



## MEASUREMENTS OF SEA LEVEL OFF TIKKAVANIPALEM - COAST INDIA

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### Abstract

*Sea level and meteorological measurements have been made, off Tikkavanipalem coast in Andhra Pradesh, in 1997-98. Sea level measurements were made in four temporal segments of one-month duration each during a one-year period, and meteorological measurements were also made during this one-year period. These measurements have indicated that the sea level along this coast contains contributions from several classes of motions, principally tidal motions and set-up/set-down motions that are induced by local and remote meteorological forcings. The sea level residue (i.e., measured sea level minus the astronomically induced sea level) in this region is particularly influenced by the local wind pattern and air pressure variations. The observed response of the sea level to the barometric pressure was generally larger than the ideal 1-cm sea level rise/fall for every 1mbar fall/rise in atmospheric pressure (inverted barometer effect). The modulations in the daily-mean sea level in this region are attributable to meteorological forcing together with the influences of local bathymetry, water circulation, and remotely generated and coastally trapped low-frequency edge waves. The present studies indicate the importance of making sea level measurements together with meteorological measurements, from as close to the seacoast as possible, for a better interpretation and understanding of the local sea level anomalies in the coastal waters.*

### INTRODUCTION

The regular pattern of semi-diurnal/diurnal fluctuations of sea level (i.e., tidal rhythms) may get modified to a great extent by meteorological, oceanographic, and topographic factors; the principal ones being the winds acting on the sea surface, atmospheric pressure, water current and bathymetry. These factors may raise/lower the sea level above/below the predicted astronomical tide, and may have periods ranging from several minutes to several days. In this paper we address the influence of local wind and air pressure on the observed sea level anomalies off Tikkavanipalem village, Andhra Pradesh, on the central East Coast of India, and hints at possible remote forcing. The measurements were made in support of oceanographic studies, conducted by the National Institute of Oceanography for the proposed Simhadri Thermal Power Plant, sponsored by National Thermal Power Corporation Limited (NTPC), New Delhi.

### INSTRUMENTATION AND METHODOLOGY

The instruments for these measurements were designed and developed at the Marine Instrumentation Division (MID) of the National Institute of Oceanography (NIO), Goa. It has been reported that meteorological anomalies heavily influence the sea level on the east coast of India (Pugh, 1987; Fernandes et al., 1991). For this reason meteorological measurements were also made from Tikkavanipalem beach to complement the sea level measurements. Sea level measurements were made using a strain-gauge absolute pressure transducer manufactured by Macurex Sensors (P) Ltd., Bangalore (Joseph, 1999). The transducer detected the total pressure over its pressure inlet (i.e., water column pressure plus atmospheric pressure). The pressure gauge was deployed ~3km off the coast, at a depth of ~10m. The deployment was made on a U-mooring arrangement so that the pressure inlet of the transducer was located at an elevation of ~1m above the sea floor. This is one of the methodologies used in Tide Gauge deployments (Jacques, 1988). This arrangement would prevent contamination of the pressure inlet from the influx of clay/sand particles on the

seabed. Dynamic pressure effects arising from flows, waves and a combination of flows and waves were minimized by locating the pressure inlet at the centre of, and flush with a circular flat plate front-end (Joseph et al., 2000). Time-averaging of numerous successive pressure samples (80 samples in the present case) over a period of 40s was sufficient to filter out short-period fluctuations in the tidal records, arising from wind-waves (Peshwe et al. 1980; Joseph and Desa, 1984; Lamy, 1988). Atmospheric pressure measurements, made from a meteorological station (Desai et al., 1997) installed on the Tikkavanipalem beach, were used to extract the desired water column pressure from the absolute pressure measurements made by the sea level gauge. CTD (conductivity-temperature-depth) profile measurements, made from the vicinity of the gauge, provided an estimate of the depth-mean water density that contributed to the hydrostatic pressure measured by the gauge. These differential pressure measurements and the depth-mean water density were used to yield the sea level record for each of the four temporal segments of measurements reported here.

Wind and atmospheric pressure, which are the meteorological parameters of greater relevance to sea level studies, were measured from an elevation of 10m (reference height) from the ground. The meteorological station was established on the beach itself to derive a realistic estimate of the meteorological conditions prevailing over the coastal waters in the vicinity of the sea level gauge. Barometric pressure was measured by a capacitive sensing element, which was coupled to an integrated thermistor and a microprocessor for temperature compensation. The pressure inlet was suitably protected to minimize wind-induced dynamic pressure effects (Elliott, 1972; Nishiyama and Bedard, 1991). The wind monitor was a hellicoid shaped propeller (speed sensor) coupled to a vane and a circular potentiometer, which was aligned with reference to the Earth's magnetic North (wind direction sensor), forming a single unit.

