study covered the period of 1976-1993 for all the parameters, excepting for the two parameters of wind (1981-1993) and SST (1976-1988). The wind data at three hourly intervals (0230, 0530, ...2330 hrs) were collected from the Naval Air Station, Cochin, while the data on parameters: SST, relative density and sea level were from the Marine Surveyor's Office, Cochin Port Trust, Cochin and air temperature, atmospheric pressure and rainfall from the Indian Daily Weather Reports. Other observations on parameters SST, air temperature, atmospheric pressure and relative density were taken at 0830 hrs, while that on atmospheric pressure was additionally taken at 1730 hrs also. The rainfall data is the total ending for 24 hours at 0830 hrs on the day of observation. The sea level data at hourly intervals was obtained from the Marine Surveyor's Office, Cochin Port Trust, Cochin. The sea level values utilised in this study are the observed sea level values, which are not corrected for atmospheric pressure. The data utilised for winds and relative density in this study are the transformed ones as explained below.

The data on wind speed and direction were used to resolve the cross-shore and along-shore components of wind stress along 339° angle with respect to the north (to conform to the general orientation of the coastline along the southwest coast of India). The wind convention followed is such that onshore and poleward wind are taken as positive, and offshore and equatorward wind as negative[2].

Long continuous time series data on subsurface temperature and salinity (to compute steric sea levels) are not available off Cochin. Hence, hydrometer determined relative density data have been used. These data, which are collected from the surface waters, have certain limitations, and defined as follows for computational ease:

Relative density = (observed relative density – 1.0)*1000

In the description of the seasonal cycle of the parameters, long term monthly means (climatological means) were generated for a month, utilising all the data available for the month from the hourly, three hourly, daily or twice daily observations. For the rainfall, monthly totals were considered. The normal monthly value (also referred to as climatological mean or mean monthly value) for a particular month at a location, was obtained by averaging the monthly mean values pertaining to that month for the period covered by the study. The monthly departures from the mean seasonal cycle is referred to as anomaly. Their use is essential to prevent spurious but significant correlation between two variables, which may lack a causal connection but undergo similar seasonal cycles.

Two approaches have been made to study the interannual correlation between sea level and associated met-ocean parameters. In the first case, the monthly anomalies were generated giving the nonseasonal time series and then the data were detrended to remove the secular trends. These data were then correlated with the sea level, and these results are discussed under unsmoothed data. In the second approach, the correlations between sea level and various elements were determined, after the deseasonalised and detrended data were smoothed with a 13 point moving average. This procedure involves a loss of 12 data points but helps to remove short period fluctuations in the time series and brings out prominent relationships between the two parameters. These results are discussed under smoothed data.

Table 1 — Details of the oceanographic and surface meteorological data collected at Cochin (1976-1993)

	Parameter	Period		Accuracy
		Start	End	
1	SST	1976	1988	0.1 °C
2	Air temperature	1976	1993	0.1°C
3	Atmospheric pressure	1976	1993	0.1 mb
4 a)	Wind speed	1982	1993	0.5 kt
b)	Wind direction	1982	1993	5.0 °
5	Rainfall	1976	1993	1.0 mm
6	Relative density	1976	1993	0.001
7	Sea level	1976	1993	2.0 cm

Results and Discussion

Unsmoothed data

Among the 9 parameters analysed, only SST, relative density and observed sea level showed significant (at 99% confidence level) linear trends with time. The SST trend was approximately 0.04°C per year. SST at well exposed sites are unaffected by the urban growth factor and are, in general, better indicators of heating and cooling trends than air temperatures[3]. The relative density showed a statistically significant increase of

0.12 units per year, suggesting that salinity is also showing an increasing trend. Further, rainfall did not show any signifcant trend for the 18 year period. The coastal water might be having a more dominating influence on the relative density at the mouth of the estuary. This has been reported elsewhere[4]. Quantifying the causes and consequences of long-term trends in salinity is a diffcult problem.

The sea level trend at Cochin is + 0.16 cm/year for the 18 year period. Sea level records indicate the differential motion between land and the sea. A rise in the recorded sea level can thus be interpreted either as increasing water level or subsiding land surface, or a combination of both. The sea level trends for a given station are not constant, but vary with time, making it difficult to assign a representative value. Based on tide gauge records, the estimates of global mean sea level change during the last 100 years indicate a rate of rise of about 0.1-0.2 cm/yr[3]. Factors contributing to the trends include vertical land motions (natural and anthropogenic); coupled atmospheric and oceanographic effects (winds, waves, currents, ocean temperature and salinity). An important anthropogenic effect which could be included in this category, is related to temperature. Because of the global warming due to greenhouse effect, thermal expansion of seawater is taking place causing sea level to rise[3]. The variance explained by the trend for SST, relative density and observed sea level were, however, not very high (6,4 and 3%, respectively).

