

Atmospheric forcing on the seasonal variability of sea level at Cochin, southwest coast of India

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Abstract

The seasonal cycles of some atmospheric parameters at Cochin (southwest coast of India) have been studied with a specific emphasis on the role played by them in forcing the seasonal sea level. Equatorward along-shore wind stress as well as equatorward volume transport by coastal currents along the Indian peninsula could play an important role in the sea level low during the premonsoon and southwest monsoon seasons. During postmonsoon season, along-shore wind stress plays no major role in the high sea level whereas this could be due to the poleward volume transport by the coastal along-shore currents. Atmospheric pressure and river discharge do not seem to influence much the sea level during the southwest monsoon period, even though the river discharge during that period is considerable. The sea level was minimal during the southwest monsoon season, when the river discharge was at its annual maximum. The difference between the seasonal march of observed and pressure corrected sea level (CSL) was not significant for the study region. Harmonic analysis of the climatological data on the various parameters revealed that air temperature is the only parameter with a dominance of the semi-annual over the annual cycle. Cross-shore wind stress indicated strong interannual variability whereas relative density showed strong seasonal variability. The climatological seasonal cycles of CSL at eight other tide gauge stations along the west coast of the Indian subcontinent are also examined, to assess the role of various forcings on the seasonal sea level cycle.

The signatures of El Nino-Southern Oscillation (ENSO) phenomenon could be seen in some of the parameters (SST, air temperature, atmospheric pressure, along-shore wind stress, relative density and sea level). The signature of ENSO was particularly strong in the case of atmospheric pressure followed by relative density, the variance accounted by the relationship being 47 and 16%, respectively.

Keywords: Atmospheric forcing; Sea level, Seasonal and long term variability; ENSO; Southwest coast of India

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1. Introduction

Seasonal sea level variability results from oceanographic, meteorological and hydrological forcings (Tsimplis and Woodworth, 1994). The contribution to the monthly mean sea level by astronomical tides is minimal - hardly 1cm (Shankar, 2000) and the three processes mentioned above are responsible for a large fraction of the seasonal and interannual variability seen in sea level records. The largest seasonal signals of sea level are, however, primarily caused by hydrological forcings (Tsimplis and Woodworth, 1994). Since seasonal signals are the most prominent ones (after excluding the semi-diurnal and diurnal tides), it is essential to understand them, before attempting to study other signals evident in the sea level records, e.g. intraseasonal, interannual, interdecadal oscillations. Though the range of the seasonal cycle of sea level is much smaller than that due to tides, the related movement of the thermocline is important - a rise in sea level being associated with a fall of the thermocline and *vice-versa* (Shankar, 2000). Observations and knowledge on the oceanographic and meteorological factors is still sparse for the tide gauge stations situated along the coastline of the Indian subcontinent (Shankar, 2000; Srinivas et al., 2005a,b), even though the sea level records of more than half century duration are available at a few of these locations. The Bombay (Mumbai) sea level record is more than a century long and is one of the longest records available in the world.

The aim of the present study is to describe the observed variability of some atmospheric parameters and to have an insight into the role played by a few of them in driving the seasonal variability of sea level, using long time series data available for the region. The interannual variability is also examined very briefly as this aspect has been described in detail, earlier (Srinivas, 2002).

Cochin is situated along the southwest coast of India, at about 300 km north of Cape Comorin - the southernmost point of the Indian Peninsula (Fig. 1). Hailed as the 'Queen of Arabian Sea', it is the biggest city along the west coast of India after Bombay and functions as a nerve center for distribution of goods due to its proximity to Cochin port. The port facilities are located at the mouth of Cochin backwaters, which forms part of a bar built estuary. Six rivers discharge into the estuarine system, the more important ones being the Periyar and Muvattupuzha. The tide gauge (9° 58'N; 76° 15'E) is

located at the mouth of the estuary. The study region comes under the influence of the seasonally varying monsoon circulations associated with the annual heating and cooling of the Asian continent. The monsoons (south-west during the summer and north-east during the winter, according to the direction of low level wind flow) are primarily caused by the differential heating between the continental areas and the oceans as a result of the zenithal march of the sun. Several studies were carried out on sea level variability at Cochin in various contexts ranging from long period waves to climate change issues (Banse, 1968; Sharma, 1978; Shetye and Almeida, 1985; Emery and Aubrey, 1989; Shetye et al., 1990; Longhurst and Wooster, 1990; Das and Radhakrishna, 1991; Clarke and Liu, 1994; Shankar and Shetye, 1997; Shankar and Shetye, 1999; Shankar, 2000; Shankar and Shetye, 2001; Srinivas, 2002; Srinivas et al., 2003 a,b; Srinivas et al., 2005 a,b).

Some of the above mentioned studies more relevant to the present study are briefly discussed below. Das & Radhakrishna (1991) analysed the sea level records at Bombay, Cochin, Madras and Visakhapatnam, concluding that all the stations show both long period (50-60 year period) and shorter period fluctuations (4.5 to 5.7 year period). Clarke & Liu (1994) demonstrated that the atmospheric pressure corrected sea level is correlated along the northern Indian Ocean boundary. Shankar and Shetye (1997) suggested that the Lakshadweep High (centered around 10° N, 70 °E) as part of an annual cycle in which high sea level forms off the southwest coast of India during the northeast monsoon (and low sea level during the southwest monsoon) subsequently propagating offshore. Murtugudde & Busalacchi (1999) examined the sea level records at some stations along the Indian coastline, in their study on the interannual variability of the dynamics and thermodynamics of the tropical Indian Ocean, and the results are similar to that of Clarke & Liu (1994) with regard to the interannual sea level variability. Shankar and Shetye (1999) reported that interdecadal variability of sea level at Bombay closely followed the variability in rainfall over the Indian subcontinent. They hypothesized that the seasonal river outflows of the monsoon rainfall into the seas around India, and the dynamics of currents along the Indian coast, provide links between the rainfall over the Indian subcontinent and the sea level along the coast of

India, with coastal salinity playing an intermediate role. Shankar (2000) reported that the seasonal cycle of sea level along the Indian coast matches that of the observed along-shore coastal currents computed from ship drifts. Shankar and Shetye (2001) showed that the mean sea level along the coast of India is higher in the Bay of Bengal than in the Arabian Sea, the difference in sea level between Visakhapatnam and Bombay being about 30 cm. They concluded from their studies that the spatio-temporal asymmetries associated with the monsoon determine the sea level difference between the Bay of Bengal and Arabian Sea coasts of India, which they suggested could serve as an index of the impact of monsoon on the Indian Ocean. Srinivas (2002) examined the interannual coherence of some surface met-ocean parameters with observed sea level at Cochin, using long term time series data. Forty percent of the variance in the interannual sea level was accounted for by the along-shore wind stress.

Statistical modelling of the monthly mean sea level at fifteen different stations along the west and east coasts of the Indian subcontinent was attempted by Srinivas et al. (2005a) using autoregressive, sinusoidal and EWMA techniques. They also described in detail, statistics pertaining to the mean seasonal cycle as well as that of interannual variability at all the stations. A strong domination of the annual cycle over the semi-annual cycle was seen at ten stations. The seasonal cycle was reported to be complex and showed remarkable variability, even at closely spaced stations. This complexity was reported to be more conspicuous along the west coast than on the east coast.

Srinivas et al. (2005b) presented evidence for the signature of ENSO phenomenon at fifteen stations along the coastline of the Indian subcontinent. The relationship between sea level and SOI was found to be positive, with the sea level decreasing during El Nino years and increasing during La Nina years. The signature of ENSO was particularly conspicuous in the sea level records on the east coast as compared to those on the west coast. Reduced rainfall over the Indian subcontinent and resultant river discharge was suggested as a probable factor explaining the low sea level along the coastline of the Indian subcontinent during ENSO events. The interannual sea level along the coastline of the Indian subcontinent displayed a near

synchronous movement - the rise and fall was nearly simultaneous, indicating that at low frequency, spatial coherence of sea level could be very large.

2. Materials and methods

2.1. Data

Long-term data on atmospheric parameters, river discharge and sea level covering the period 1976-1993 were used for the present analysis, of which SST data was available for 1976-1988, wind data for 1981-1993 and river discharge data for 1986-1993. The three hourly wind data was collected from the Naval Air Station at Cochin, while the data on SST, relative density and sea level were collected from the Marine Surveyor's Office, Cochin Port Trust, Cochin. Air temperature, atmospheric pressure and rainfall data were obtained from the Indian Daily Weather Reports (India Meteorological Department, Pune). Observations on SST, air temperature, atmospheric pressure and relative density were taken at 0830 hrs, while atmospheric pressure was taken at 1730 hrs also. The rainfall data is the total for 24 hrs ending at 0830 hrs on the day of observation. The sea levels were digitized at hourly intervals from Marigrams, recorded by a stilling-well type tide gauge, and from these values monthly means were determined. The data utilized 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° with respect to the north (to conform to the general orientation of the coastline along the southwest coast of India). The onshore and poleward wind stress are taken as positive, and offshore and equatorward wind stress as negative (Hsu, 1988). Wind stress was computed following Pond and Pickard (1983). Discharge data of the six rivers have been taken from CUSAT (1999).