## **BAROMETRIC PRESSURE AND WIND**

The study area comes under the influence of south-west (SW) and north-east (NE) monsoons and, therefore, it would be interesting to examine the seasonal variations of barometric pressure and wind that might exert some influence over the sea level oscillations as well. Scatter plots of barometric pressure (air pressure) and wind speed & direction during the four temporal segments of the measurements, covering November 1997 to August 1998, are shown in Fig. 1. Temporal variations of air pressure and wind speed are shown as scatter plots in a 24-hour clock format. Direction-dependence of wind is shown in a circular format, with wind blowing from the North direction being represented as 0°. The solid line passing through the center of the circle shows the alignment of the coastline (~70° with reference to the North). These scatter plots indicate the trend in the variation of air pressure and wind during the indicated temporal segments. Fig. 1(a) shows that, in all cases, the envelope of the minimum air pressures and those of the maximum air pressures formed approximate elliptical patterns. The major axes of these elliptical patterns passed through ~10 hr and ~22 hr of the day. These elliptical patterns' minor axes passed through ~4 hr and ~16 hr of the day. The lengths of the elliptical patterns' axes showed seasonal variations, thereby indicating a seasonal change in air pressure. The mean air pressure during November/December 1997 (segment-1) was 1013.6 mbar and that during January/February 1998 (segment-2) was 1014.9 mbar. However, a general decrease in barometric pressure has been observed during May/June 1998 (segment-3) and July/August 1998 (segment-4) in which the mean barometric pressures were 1000.5 mbar and 1000.1 mbar respectively. The U.S. Navy Report (1976) has also indicated a similar seasonal dependence of barometric pressure in the Indian Ocean in the vicinity of Andhra Pradesh coast. Fig.1 (b) shows the time-dependence of the scalar wind speed. The maximum wind speeds during segments 1, 2, 3 & 4 were 7.1m/s, 9m/s, 8m/s & 6.9 m/s respectively. In all these temporal segments, the maximum wind speed has been found to occur predominantly in the afternoon, from ~13hr to ~17hr. During segment-1, a clearly defined lull has been found to occur from ~5hr to ~9hr, the maximum wind speed being within 3m/s. Fig. 1(c) indicates a clear trend of changing wind direction with season. During segment-1, wind blew predominantly from northeast (NE) direction (mean wind direction being ~50° relative to the north), and the scatter was minimal. Thus, during temporal segment-1, the mean wind blew at an angle of 20° relative to the coastline. However, wind was heavily scattered during segment-2 (the largest scattering of the wind field during the entire 1-year meteorological measurement period being in this segment). Also, the mean direction of wind appears to have exhibited a rotation relative to that during segment-1. Wind direction during temporal segment-3 also revealed a comparatively significant scatter, and the wind was predominantly from the southwest (SW) direction (mean wind direction being 215°). By July/August 1998 (i.e., segment-4) the wind became concentrated in the SW direction (mean wind direction being 244°). We thus observe a 194° rotation of wind during the period from November/December 1997 (segment-1) to July/August 1998 (segment-4). The observed rotation of wind is consistent with that reported by the U.S. Navy (1976) from Andhra Pradesh coast, wherein the wind direction in November/December has shown a reversal compared with that in May-

August. The wind roses reported by Mani and Mooley (1983), based on meteorological measurements from Visakhapatnam aerodrome station, also shows a clear seasonal rotation of wind direction. However, these wind roses lead our measurements by  $\sim 40^\circ$ , and do not reveal a complete reversal in direction. The reason for the observed closer agreement of our measurements (made from the beach) with those reported by the U.S. Navy (our measurements leading only by  $\sim 5^\circ$  in segment-1, and  $\sim 19^\circ$  in segment-4), is probably because both these measurements represented the wind field over the ocean. The observed offset in wind direction, between our measurements at the Tikkavanipalem beach and those reported by Mani and Mooley (1983) from a distance of  $\sim 20$  km might be because the latter measurements were influenced by orographic effects (i.e., those arising from the influences of hills, landmasses, and such obstructions). Visakhapatnam abounds in many tall hills and, therefore, orographic effects are expected. Thus, comparison of the wind fields measured from these three spatially separated locations [i.e., (1) offshore region of Andhra Pradesh, (2) Tikkavanipalem beach, and (3) Visakhapatnam aerodrome station] reveal a progressive lead of the mean wind direction from the open sea to the land. The wind directions measured at the beach were in closer agreement to those reported over the open waters than over the land.