The interannual correlations between the various met-ocean parameters and sea level are presented in Table 2. The fitted regression line between the SST and observed sea level gave a slope of 1.39 cm/°C. This positive association between sea level and SST, is in accordance with some of the earlier results reported at some other locations[5]. The data on air temperature revealed no significant relationship with the observed sea level. The random variations are larger in the air temperature than in the SST. The correlation between SST and air temperature was, however, significant and positive explaining about 18% of the variance of air temperature. Similar findings have been reported elsewhere[6].

The fitted regression line between the observed sea level and the atmospheric pressure gave a slope of -1.52 cm mb^{-1} (Table 2). The theoretical "inverted barometer" response is -1 cm mb^{-1}. The difference between the perfect "inverted barometer" response from the observed may be due to the winds which are correlated with atmospheric pressures[7]. The more random changes may also be due to interannual oceanographic changes.

The regression of scalar wind on the observed sea level gave a regression coefficient of -3.19 cm /m/s. This could be due to enhanced evaporation associated with increased wind speed. The cross-shore wind stress reveals that with an onshore increase of wind stress of 1 dyne/cm^2, the sea level rises by 96 cm which is to be expected because of land boundary

Table 2 — Regression coefficients of the unsmoothed nonseasonal data on various oceanographic and surface meteorological parameters against observed sea level at Cochin

Parameter	Number of months	Regression coefficient	Correlation coefficient	Percentage variance explained by the relationship
SST	156	1.39	0.17*	2.89
Air temp.	216	–04	–0.01^{ns}	0.01
Atmos. press.	216	–1.52	–0.24**	5.76
Scalar wind	144	–3.19	–0.23**	5.29
Cross-shore wind stress	144	95.93	0.26**	6.76
Along-shore wind stress	144	119.58	0.41**	16.81
Rainfall	216	0.10	0.34**	11.56
Relative density	216	–0.34	–0.23**	5.29

* – Significant at 95% level
** – Significant at 99% level
ns – Not significant

(piling up) and *vice versa*. The along-shore wind stress, on the other hand, reveals that with an increase of poleward wind stress of 1 dyne/cm^2, the sea level rises by 120 cm. With equatorward wind, the effect will be opposite. This result for the along-shore component of wind is in good agreement with Ekman dynamics in the Northern Hemisphere[8]. The most offshore transport of surface water and hence the most upwelling, occurs in response to along-shore equatorward winds, not offshore winds[9]. This probably explains the higher regression coefficients for the along-shore wind than the offshore wind, in their relationship with sea level. Such a relationship has already been reported[10]. Many workers have suggested that the along-shore winds cause upwelling or downwelling depending on the hemisphere (set-down or set-up of coastal sea level) and this effect can be opposite in sign to the pressure effects on sea level[11]. The annual range of along-shore wind stress is 0.2 dyne/cm^2 at Cochin[12]. This is in contrast to that along the east coast (Visakhapatnam has an annual range of 2 dyne/cm^2). These observations are based on open ocean data. In the present study, the wind data are from a land based observatory and hence the stress values are much lower because of frictional effects. The standard deviations of the along-shore wind stress for the mean seasonal cycle, observed and anomaly time series are 0.01354, 0.01968 and 0.01428 dyne/cm^2, respectively. As the numerical values of the observed wind stress are small, the residuals (i.e. anomalies) are still smaller. Further, the seasonal signal component in the cross-shore and along-shore wind stress time series was 25.4 and 47.3%, respectively, suggesting strong interannual variability.

The regression of rainfall on non-seasonal observed sea level showed that for an increase of 1 cm of rainfall, increase in sea level is 0.10 cm. The interdecadal changes in sea level at Bombay was shown to mimic rainfall over the Indian subcontinent[13].

The regression of data on relative density with the observed sea level revealed that with an increase of