Good agreement between annual sea level changes and those computed from observed density changes in the water column at lower latitudes has been reported (Pugh, 1987). Long and continuous time series data on subsurface temperature and salinity (to compute steric sea levels) are not available for the coastal waters off Cochin. Hydrometer determined relative density data, to broadly understand the salinity variations, have been thus used in the present study. These data, which are collected

from the surface waters, have obvious limitations, and are defined here as follows for computational ease:

$$\text{Relative density} = (\text{observed relative density} - 1) * 1000$$

The observed relative density values range from 1.000 for fresh water and 1.026 for seawater.

In all the discussions on the seasonal cycle of the parameters, the long-term monthly means (climatological mean or mean monthly value) were used. For rainfall as well as river discharge, monthly totals were determined.

Pressure correction is applied to the observed sea level to account for the “inverted barometer effect” causing the sea level to decrease (increase) by about 1 cm for a corresponding increase (decrease) of 1 mb in atmospheric pressure. This correction factor becomes important to zones near to the limits of the tropics. The series corrected for sea level pressure (CSL) was generated by adding the equivalent of atmospheric pressure to the sea level (e.g. Clarke and Liu, 1994). The climatological seasonal cycles of CSL at eight other stations along the west coast of the Indian subcontinent are also examined to appreciate how well they agree with that at Cochin, using sea level data sets from the Permanent Service for Mean Sea Level (PSMSL), United Kingdom (Srinivas, 1999). The roles of various forcings on the seasonal cycle of sea level at these stations are also briefly explained.

2.2. *Harmonic analysis of the seasonal cycle*

Seasonality of any parameter is better understood through a fit of the data to annual and semi-annual harmonics. For climate monitoring purposes, the sub-seasonal (annual and semi-annual) periods give most of the information. The seasonal cycle of the mean sea level at any tide gauge station can be described as the sum of several harmonics - annual, semi-annual and ter-annual (Emery and Thomson, 1998). Harmonic analysis was, therefore, carried out for determining the annual, semi-annual and ter-annual cycle parameters (amplitude and phase) of the mean seasonal cycle for sea level as well as the other atmospheric parameters. This was done for the climatological data as well as for the individual years, to appreciate the interannual

variability in the three cycles, for the sea level and other parameters (Tsimplis and Woodworth, 1994; Bell and Goring, 1998).

2.3. *Long-term seasonal variability*

A major component of the climate of the Indian subcontinent is the summer monsoon, which is linked to global climate through planetary scale processes in the atmosphere and ocean. To appreciate the seasonal variations, the data collected were categorized into three seasons, each comprising a four-month period, *viz.* premonsoon (February-May), summer or southwest monsoon (June-September) and postmonsoon (October-January). This categorization of the seasons is in accordance with earlier studies reported for the region (Menon et al., 2000).

2.4. *Seasonal versus interannual variability*

Measures of seasonal and interannual variability are provided by standard deviations of the parameter of interest (Servain et al., 1985). An estimate of the seasonal variability is the standard deviation of the 12 months of the mean seasonal cycle. The month-wise departure from the mean seasonal cycle is referred to as anomaly (Sultan et al., 1995a; Bell and Goring, 1998). The standard deviation of the monthly anomalies for the entire series is a measure of the interannual variability. This estimate of the interannual variability will take into account phase shifts of the mean seasonal cycle, amplitude changes in the seasonal cycle, and events dissociated from this cycle. The variance of the original monthly time series and that of the anomalies are used to calculate the percentage of variance accounted by the seasonal signal in the entire time series (Sultan et al., 1995a).

2.5. *Interannual correlations of the parameters with ENSO*

The SOI series used here is the standardized pressure difference between Tahiti and Darwin (International Research Institute for Climate Prediction, USA). The extreme values of SOI have received attention because of association of strong negative values with the occurrence of El Nino events and strong positive values with La Nina events. During the period of the study, the highest negative value of 4.6 (El Nino) occurred during February, 1983.

Before examining the statistical correlation between the parameters with SOI, the data were subjected to techniques like deseasonalisation, detrending and smoothing. The SOI data were detrended and smoothed with a 13 point moving average whereas the other parameters were first deseasonalised, detrended and subsequently smoothed with a 13 point moving average. The smoothing involves a loss of 12 data points but helps to remove short period fluctuations in the time series and brings out the underlying relationships prominently between the two parameters. The deseasonalisation is essential to prevent spurious but significant correlation between two variables, which may lack a causal connection but undergo similar seasonal cycles.

3. Results and discussion

3.1 Seasonal march of the parameters

The seasonal march of the various atmospheric parameters as well as that of their standard deviations, to understand the interannual variability during the study period are presented [Figs. 2-4]. Totals for each month were used in the case of rainfall and river discharge whereas for the rest of the parameters monthly means were used.

Sea surface temperature (SST) showed a bimodal pattern with the primary maximum in April (30.9 °C) and primary minimum in August (27.8 °C), thus showing a range of 3.1 °C [Fig. 2(A)]. The high temperature during April could be due to high incident solar radiation and low surface heat losses in the premonsoon period. The relatively intense premonsoon heating causes very high sea surface temperatures (SST > 30 °C) in the eastern Arabian Sea, being part of the Indian Ocean Warm Pool (Sanilkumar et. al., 2004). Based on observations off Cochin, Hareeshkumar et al. (1996) reported very high magnitudes and diurnal ranges of SST, with episodic increase during April and May/June. The low values seen in the present study for the summer monsoon period could be due to coastal upwelling, overcast skies, evaporation and rainfall, which is consistent with some of the earlier studies (Muraleedharan et al., 1995). The maximum interannual variability was observed during May-June [Fig. 2(B)]. The summer monsoon is a variable phenomenon – the date of onset and withdrawal of the summer monsoon (June-September) over Kerala varies from year to year.

Similarly, the quantum of rainfall over the Indian subcontinent as well as its spatial distribution is also variable.

Seasonal march of air temperature too showed a bimodal pattern [Fig. 2(C)]. The maximum air temperature of 29.0 °C occurred during April, whereas the minimum of 24.8 °C during January. The primary maxima occurred during April and the secondary maxima during October. The primary minima occurred during January and the secondary minima during July, in accordance with the earlier observations for the region (Ananthakrishnan et al., 1979; Rameshkumar and Ananthakrishnan, 1986). The rise from January to April and the subsequent drop from April to July were quite sharp. The sharp drop from April to July could be attributed to the summer monsoonal effects (such as overcast skies, high rainfall as well as high winds). The correlation between the SST and air temperature was positive and high, the percentage variance explained by the relationship being 82%. The drop from the premonsoon high to summer monsoon low is particularly sharp in the case of the air temperature as compared to SST. Another conspicuous difference is the appearance of the primary minima in SST during August as compared to that for the air temperature during January, attributable to the effects of upwelling, rainfall, etc. for the former and winter effects in the case of the latter. The maximum interannual variability [Fig. 2(D)] was during the onset time of the summer monsoon (May-June). The seasonal march of the standard deviations of the SST and that of the air temperature were similar, but for the conspicuously high values during May and June, for air temperature.

The seasonal march of the atmospheric pressure showed a concave pattern, with the least value during May and high values during the premonsoon and postmonsoon months [Fig. 2(E)]. The highest atmospheric pressure occurred during January (1013.4 mb) and the lowest during May (1009.3 mb), the range being 4.1 mb. The seasonal march of atmospheric pressure displayed a sharp drop from January to May, and a gradual increase from May to December. While the decrease is during the premonsoon period, the increase appears to be from the beginning of the summer monsoon to the end of postmonsoon period. This result is in agreement with the earlier observations (Ananthakrishnan et al., 1979; Rameshkumar and Ananthakrishnan,

1986). The large heat capacity of the water and the low heat capacity of the soil cause high thermal contrast in summer and winter between the Asia-Europe-Africa land complex on one hand and the Arabian Sea-Bay of Bengal-West Pacific Ocean water complex on the other, causing this seasonal variability (Ananthakrishnan et al., 1979). The seasonal cycle of atmospheric pressure at a number of coastal tide gauge stations along the Indian subcontinent was seen to be remarkably consistent, with a concave shape, the low appearing during the summer monsoon season (Srinivas, 1999). However, the amplitude of the annual harmonic showed a systematic increase towards north. Srinivas et al. (2005b) based on atmospheric pressure data at Bombay (1878-1988), showed that the interannual signal was minimal, hardly 7% whereas the seasonal variance was responsible for about 93% of the entire time series. The maximum interannual variability in the present study was observed during February whereas the other months did not show much variation [Fig. 2(F)].

The seasonal march of the wind speed showed a convex shape with high values during April - September [Fig. 2(G)]. The increase from January to April was sharp as compared to the drop from September to December, the maximum value of about 2.5 m/s occurred during April and the lowest value of 1.6 m/s during November, thus showing an annual range of 0.9 m/s. Observed wind speed was reported to have varied between 2 and 10 m/s (with mean 3.5 m/s), at Cochin beach during the southwest monsoon period of 1986 (Sarma et al., 1992). The high values observed by them could probably be due to the proximity to the sea, with minimal frictional effects. The general low-level airflow is directed from the sea to land during summer monsoon months and from land to sea during winter monsoon (November- February) months. The southwest monsoon winds are strong (10-12 m/s), humid and are of maritime origin whereas the northeast monsoon winds are weak (2-4 m/s), dry, cool and of continental origin (Prasanna Kumar and Prasad, 1999). The inverse relationship between the atmospheric pressure and the wind speed is clearly evident from the seasonal march of the two parameters. The maximum interannual variability was observed during the summer monsoon months as well as during December [Fig. 2(H)]. The high variability during the southwest monsoon season must be due to the interannual variability in the

onset and withdrawal of the summer monsoon over the Indian subcontinent, as previously suggested for SST, air temperature and atmospheric pressure.