### EFFECT OF WIND AND AIR PRESSURE ON SEA LEVEL

Sea level measurements from the open waters, off Tikkavanipalem beach, were found to have strong seasonal modulations. The daily-mean water levels during the four monthly observations revealed that the low-frequency variations were super-imposed by surges and small amplitude oscillations of non-tidal origin. Thus, the measured sea level changes were dependent not only on the astronomical forces but also influenced by local meteorological forcing, local bathymetry, and possibly remote meteorological forcing. One method of obtaining an estimate of the quantum of low-frequency noise superimposed on the highly periodic tidal variability, which has astronomical origins, is to de-tide the measured sea level fluctuations using an appropriate low-pass filter, thereby removing the contributions to the sea level from the tidal constituents. The resulting residue can then be associated with the influences of non-astronomical contributions, assuming that surges and astronomical tide combine in an additive way. Several low-pass digital filters are available to suppress tidal frequencies (e.g., Doodson and Warburg, 1941; Groves, 1955; Godin, 1972; Walters and Heston, 1982; Rory and Thompson, 1983). We have used Doodson's filter in the present study.

In order to obtain a quantitative assessment of the non-tidal contributions in the observed sea level, the sea level residue (i.e., measured sea level minus astronomically induced sea level) for all the four temporal segments of measurements have been estimated. Fig. 2 shows the time-dependence of the residues, and their relationship with the corresponding daily-mean values of atmospheric pressure, along-shore wind, and cross-shore wind. In Fig. 2 the along-shore wind component has been considered positive when it occurred from northeast direction along the shoreline, and negative when it was from southwest direction along the shoreline. Similarly, the cross-shore wind component has been considered positive when it was from the sea to the land (i.e., land ward) in a direction perpendicular to the shoreline, and negative when it was from the land to the sea (i.e., sea ward) in a direction perpendicular to the shoreline.

Sea-level residues during segment-1 (i.e., in November/December 1997) exhibited both negative (i.e., depressed sea level) and positive (i.e. elevated sea level), and were within  $\pm 15$  cm [Fig. 2 (a)]. The daily-mean air pressure values also exhibited two significant dips ( $\sim 5$ mbar and  $\sim 7$ mbar) in response to two successive cyclonic depressions. An interesting observation is a negative residue in sea level (i.e., a dip in the daily-mean sea level) during a period of approximately 12 days (spanning from 18 November to 2 December 1997) corresponding to a cyclonic depression, contrary to the expected *inverted barometer* rise in the daily-mean sea level. Experience shows that cyclone-induced fall in barometric pressure need not necessarily give rise to an increased mean sea level in the coastal waters. For example, Sunder et al. (1999) have observed that during the 6-10 August 1979 storm event the sea level at Paradip was depressed, whereas the same site exhibited a surge during other cyclonic events.

In the present case, as the daily-mean cross-shore wind time-series was more or less bi-directional during this segment, its role in modulating the daily-mean sea level by set-down effect was negligible. However, there was a consistently unidirectional and strong (up to 3 m/s) positive (i.e., northeasterly) along-shore wind. The study area is situated on the East Coast of India, and is located in the Northern Hemisphere. In the Northern Hemisphere, a north-easterly wind introduces down-welling along this coast as a result of Ekman transport acting towards the coast. When the wind stress acts parallel to a coastline the onset of Ekman transport is followed by the development of sea level differences. The along-shore wind also generates a sea level gradient normal to the coast that is in geostrophic equilibrium with the water current. Corresponding to this equilibrium is a change of coastal sea levels with time, both current flows and sea level changes being

greatest when the water is shallow (Pugh, 1987). Thus, these locally generated surges, in response to Ekman transport, was expected to contribute to an enhanced sea level at the study area. Even the two major dips ( $\sim 5$  mbar and  $\sim 7$  mbar) observed in the daily-mean air pressure values in response to two successive cyclonic depressions were expected to introduce an enhanced sea level as a result of inverted barometer effect. Paradoxically, we observe an opposite situation. It appears, therefore, that remotely forced coastally trapped waves [known as edge waves or shelf waves (Gill and Clarke, 1974; Gill, 1982) that propagate along the coast caused the observed oscillations in the daily mean sea level.