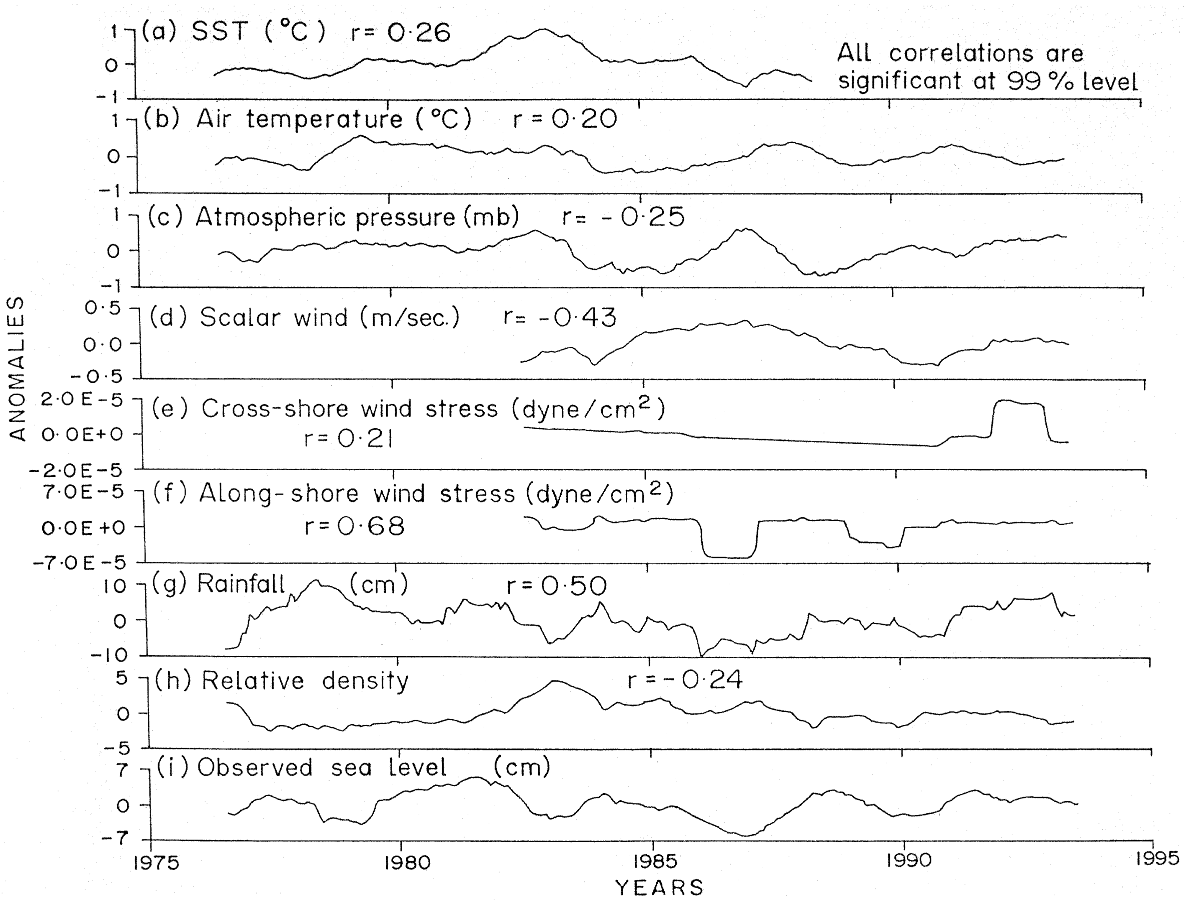

Fig. 2 — Detrended monthly anomalies of different parameters smoothed with a 13-point moving average. The correlation coefficients between the observed sea level and the parameters are also shown

1 unit in the relative density, the sea level depresses by 0.34 cm. This is to be expected as denser waters depress the water level[5].

Seasonally, the circulation off the southwest coast of India during the southwest monsoon (June-September), though weak, is dynamically similar to the wind-forced eastern boundary currents found elsewhere in the oceans[14]. These wind-induced changes in ocean circulation can significantly affect the eastern boundary sea level.

Smoothed data

The results of the correlation study between sea level and the met-ocean parameters are presented in Fig. 2. The relationship between the observed sea level and the air temperature, which was not found to be significant in the previous section on unsmoothed data, turned out to be important with the application of moving averages, pointing out that the original observed air temperature time series has a dominance of irregular variation. The cross-shore and along-shore wind stress components were responsible for 4.3% and 46.7% of the variance of the sea level. Figures 2e and 2f show jumps, because of the small numerical values involved, which are not seen for other parameters. The along-shore wind stress thus explains more than 10 times the variance explained by the cross-shore wind stress in its relationship with sea level. Since Cochin lies at a low latitude, relatively weak wind stress can still produce significant offshore transport[15]. The along-shore wind stress, followed by the rainfall, explained the maximum variance in their relationship with sea level.

The sea level shows a very good relationship with the along-shore wind stress. The statistical relationship between along-shore wind stress and SST, on the other hand, was found to be very poor. This could be due to the fact that the SST in the estuarine region is very much influenced by land effects (river discharge, heating and cooling of the land, etc.). In the regions dominated by upwelling processes, one would normally expect a drop in surface water temperature associated with the upwelling process. At a number of sites along the west coast of America, the along-shore wind stress was shown to have a dominating influence on the sea level as compared to that on the shore temperature[16].

Because large interannual and decadal basin wide fluctuations can overshadow the sea level rise signal in tide gauge data spanning less than 40 years, it is always advisable to use very long time series. The tropical asia tide gauge data show high decadal and interannual variability[17]. Additionally, very large differences in sea level variation exist for Indian guages over any common time interval[18]. The met-ocean data should be continuously collected on a routine basis at the coastal sites for a proper understanding of the mechanisms that drive seasonal and interannual variability of sea level.

The present study showed that the parameters SST, relative density and observed sea level have significant long term trends. The influence of along-shore wind stress was particularly strong on the sea level.

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