The cross-shore and along-shore wind stresses vary within a very narrow range (hardly 0.1 dyne/cm^2). Seasonal march of the cross-shore wind stress showed a largely convex shape [Fig. 3(A)]. The maximum westerly value occurred in June (0.0232 dyne/cm^2) and the minimum during December (0.0010 dyne/cm^2) thus giving an annual range of 0.0222 dyne/cm^2 . The cross-shore wind stress was directed onshore throughout the year, which matches well with the earlier findings (e.g. SHARMA, 1978). The interannual variability was seen as a conspicuous maximum during June [Fig. 3(B)].

The along-shore wind stress showed a concave shape with a decrease during June [Fig. 3(C)]. The along-shore component was northerly throughout the year. The minimum along-shore stress was $-0.0009 \text{ dyne/cm}^2$ during November and maximum during August ($-0.0432 \text{ dyne/cm}^2$). The change from August to November was quite sharp. Near the Kerala coast, there is an equatorward component of wind stress throughout the year (Shetye et al., 1985; Muraleedharan et al., 1995). Shetye et al. (1985) and Muraleedharan et al. (1995) also reported that the monthly mean along-shore component of wind stress throughout the year is directed equatorward, along the west coast of India. Based on climatological data, Muraleedharan et al. (1995) also reported that the wind stress is high during August and low during November off Cochin. Though the present results are in good agreement with the above studies, with regard to the annual march, the values are found to be an order of magnitude higher than that reported here. This could be due to the fact that frictional effects could be higher in the data reported in the present study, as they are land based whereas the former are sea based.

Though the winds blow predominantly from the southwest direction during the southwest monsoon and northeast direction during the postmonsoon over the north Indian Ocean as a whole, significant variations have been reported in the orientation of the winds from these directions from location to location (Shetye et al., 1985). The maximum interannual variability was observed during July-August (southwest monsoon) and the least during the postmonsoon period of November-January [Fig. (3D)].

Seasonal variations of the along-shore and cross-shore winds are interlinked with the seasonal variations in the pressure distribution, which in turn, are coupled with the temperature field. In general, the seasonal variation of these parameters is less in southern latitudes as compared to northern latitudes (Ananthakrishnan et al., 1979; Srinivas, 1999).

Seasonal cycle of rainfall showed a bimodal pattern with a sharp rise from April to June, which gradually dropped to September [Fig. (3E)]. The primary peak occurred during June and the secondary peak during October. The maximum rainfall of 83 cm was recorded during June (beginning of the summer monsoon season), whereas the minimum of 2 cm was recorded in January (end of the postmonsoon season). In the present study, southwest monsoon months accounted for as much as 68% of the annual total, which is in conformity with the earlier results (Ananthakrishnan et al., 1979; Rameshkumar and Ananthakrishnan, 1986). The Western Ghats at the eastern boundary of southwest coast of India, which have an average elevation of 1 km, provide orographic lifting of the southwest monsoon winds, resulting in heavy precipitation over the western slopes as well as the midlands and lowlands. The Western Ghats (Sahyadri Hills), are formed by the Malabar Plains and the chain of mountains running parallel to India's western coast, about 30 to 50 kilometers inland. They cover an area of about 160,000 km² and stretch for 1,600 kilometers from the country's southern tip to Gujarat in the north, interrupted only by the Palghat Gap (30 kilometers). The maximum interannual variability of the rainfall was during the summer monsoon months, for reasons already mentioned [Fig. (3F)].

The relative density was more or less constant at 20 units during the premonsoon season [Fig. (3G)]. A sharp drop of 19 units from April to July with a gradual rise till December was observed. The seasonal cycle of rainfall and relative density showed an inverse relationship. However, the lowest value is noted during July, for relative density. May-June are the months of maximum interannual variability and July the least [Fig. 3H].

The premonsoon season is a period of minimal river discharge whereas the southwest monsoon season displays the maximum river discharge, followed by a weak

secondary maxima during October-November [Fig. 4 (A)]. The maximum interannual variability is seen during June-July and the minimum interannual variability during the premonsoon season [Fig. (4B)]. Rainfall and the associated river discharge induce a sudden decrease in the relative density with the onset of the southwest monsoon rains and hence low values occurred during the southwest monsoon season. In estuarine and coastal waters, salinity is the dominant factor in controlling density, while temperature variations are of secondary importance (Pickard and Emery, 1982). River discharge, generally, has a pronounced seasonal variation, which gives rise to large seasonal fluctuations of salinity in coastal waters than seen in the open ocean. The direct effect of river discharge is to reduce the salinity of the surface layers, and even of the deeper waters, if there is sufficient vertical mixing.

The seasonal march of the observed sea level and CSL showed a concave shape [Fig. (4C)], the maximum sea level occurring during postmonsoon and the minimum during summer monsoon periods. There is no significant difference between the seasonal march of the observed sea level and CSL, thus pointing out that the 'inverted barometer effect' is not an important factor for the seasonal time scales at Cochin. However, the corrected sea level is lower than the measured sea level during the southwest monsoon and higher during premonsoon and postmonsoon seasons. The range, however, is marginally higher in the case of the CSL (20.1 cm) as compared to the observed sea level (17.9 cm). The seasonal changes observed in the corrected sea level could be due to two factors, such as wind driven coastal currents and thermohaline effects (Shankar, 2000). The interannual variability of CSL for each month is presented in Figure 4(D) and the maximum interannual variability is during the November – December period. Srinivas et al. (2005a) reported that the interannual variability is maximum during these periods for most of the tide gauge stations along the east coast of the Indian subcontinent. However, at Cochin, the summer monsoon months also exhibited a high degree of interannual variability.

In a recent study, de-tided sea level data for Cochin were examined (Ramaiah et al., 2005) and the results showed that de-tided sea level reached its minimum during September, which is in agreement with the present as well as other earlier studies (e.g., Shankar, 2000; Srinivas et al., 2005a). The observed low in sea level implies that in the

region, thermocline is shallow and mixing by bursts of wind can bring up high quantities of nutrients to the surface waters leading to the formation of blooms (Ramaiah et al., 2005).

The climatological data on currents are for the period 1854-1974 for a $2^{\circ} \times 2^{\circ}$ grid off Cochin (Cutler and Swallow, 1984). The seasonal cycle of the coastal along-shore current [Fig. 4(E)] shows a concave shape with the direction of currents being southerly during the premonsoon and southwest monsoon seasons whereas during the postmonsoon season, it is northerly. Eventhough the current displays a gradual equatorward increase from around February to August, the change in direction to the northerly direction is relatively fast during the postmonsoon season. The currents during the premonsoon and summer monsoon seasons have a relatively strong wind forcing component whereas during the postmonsoon season, the currents flow in opposition to the large scale northeasterly winds suggesting that they are forced by thermohaline gradients. 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 (Madhupratap et al., 1994). These wind-induced changes in ocean circulation can significantly affect the eastern boundary sea level.

3.2. *Wind direction and steadiness*

To understand the nature of distribution of the wind direction, a frequency histogram of the wind direction was constructed [Fig. 4(F)]. The percentage of observations in the class interval 270° - 300° is 35.5%; for the class interval 300° - 330° , it is 17.2% thus 52.7% of the observations fall in the range 270° - 330° . From the frequency distribution, it appears that the Western Ghats have a profound influence on the wind direction. The most frequent wind direction is found to be more or less in agreement with the orientation of the Western Ghats, which is a major geographic feature along the west coast of India.

The steadiness parameter gives information on how steady the wind is with respect to its direction (Tolmazin, 1985; Rao et al., 1995). The seasonal cycle of this parameter displayed a convex shape, the highest value of 88% was recorded during

August and the lowest of 46% during December [Fig. 4(G)]. The steadiness of wind was maximum during southwest monsoon (81.0%), followed by premonsoon (73.5%) and least during postmonsoon (54.7%) seasons. More than the mean winds, steady winds are of importance in the context of upwelling, as it is a slow but steady process, and steadiness would be thus of importance during the summer monsoon period.

3.3. *Amplitudes of the climatological seasonal cycle*

The seasonal cycle parameters (amplitude and phase of the annual, semi-annual and ter-annual components) of the climatological mean data for the various elements are presented in Table 1. Air temperature is the only parameter that shows the dominance of the semi-annual cycle over the annual cycle. The contribution of the ter-annual cycle was more than 10% of the total variance for cross- and along-shore wind stresses, rainfall and river discharge. In all the cases, the first three cycles explained more than 94% of the total variance. The signal due to astronomical forcing contained in the hourly sea level data for each year, for the period 1988-1993, varied from 91%-95%, but for most of the years, it hovered around 95% (Srinivas et al., 2003b). The non-tidal signals that are of interest to ocean dynamics (i.e. oceanographical, meteorological and hydrological) are contained in the remaining 5%. Further, the O_1 , K_1 , M_2 and S_2 tidal amplitudes were found to be 9.3, 17.6, 20.4 and 7.5 cm, respectively. The amplitude of the annual harmonic of the observed sea level is about 8.5 cm and that of the semi-annual harmonic is 2.3 cm.

The seasonal amplitudes of the meteorological parameters at the southern stations in India were generally lower than the corresponding ones at the northern stations, particularly for air temperature, winds and atmospheric pressure whereas, it was higher for the rainfall (Ananthkrishnan et al., 1979).