The daily mean sea level residue during segment 2 [Fig 2(b)] was negligible for 21 days, from 22 January to 11 February. During this period, both along-shore and cross-shore winds were bi-directional and, therefore, did not contribute to sea level residue. In the subsequent days, the daily-mean residue revealed a rapidly rising trend, reaching up to  $\sim 1$  m. The coasts of India and Bangladesh which surround the Bay of Bengal are known to be vulnerable to severe flooding due to tropical cyclones, where surge levels much more than 1 m have been found to occur during the northeast monsoon season i.e. January/February (Murthy et al., 1986). Emery and Aubrey (1989) have also observed that our study area is one of the few locations in India where the coastal sea level is strongly influenced by floods that are primarily caused by storm-surge episodes. In the present case, the fall in atmospheric pressure was up to 7 mbar. The observed increase in sea level (up to  $\sim 1$  m) was significantly higher than the expected 1 cm sea level rise for every 1 mbar fall in atmospheric pressure (*inverted barometer effect*). During 11-20 February 1998, the cross-shore wind ( $< 2$  m/s) blew consistently from the sea towards land. However, the piling up effect associated with this landward wind would not contribute to an increase in the positive sea level residue because during the same period there was a SW along-shore wind that acts to depress the sea level at the study area. Thus, the enhanced inverted barometer effect observed during 11-20 February 1998 cannot be explained based on the observed wind forcing. The observed enhancement in the positive sea level residue during 11-20 February 1998 could be because; in shallow coastal waters the inverse relationship between sea level variation and air pressure variation need not exactly be the ideal inverted barometer response (Pugh, 1987). An almost persistent positive residue in the sea level in May/June 1998 [Fig. 2 (c)], reaching  $\sim 25$  cm, was accompanied by a persistent low air pressure (depression reaching  $\sim 11$  mbar), clearly revealing an inverted-barometer effect. The unidirectional (land ward) cross-shore wind was weak ( $< 2$  m/s) and, therefore, could have contributed to a weak piling up effect and a resulting weak rise in sea level rise at the study area. However, during the same period, there was a strong ( $> 3$  m/s) and consistent SW directed along-shore wind that was favorable for upwelling and a resulting depression in the sea level. However, the consistent SW directed along-shore wind (favorable for depression in sea level) was stronger than the landward cross-shore wind (favorable for rise in sea level) and, therefore, the resultant effect of wind forcing was to give rise to a weak depression in sea level. This could be the reason that the observed enhancement in the positive sea level residue resulting from the inverted barometer effect in the present case was weaker than a similar positive sea level residue that occurred during 11-20 February 1998.

Sea level residues in July/August 1998 [Fig. 2(d)] had positive and negative swings, and were within  $+20$  cm and  $-15$  cm. The daily-mean air pressure values also exhibited large swings (up to  $\sim 8$  mbar). However, the sea level residues during this segment do not reveal a clearly defined inverted barometer response. Rather, during certain sub-segments we observe a time lag of up to  $\sim 3$  days between some of the peaks in the sea level residue graph and the corresponding troughs in the air pressure graph. The daily-mean cross-shore wind was almost negligible during this entire segment and, therefore, did not contribute to the observed fluctuations in the daily-mean sea level. In Fig. 2(d), we observe a steadily increasing along-shore wind from the southwest direction. However, the observed sea level anomaly does not reveal a similar steadiness in its trend. Thus, neither air pressure variations nor wind variations can satisfactorily explain the observed sea level residues during July/August 1998. One probable reason for the observed oscillations in the daily-mean sea level residue could be locally generated or remotely driven coastal up-welling/down-welling events, which give rise to reduced/enhanced dynamic heights. Both remote and local forcings have been reported to be active along the Indian coasts. It appears that a possible reason for the observed sea level residue is remotely forced coastally trapped long-period waves, known as edge waves or shelf waves, which propagate along the coast.

## CONCLUSIONS

Sea level and meteorological measurements that have been made off Tikkavanipalem coast in Andhra Pradesh, have indicated that the regular tidal movements of the coastal waters in this region are usually modified to a greater or lesser extent by the effects of the weather. The relative importance of tidal and non-tidal contributions to the sea level variations has been found to depend on the time of the year, as the

meteorological parameters in this region suffer large seasonal variations. We have observed that the local wind pattern and air pressure particularly influence the sea level variations in this region. The magnitude of the sea level residue was generally larger than the local air pressure variation. The observed disparity can generally be attributed to the local wind, but remote forcing also seem to play an occasional role in modulating the sea level in this region. Thus, because of weather effects, the actual sea level variations in the study area often differed significantly from the astronomically induced sea level.