3.4. *Year-to-year variability of the seasonal cycle amplitudes*

To assess the interannual variability of the seasonal cycle parameters, the seasonal data for the individual years were subjected to harmonic analysis (Table 2). The mean of the annual cycle amplitudes was found to be the largest, followed by the

semi-annual or ter-annual amplitudes (except for air temperature). The standard deviations of the annual cycle amplitudes were found to be greater than those of the semi-annual or ter-annual amplitudes for all the parameters. The coefficients of variation were higher for the ter-annual amplitudes, as compared to the annual or semi-annual amplitudes - except for relative density.

3.5. Long-term seasonal variability

For most of the parameters, the changes brought about by the summer monsoon season were conspicuous than those brought about by the premonsoon and postmonsoon seasons (Table 3). In general, the premonsoon and postmonsoon data showed high values as compared to the summer monsoon season (except for rainfall and river discharge). Wind speed during the summer monsoon showed intermediate values to those of during premonsoon and postmonsoon periods.

SST, air temperature, rainfall, relative density and river discharge showed sharp gradients from the premonsoon to summer monsoon season. Sharp gradients from summer monsoon to postmonsoon season were observed for atmospheric pressure, winds and CSL.

3.6. Seasonal versus interannual variability

The seasonal variances (%) contained in the entire time series, for the various parameters are presented in Table 4. It is clear that cross-shore wind stress showed the minimum (25.4%) and relative density, the maximum (83.5%) seasonal signals. Cross-shore wind stress followed by the scalar wind speed displayed strong interannual variability whereas relative density and air temperature displayed strong seasonal variability.

3.7. Seasonal relationships between the atmospheric parameters and sea level

Atmospheric pressure: The similar seasonal march of atmospheric pressure and observed sea level at Cochin suggest that seasonal sea level changes are not due to the 'inverted barometer effect'. Similar findings have been reported for other regions (Shetye and Almeida, 1985; Sultan and Ahmad, 2000).

Cross- and along-shore wind stresses: The cross-shore wind stress is directed onshore throughout the year, with increased values during the southwest monsoon months. However, during the southwest monsoon months, the CSL is the lowest, thus suggesting that the onshore winds have little influence on sea level. The along-shore wind stress is directed equatorward all the time (with low values during November-December). The seasonal march of the along-shore wind stress and CSL are similar, suggesting that the along-shore wind stress could drive the sea level variability, especially during the premonsoon and summer monsoon seasons. This is in accordance with Ekman dynamics. The most offshore transport of surface water and hence the most upwelling, occurs in response to along-shore equatorward winds, not offshore winds (Sultan et al., 1995b). The correlation coefficient between along-shore wind stress and CSL was 0.79, a significant statistical relationship, explaining 64% of the total variance. In the study region, relatively weak wind stress can produce significant offshore transport, because it lies at low latitude (Longhurst and Wooster, 1990). The strong relationship between along-shore wind and sea level has been reported elsewhere too (Pugh, 1987; Sultan et al., 1995b; Bell and Goring, 1998). On seasonal scales, atmospheric pressure does not force the sea level changes directly whereas the along-shore wind stress does. This relationship holds good even for fluctuations in sea level caused by transient weather phenomena e.g. storm surges (Sundar et al., 1999).

Shankar (2000) reported that the seasonal cycle of sea level along the Indian coast matches that of observed along-shore coastal currents computed from ship drifts. A comparison of sea level with the local along-shore winds, however, showed a mismatch, suggesting that remote forcing of the coastal circulation is important. In the present study, it was observed that during the postmonsoon season, the equatorward along-shore wind stress is the weakest, whereas the sea level is the highest. The annual range of along-shore wind stress was reported to be less than 0.2 dyne/cm^2 at Cochin, whereas along the east coast, the range was as high as 2 dyne/cm^2 at Viskhapatnam (Shankar, 2000).

The contribution of the “steric oscillations”, which are due to changes in specific volume, is an important factor contributing to the seasonal cycle of sea level at a coast.

The steric sea level is low (high) when the water is cold (warm), or has high (low) salinity. Coastal currents forced by winds cause changes in the local mass field by forcing coastal upwelling or downwelling, thereby influencing the steric level (Shankar, 2000). He also opined that the direct and indirect effects of weather, particularly the seasonal and interannual changes in wind and solar heating are the most important. Enfield and Allen (1980) showed in their study that over a common period, the shore temperature, followed by along-shore wind stress and pressure corrected sea level showed strong seasonal variability for a number of stations along the Pacific coast of America. In the present study, the seasonal signal component in the cross-shore and along-shore wind stress time series were less: 25.4 and 47.3%, respectively, thus suggesting strong interannual variability.

Shankar (2000) pointed out the mismatch between the strength of the local winds and the range of the seasonal sea level for the east coast of India. The range of along-shore wind stress is about 5-6 times that along the west coast, and the range of the seasonal sea level on the east coast is only about twice that on the west coast. The wind stress cycle at Colombo resembles that along the east coast of India, but the sea level cycle resembles that of Cochin.

River discharge: During the southwest monsoon (the period of maximum rainfall, about 68% of the total annual rainfall occurs), the sea level is the least. If the river discharge, indicative of the net rainfall for a much larger region is considered, a similar picture emerges – low sea level during the southwest monsoon season. Nearly 66% of the annual discharge of the six rivers of the region occurs during the southwest monsoon season. From premonsoon to southwest monsoon season, the river discharge increases from 418 to 3302 Mm³ (million meter cube) per month, whereas for the same period, the sea level drops by 8.7 cm. Similarly, from southwest monsoon to postmonsoon season, the river discharge decreases from 3302 to 1278 Mm³ per month, whereas the sea level increases by 14.6 cm. The average river discharge was 0.0002, 0.0013 and 0.0005 Mm³/s for the premonsoon, southwest monsoon and postmonsoon seasons, respectively. The volume transports off the southwest coast are: -5, -4 and +8 Mm³/s for the three seasons (Shankar, 2000). The freshwater discharge is very negligible compared to the volume transported by the West India Coastal Current. This

points out the dominating role of oceanographic phenomena over the hydrological phenomena in their influence on the seasonal march of sea level, at Cochin. However, the largest seasonal signals of sea level are primarily caused by hydrological forcings. In the Bay of Bengal, very large seasonal ranges in excess of 1m occur, due to seasonal monsoon effects and to changes in steric levels because of fresh water flow. Further, the low saline water brought to the southwest coast of India by the West India Coastal Current during the postmonsoon season from the Bay of Bengal, may play an important role in the convective activity in the southeast Arabian Sea, as they trap most of the heat during the primary heating season, leading ultimately to the formation of the warm pool (Rao and Sivakumar, 1999). The rise from the southwest monsoon low to postmonsoon high in CSL, which is more than 1.7 times the drop from premonsoon high to southwest monsoon low, will therefore be indicative of the intrusion of the Bay of Bengal waters into the eastern Arabian Sea (Table 3). River discharge could marginally add to the CSL during the postmonsoon season. Similarly, the drop from postmonsoon high to the following southwest monsoon low will be indicative of the intensity of upwelling that takes place off the eastern Arabian Sea. The sea level would have been lower had there not been river discharge effects during the summer monsoon season. However, the low sea level combined with the high river discharge could play an important role in flushing out pollutants from inside the Cochin estuary.

Coastal along-shore currents: A few studies e.g. Banse (1968), Shetye and Almeida (1985), Srinivas (1999) and Shankar (2000) established that reversals in the currents were clearly reflected in the sea level changes, suggesting that these records would be useful for long term monitoring of the surface geostrophic flow along the coastline of India. In the above studies, the data on alongshore currents were based on ship drift data. One of the major constraints for interannual studies on coastal along-shore currents is the lack of data on interannual time scales for locations off the tide gauge stations, for Indian locations. This is due to the concentration of ship drift data to shipping lanes only. It is thus not possible at present to include a long and continuous interannual time series for currents, as the information available for each month is sparse, but the available data is suitable for generating a mean climatology. However, as we are aware that they play an important role in the seasonal march of mean sea

level along the coastline of the Indian subcontinent, an attempt has been made to examine how well the seasonal cycle of coastal along-shore current matches that of the seasonal cycle of sea level [Fig. 4(E)]. The agreement between the currents and CSL is good, the percentage variance explained by the relationship being 64%.

The seasonal variance of coastal along-shore currents was found to be more on the east coast than on the west coast of the Indian subcontinent (Srinivas, 1999), indicating that the along-shore currents are more energetic along the east coast than 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 along-shore 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. The strong and energetic coastal currents along the east coast could be the reason for higher ranges in sea level observed along the east coast. The interannual variability in sea level also shows a complex nature along the west coast whereas along the east coast, the maximum interannual variability was consistently seen during November, due to the interannual variation in rainfall over the Indian subcontinent and associated river discharge during that month (Srinivas, 1999). The annual maximum in rainfall is also seen during that month for most of the southern stations along east coast of India (south of Visakhapatnam). In the present study, the seasonal cycles of along-shore wind stress and that of the coastal along-shore current at Cochin are positively correlated, with the percentage variance explained by the relationship being about 38%. However, it is to be emphasized that along-shore wind stress is an important forcing factor for the coastal currents during the southwest monsoon season, whereas during the postmonsoon season the coastal currents and the along-shore wind stress are in opposition, thus suggesting that the horizontal density gradients could be the main forcing during that time.

3.8. *How does the seasonal cycle of CSL at Cochin compare with that at other stations along the west coast of the Indian subcontinent*

To appreciate as to how well the seasonal cycle of CSL at Cochin matches with that at other stations along the west coast of the Indian subcontinent, the CSL data for

the nine stations (including Cochin) is presented in Figure 5. The Revised Local Reference (RLR) data of PSMSL, UK, which are accurate and suitable for time series analysis (Woodworth and Player, 2003) were utilised for this purpose (Table 5). The latitudinal distance on the west coast between the southernmost and northernmost stations (Cochin and Karachi) is 1650 km. The data on seasonal sea level have been corrected for the effects of atmospheric pressure, using climatological tables of meteorological data (Srinivas, 1999). Srinivas et al. (2005b) reported the interannual signal to be high (about 74%) in the entire observed monthly mean sea level time series, whereas the seasonal signal was responsible for about 26% of the variance, based on data at Bombay (1878 -1988). However, the atmospheric pressure time series at Bombay for the same period, showed a strong seasonal variability (93%) and very less interannual variability (7%), suggesting broadly that oceanographic conditions off Bombay show much larger interannual variability than the meteorological ones.

The standard deviations of the observed sea level and their anomalies 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 (Shankar, 2000; Srinivas et al., 2005a,b). Bhavnagar on the west coast has the highest seasonal and interannual variations, due to the freshwater discharge of the rivers Mahi and Narmada, and also due to its unique location, inside the Gulf of Cambay. 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 showed higher values at stations along the east coast than those along the west coast (Srinivas et al., 2005a,b).

From the CSL data presented for the nine stations, the general picture that emerges is that prolonged periods of low sea level dominate the region south of Bombay and north of Bombay the periods of low sea level coincide with the southwest monsoon season only. The first signals of marked low sea levels, indicating the process of upwelling are seen in the south (off Cochin) and off Pakistan, they are seen around July. The Gulf of Cambay is very much dominated by winter cooling processes (Prasanna Kumar and Prasad, 1999) because of the landlocked nature and shallow depths during the first quarter of the year and subsequently during July-October, the

hydrological forcing is dominant. The region beyond Bhavnagar also comes under the influence of winter cooling but the signal seen in the sea level is relatively weak. November-January period is dominated by conspicuously high sea levels suggesting signatures of the northward flowing West India Coastal Current, carrying low salinity waters of the Bay of Bengal. The marked high seen in sea level at Mangalore during July is due to the freshwater discharge of the Gurupur river, on the banks of which the Mangalore tide gauge is located. It has been suggested that estuarine regions will be significantly affected by fresh water flow in their annual cycle of sea level changes (Pugh, 1987). Even though the Cochin tide gauge is also located at the lower reaches of an estuary, with very high river discharge, the hydrological signal is not conspicuous.

3.9. *Long term trends and interannual cycles in the region*

Srinivas (2002) described the interannual correlation between the observed sea level and few met-ocean parameters at Cochin. A summary of their findings follows. 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 (Houghton et al., 2001).

The sea level trend at Cochin is +0.16 cm/year for the 18 year period, which is in agreement with the estimates of global mean sea level trends of about 0.1-0.2 cm/yr (Houghton et al., 2001). Factors contributing to the trends include vertical land motions and coupled atmospheric - oceanographic effects. 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 interannual correlation between SST and air temperature was, however, positive as reported elsewhere (Tont, 1989), explaining about 18% of the variance.

The fitted regression line between the observed sea level and the atmospheric pressure on interannual time scales, gave a slope of -1.52 cm mb^{-1} . 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 (Pugh, 1987).

The interannual data on along-shore wind stress revealed that with an increase of poleward wind stress, the sea level rises and *vice-versa*. This result for the along-shore component of wind is in good agreement with Ekman dynamics (Pugh, 1987). The deseasonalised, detrended and 13 month smoothed data on cross-shore and along-shore wind stress components were responsible for 4.3% and 46.7% of the variance of sea level. The statistical relationship between along-shore wind stress and SST was found to be very poor. This was attributed 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 (Enfield and Allen, 1980).

The data on SST, air temperature, atmospheric pressure and relative density showed a negative relationship with the SOI series which indicates that during the El Nino periods, the SST, air temperature, atmospheric pressure and the relative density increase (Fig. 6). The percentage of variance accounted by this relationship is about 47%, 16% and 9% for atmospheric pressure, relative density and SST, respectively. The along-shore wind stress and CSL showed a positive relationship with the SOI series. This means that during the El Nino periods, more equator wind stress and lower sea levels are to be expected. The anomalies observed at Cochin are thus larger than normal relative densities, air and sea surface temperatures, atmospheric pressures and lower sea levels during 1982-'83 as compared to 1981 and 1984

Many workers have examined the relationship between the rainfall over the Indian region and ENSO events (Rao, 1998). The general conclusion from these studies is that Indian monsoon rainfall and ENSO phenomenon are closely associated - the monsoon rainfall over India is poor during the years of El Nino occurrence. The influence of the Southern Oscillation on the surface meteorological fields (sea surface temperature, air temperature, winds, atmospheric pressure and cloud cover) over the Indian Ocean has been reported (Cadet, 1985). These studies cover data sets of 2 to 3 decades, but the major 1982-'83 event was not included.

4. Conclusions

The seasonal cycle of some atmospheric parameters have been studied with a specific emphasis on the role played by them in forcing the seasonal cycle of sea level at Cochin, along the southwest coast of India, using long-term time series data. Equatorward along-shore wind stress as well as equatorward alongshore currents were found to be important factors responsible for the drop in sea level during the southwest monsoon season, whereas during that period atmospheric pressure and river discharge do not seem to have much influence on the sea level. During postmonsoon season, along-shore wind stress does not play any major role and the high sea level is due to the poleward volume transport by coastal along-shore currents. The climatological seasonal cycles of CSL at eight other stations along the coastline of the Indian subcontinent were also examined, to appreciate as to how well they agree with that seen at Cochin, using PSMSL data sets. During El-Nino episodes we can expect higher than normal relative densities, air temperatures, sea surface temperatures, atmospheric pressures and lower sea levels.

Measurements made at a single point over a relatively long period of time could provide useful information about interactions between physical and biological parameters (Tont, 1981). It was reported that abundance of several species of diatoms respond to fluctuations in SST, air temperature, sea level and along-shore wind stress. An attempt on similar lines can be initiated at Cochin, the coastal waters of which have been witnessing phytoplankton blooms, seasonally.

To have a deeper insight into the extent of intrusion of Bay of Bengal waters into the eastern Arabian Sea, tide gauge data pertaining to Kavaratti (Lakshadweep Islands) would be useful. This data along with those on other meteorological and oceanographic ones, particularly the surface and subsurface temperature and salinity information (e.g. ARMEX program – Arabian Sea Monsoon Experiment), from vessels of opportunity (Cochin – Lakshadweep Islands) would be very helpful. Interannual data on currents (and associated oceanographic and meteorological data) from moored meters at surface and subsurface depths would also be very useful, e.g., the surface data available under the National Data Buoy Program.

An integrated study including hydrography, moored instruments and sea level (tide gauge as well as satellite) along with associated meteorological observations in the eastern Arabian Sea would be potentially of immense help, for a better understanding of the physical processes taking place in this region. This, in turn, would be useful for providing valuable insights into the onset of the summer monsoon, a very important parameter in the context of annual rainfall, on which the economy of the country ultimately rests.

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Table 1. Results of harmonic analysis of the atmospheric parameters and sea level (climatological means).

Parameter	1	2	3	4	5	6	7	8	9	10	11
SST (°C)	1976-1988 (13)	58	37	3	98	1.1	0.8	0.2	2.9	9.8	11.5
Air temperature (°C)	1976-1993 (18)	32	64	2	98	1.0	1.4	0.3	3.7	9.6	11.4
Atmospheric pressure (mb)	1976-1993 (18)	89	10	0	99	1.7	0.6	0.0	11.9	1.4	11.3
Scalar wind (m/s)	1982-1993 (12)	87	11	2	100	0.3	0.1	0.1	4.8	8.7	11.6
Cross-shore wind stress (dyne cm ⁻²)	1982-1993 (12)	79	5	10	94	0.0082	0.0021	0.0030	5.1	8.8	9.9
Along-shore wind stress (dyne cm ⁻²)	1982-1993 (12)	63	23	12	98	0.0152	0.0091	0.0067	11.6	11.2	9.6
Rainfall (cm)	1976-1993 (18)	74	11	12	97	30.7	12.0	12.2	6.7	11.8	9.8
Relative density	1976-1993 (18)	93	1	5	99	10.0	1.2	2.3	1.6	9.6	0.1
River discharge (Mm ³)	1986-1993 (8)	80	8	10	98	1746	539	616	7.4	0.5	10.2
CSL (cm)	1976-1993 (18)	93	4	1	98	10.1	2.1	1.3	0.5	11.6	10.6
Along-shore current (cm/s)	1854-1974 (121)	91	6	1	98	17.6	4.4	1.4	11.8	10.8	9.9

1. Period of the data (number of years)
2. Percentage contribution of the annual cycle to the total variance
3. Percentage contribution of the semi-annual cycle to the total variance
4. Percentage contribution of the ter-annual cycle to the total variance
5. Contribution of the three cycles to the total variance (%)
6. Amplitude of the annual cycle
7. Amplitude of the semi-annual cycle
8. Amplitude of the ter-annual cycle
9. Phase of the annual cycle: in months centered to mid-month
10. Phase of the semi-annual cycle: in months centered to mid-month
11. Phase of the ter-annual cycle: in months centered to mid-month

Table 2. Year-to-year variability of the seasonal cycle amplitudes for the atmospheric parameters and sea level at Cochin.