It has been observed, by inter-comparison measurements, that wind measured at the beach is more representative of the sea surface wind than that measured from a land-based meteorological station located ~20 km from the beach. This is because the latter measurements tend to be modified by orographic influences. The present studies indicate the importance of making sea level measurements together with meteorological measurements, from as close to the seacoast as possible.

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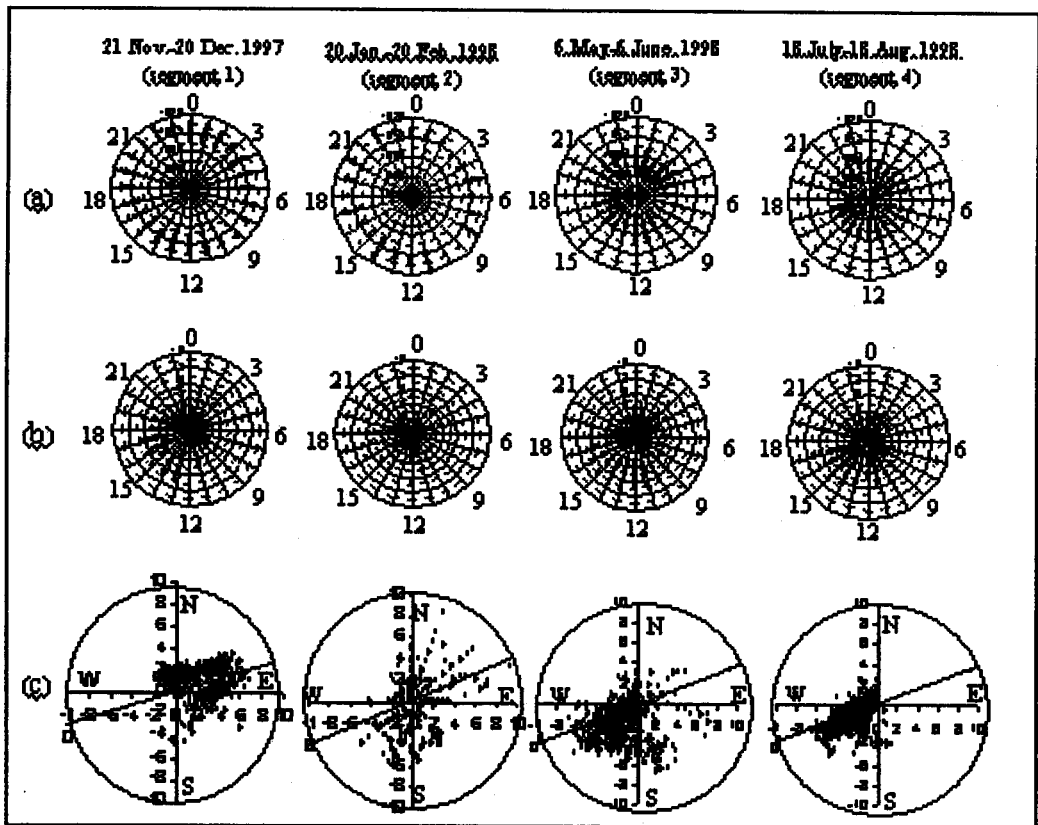


Fig. 1 Air pressure and wind during the indicated four temporal segments of measurements. Time-dependence of daily-mean air pressure (mb); (b) Time-dependence of daily-mean wind (m/s); (c) Direction-dependence of wind (the thick line passing through the center represents the coastline).