Parameter	Years	Annual			Semi-annual			Ter-annual		
		Mean	SD	CV	Mean	SD	CV	Mean	SD	CV
SST (°C)	13	1.1	0.3	27.3	0.9	0.2	22.2	0.3	0.2	66.7
Air temperature (°C)	18	1.0	0.3	30.0	1.4	0.2	14.3	0.3	0.2	66.7
Atmospheric pressure (mb)	18	1.8	0.3	16.7	0.7	0.2	28.6	0.3	0.2	66.7
Scalar wind (m/s)	12	0.4	0.1	25.0	0.2	0.1	50.0	0.1	0.1	100.0
Cross-shore wind stress (dyne cm ⁻²)	12	0.0098	0.0065	66.3	0.0052	0.0027	51.9	0.0038	0.0041	107.9
Along-shore wind stress (dyne cm ⁻²)	12	0.0174	0.0078	44.8	0.0118	0.0035	29.7	0.0079	0.0045	57.0
Rainfall (cm)	18	31.3	6.9	22.0	14.1	4.9	34.8	14.3	6.2	43.4
Relative density	18	10.3	1.0	9.7	2.1	0.9	42.9	2.7	0.8	29.6
River discharge (Mm ³)	8	1774	407	22.9	621	301	48.5	683	294	43.0
CSL (cm)	18	10.5	1.5	14.3	3.0	1.0	33.3	2.1	1.1	52.4

Mean - Mean amplitude
SD - Standard deviation
CV - Coefficient of variation (%) : (SD/Mean) x 100

Table 3. Long-term mean for the entire data as well as for the premonsoon, summer monsoon and postmonsoon seasons.

Parameter	1	2	3	4	5	6
SST (°C)	29.0	30.2	28.1	28.7	2.1	0.6
Air temperature (°C)	26.6	28.0	25.9	26.0	2.1	0.1
Atmospheric pressure (mb)	1011.3	1011.2	1010.3	1012.5	0.9	2.2
Scalar wind (m/s)	2.0	2.2	2.1	1.7	0.1	-0.4
Cross-shore wind stress (dyne cm ⁻²)	0.0124	0.0161	0.0159	0.0051	0.0002	-0.0108
Along-shore wind stress (dyne cm ⁻²)	-0.0195	-0.0254	-0.0298	-0.0033	0.0044	0.0265
Rainfall*** (cm)	322.6	44.3	219.8	58.5	-175.5	-161.3
Relative density	11.4	18.2	2.8	13.1	15.4	10.3
River discharge*** (Mm ³)	19990	1672	13206	5112	-11534	-8094
CSL (cm)	76.5	77.4	68.7	83.3	8.7	14.6

*** Totals

1 - Annual data

2 - Premonsoon data

3 - Summer monsoon data

4 - Postmonsoon data

5 - (Column 2 - Column 3)

6 - (Column 4 - Column 3)

Table 4. Seasonal and interannual variability of the atmospheric parameters and sea level at Cochin, for the 1976 - 1993 period.

Parameter	N	1	2	3	4	5
SST (°C)	13	1.0	1.2	0.6	1.6	71.3
Air temperature (°C)	18	1.2	1.4	0.6	2.2	82.8
Atmospheric pressure (mb)	18	1.3	1.5	0.8	1.7	75.4
Scalar wind (m/s)	12	0.3	0.4	0.3	0.8	40.6
Cross-shore wind stress (dyne cm ⁻²)	12	0.0065	0.0130	0.0112	0.6	25.4
Along-shore wind stress (dyne cm ⁻²)	12	0.0135	0.0197	0.0143	0.9	47.3
Rainfall (cm)	18	25.3	29.6	15.5	1.6	72.7
Relative density	18	7.4	8.0	3.3	2.3	83.5
River discharge (Mm ³)	8	1377	1568	751	1.8	77.1
CSL (cm)	18	7.4	8.7	4.6	1.6	72.3

- N - Number of years
- 1 - Seasonal standard deviation (based on climatological means)
- 2 - Standard deviation of the observed data
- 3 - Standard deviation of the anomalies
- 4 - Ratio of 1 to 3
- 5 - Seasonal variance (%) contained in the entire series

Table 5 - Details of the CSL data used for the west coast of the Indian subcontinent.

Station	Start Year	End Year	Number of Years	Range of sea level (cm)	Percentage contribution of the annual cycle to total variance	Percentage contribution of the semi-annual cycle to total variance
Karachi	1937	1947	11	15.4	72	25
Kandla	1950	1987	38	6.5	27	49
Veraval	1955	1965	11	23.7	84	13
Bhavnagar	1937	1955	19	57.5	98	1
Bombay	1878	1988	111	17.6	72	16
Mormugao	1969	1980	12	23.1	91	4
Karwar	1970	1988	19	25.6	89	9
Mangalore	1961	1976	16	21.2	16	48
Cochin	1939	1988	50	19.9	87	7

Legend to figures

Figure	Legend
1	Location map
2	Seasonal march of (A) SST (B) standard deviation of SST (C) air temperature (D) standard deviation of air temperature (E) atmospheric pressure (F) standard deviation of atmospheric pressure (G) wind speed and (H) standard deviation of wind speed.
3	Seasonal march of (A) cross-shore wind stress (B) standard deviation of cross-shore wind stress (C) along-shore wind stress (D) standard deviation of along-shore wind stress (E) rainfall and (F) standard deviation of rainfall (G) relative density and (H) standard deviation of relative density.
4	Seasonal march of (A) river discharge (B) standard deviation of river discharge (C) sea level (D) standard deviation of CSL (E) along-shore current (F) frequency histogram of wind direction and (G) seasonal march of steadiness of wind.
5	Seasonal cycle of CSL for the stations along west coast of the Indian subcontinent. The scales on the y-axes are different.
6	Interannual variability of the atmospheric parameters and sea level <i>vis-à-vis</i> SOI. The along-shore wind stress has been scaled by 10^5 .

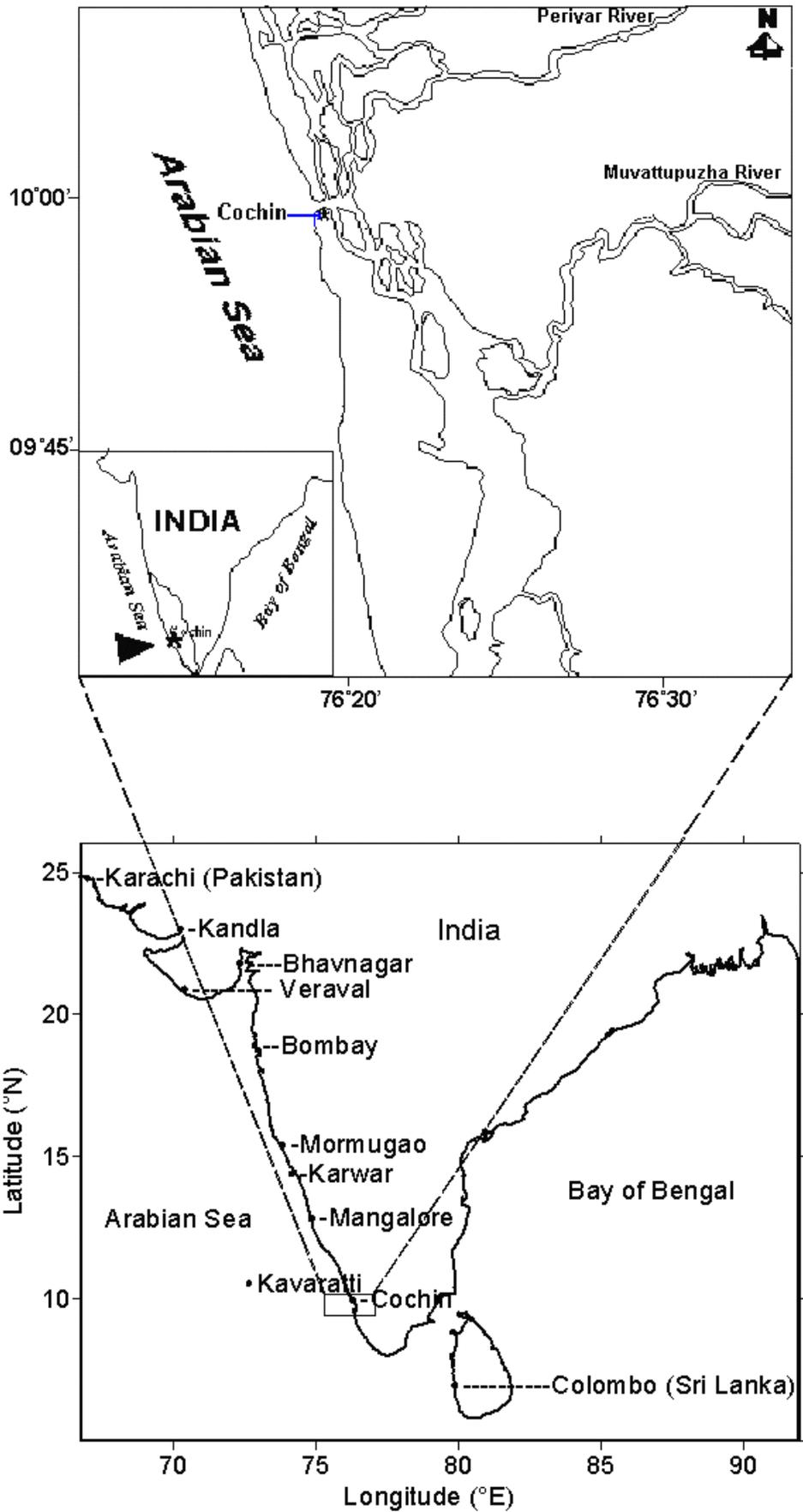


Fig. 1

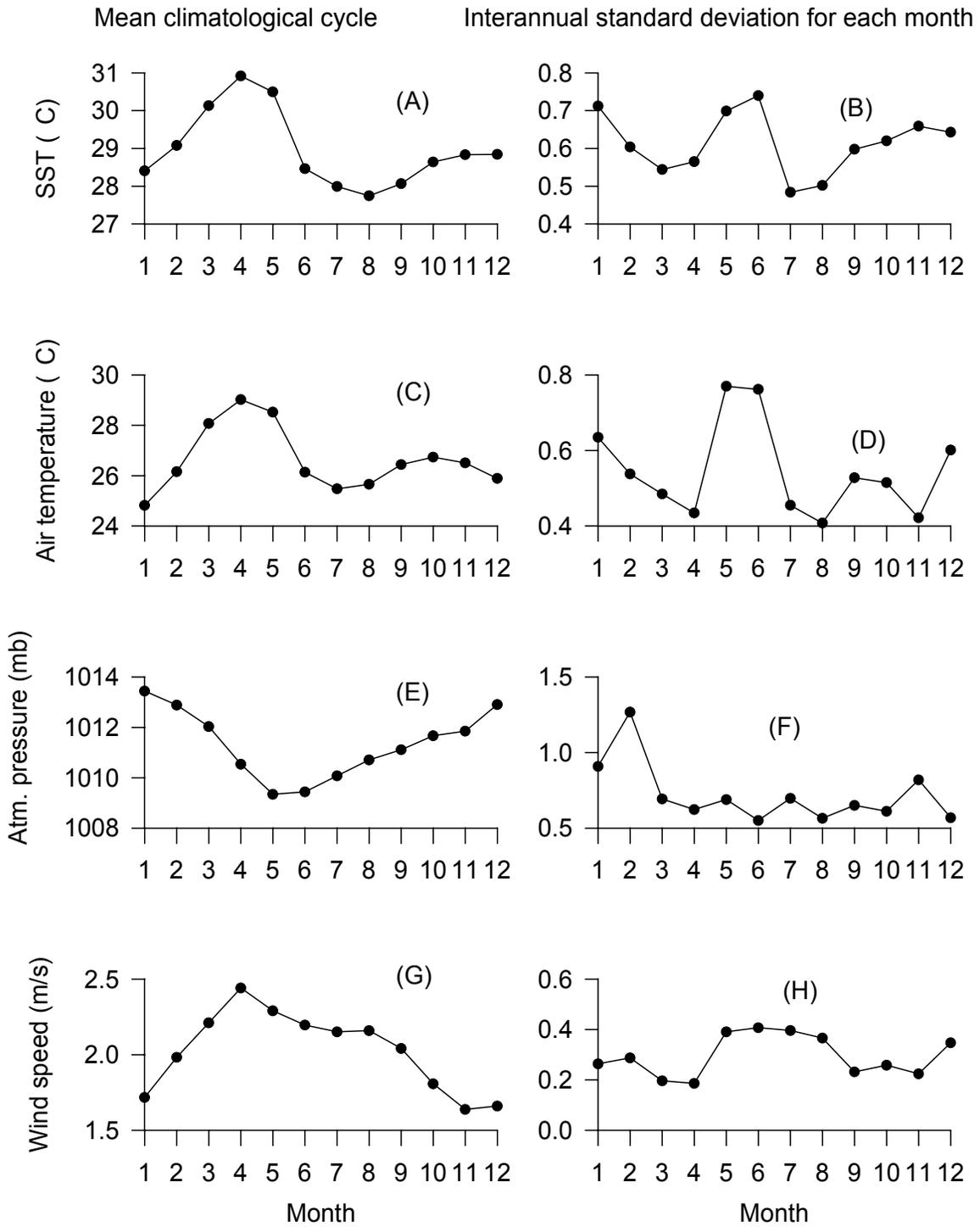


Fig. 2

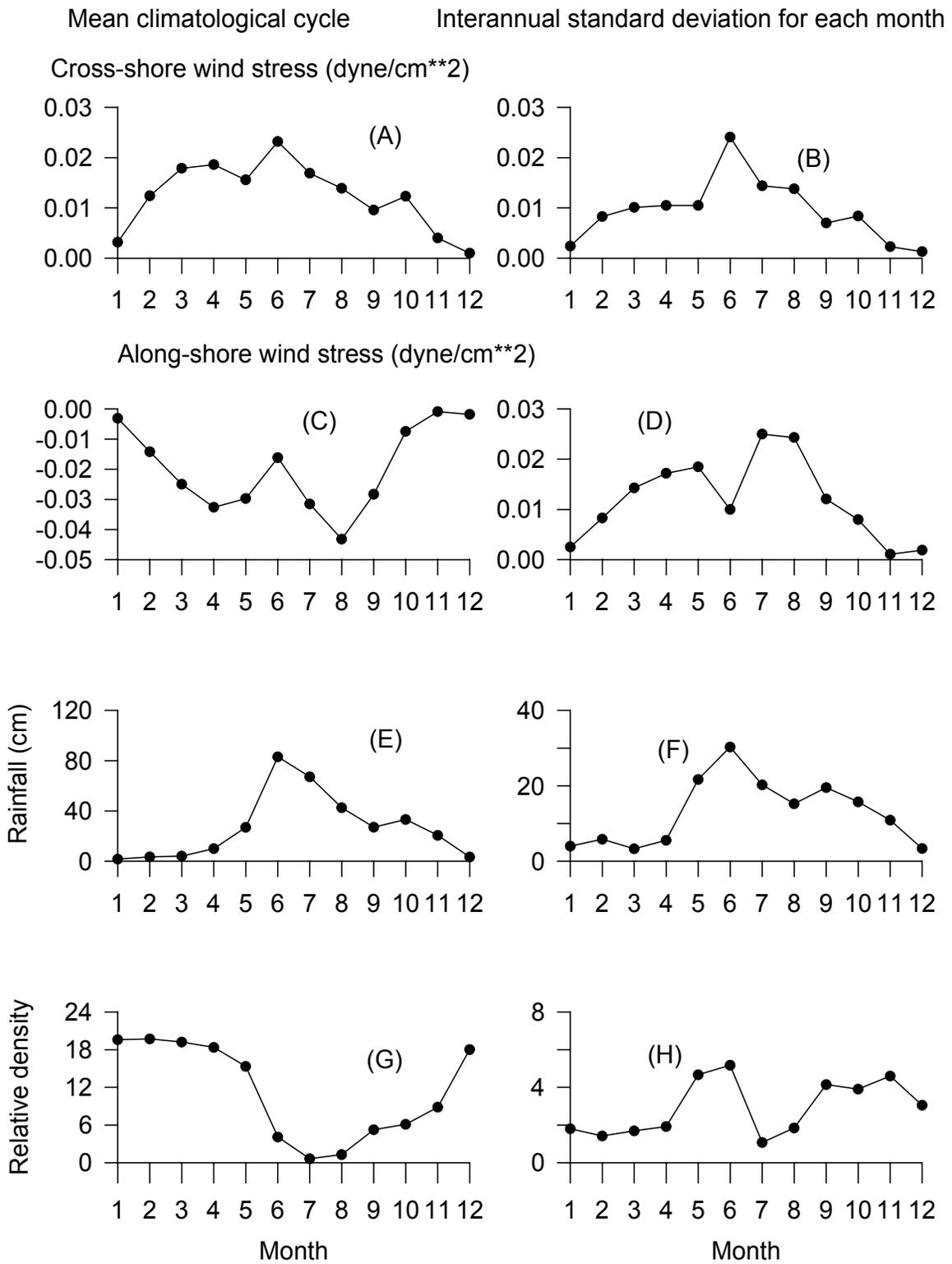


Fig. 3.