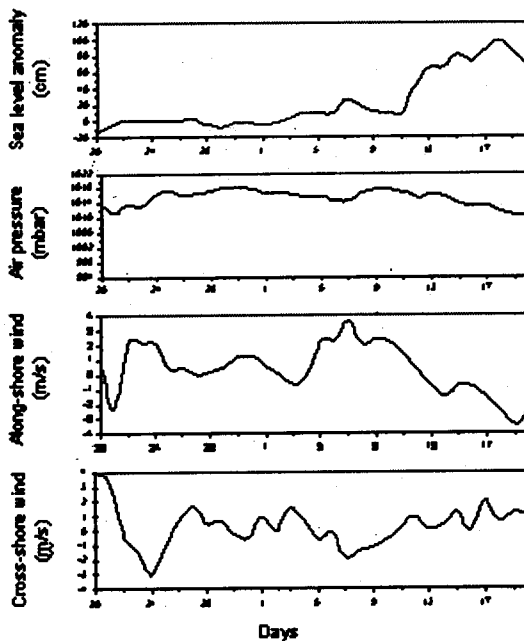
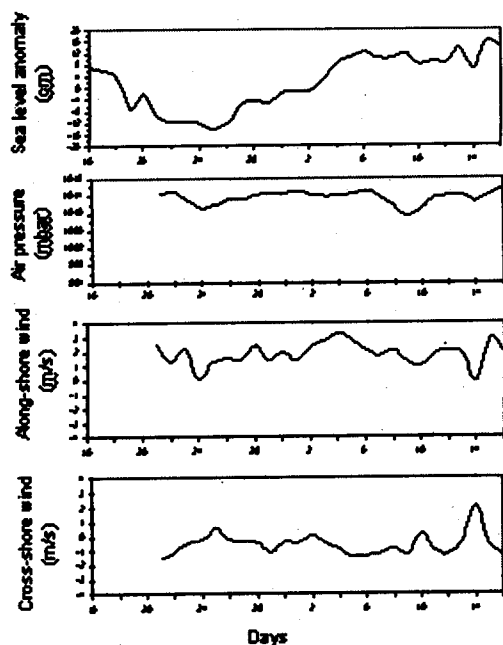


Fig.2(a) Time-dependence of daily mean sea level anomaly during segment-1 (Nov-Dec 1997) and its relationship with air pressure and wind

Fig.2(b) Time-dependence of daily mean sea level anomaly during segment-2 (Jan-Feb 1997) and its relationship with air pressure and wind

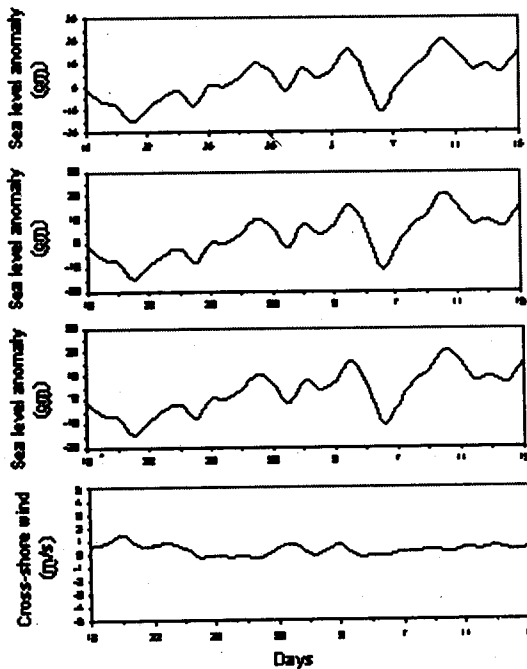
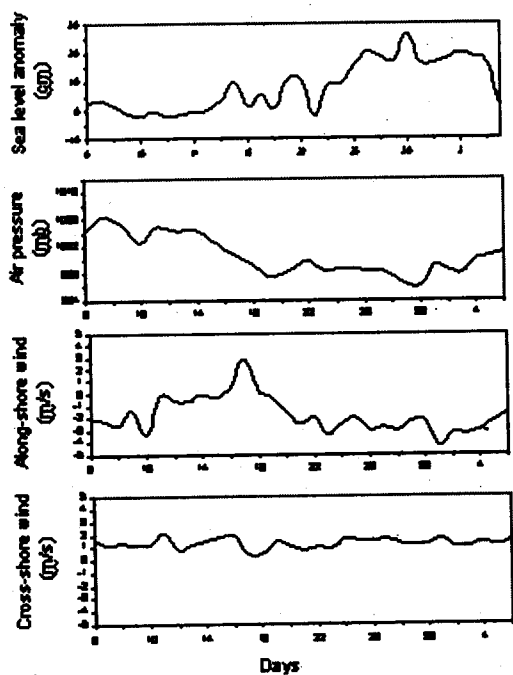


Fig.2(c) Time-dependence of daily mean sea level anomaly during segment-1 (May-June 1998) and its relationship with air pressure and wind

Fig.2(d) Time-dependence of daily mean sea level anomaly during segment-1 (Jul-Aug 1998) and its relationship with air pressure and wind