Mean climatological cycle

Interannual standard deviation for each month

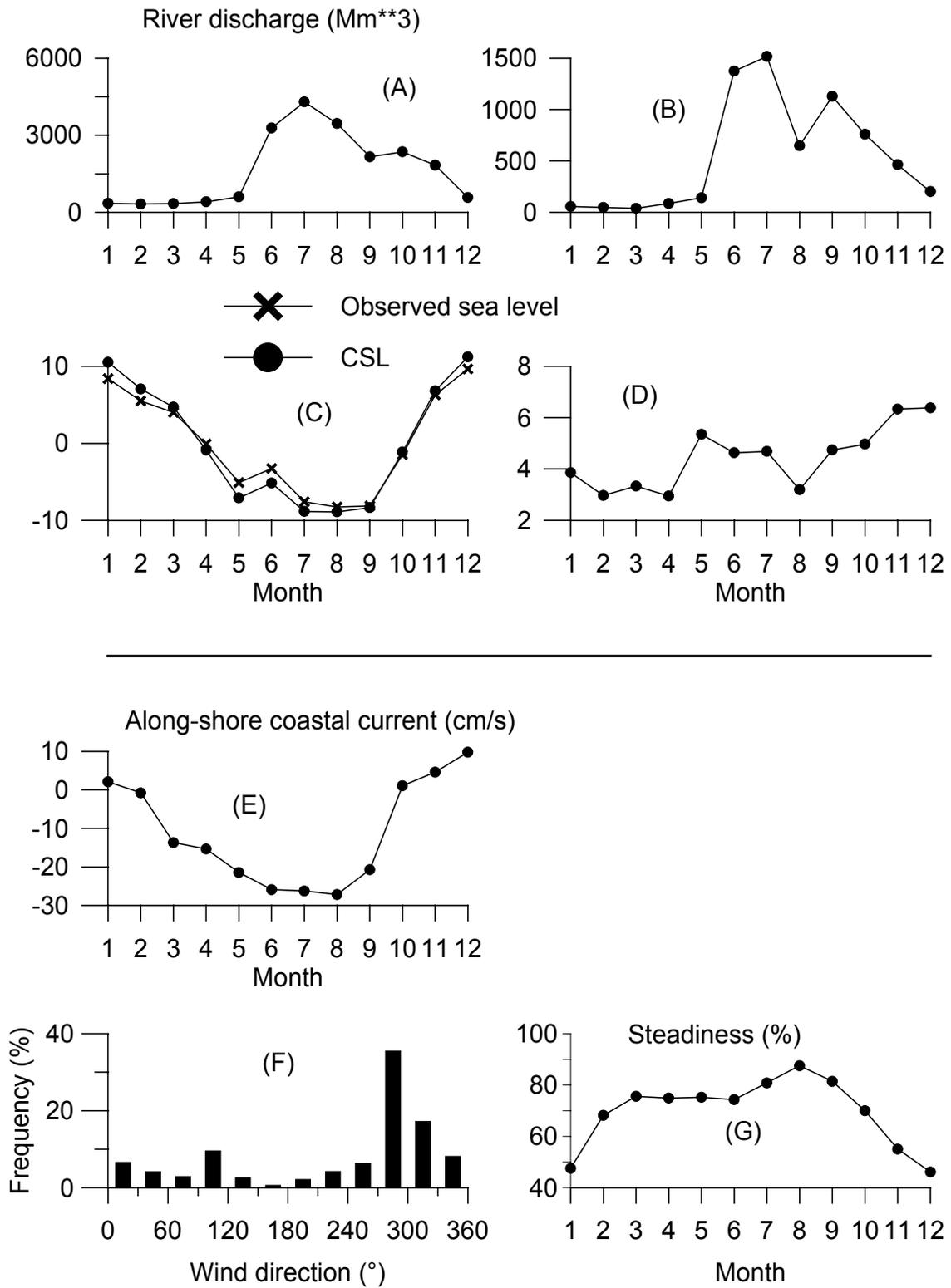


Fig. 4.

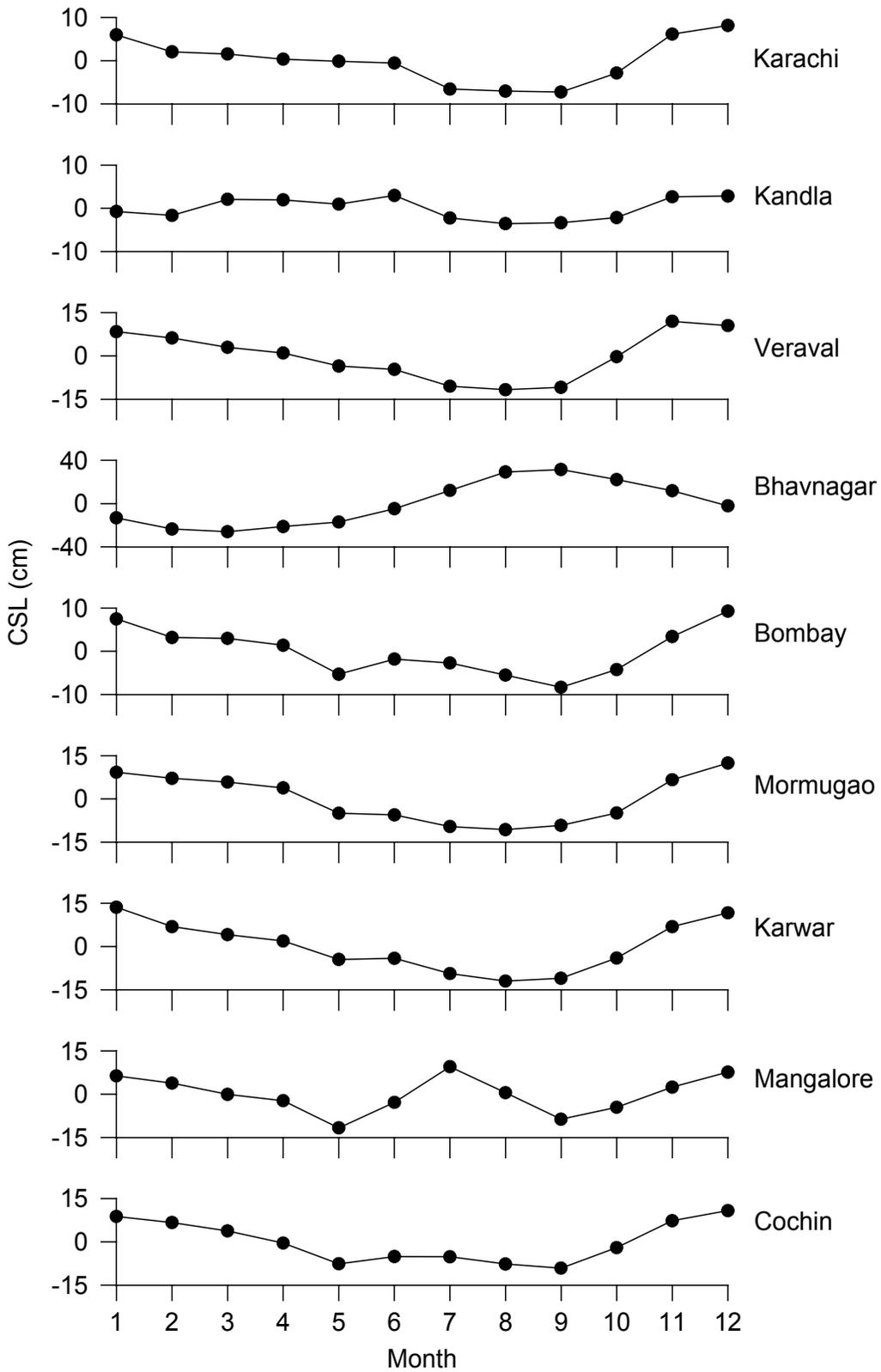


Fig. 5

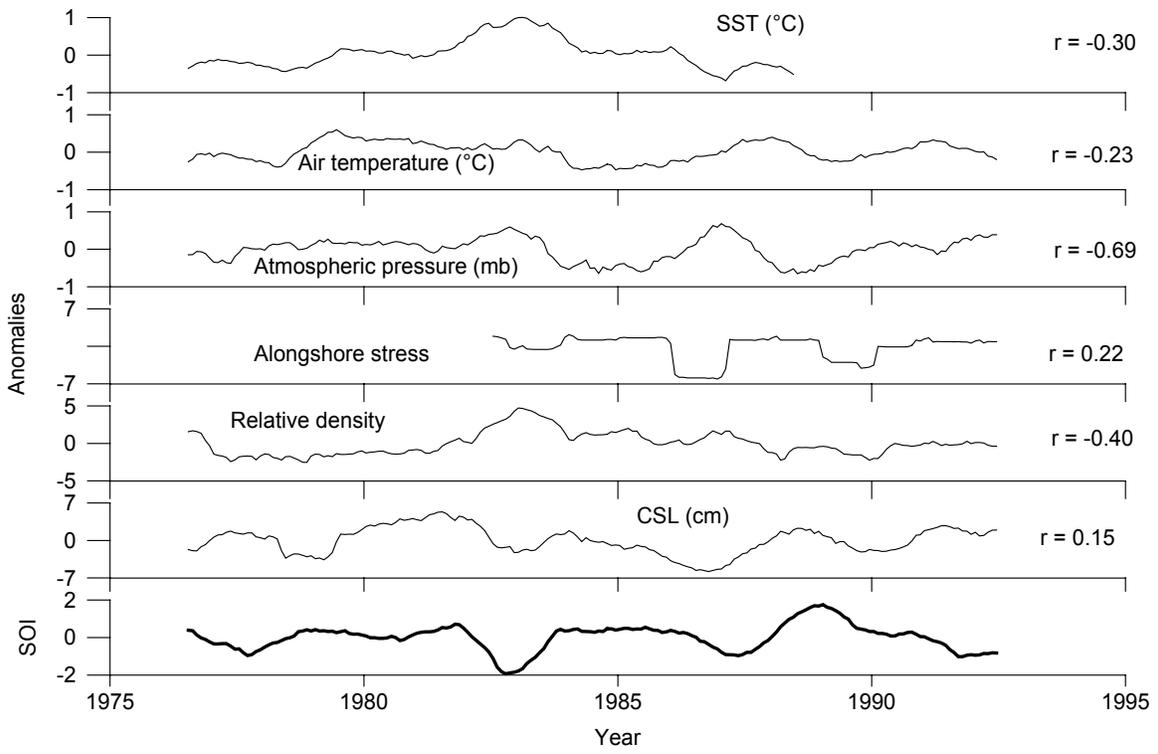


Fig. 6