SEASONAL AND INTERANNUAL VARIABILITY OF SEA LEVEL AND ASSOCIATED SURFACE METEOROLOGICAL PARAMETERS AT COCHIN

THESIS SUBMITTED TO THE
COCHIN UNIVERSITY OF SCIENCE AND TECHNOLOGY
FOR THE DEGREE OF

DOCTOR OF PHILOSOPHY
IN
PHYSICAL OCEANOGRAPHY

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APRIL, 1999

Dedicated to my beloved parents

DECLARATION

I hereby declare that this thesis entitled " SEASONAL AND INTERANNUAL VARIABILITY OF SEA LEVEL AND ASSOCIATED SURFACE METEOROLOGICAL PARAMETERS AT COCHIN " is an authentic record of the research carried out by me, at the Centre for Earth Science Studies, Trivandrum, under the supervision and guidance of Dr. R. R. Rao, Scientist - F, Naval Physical and Oceanographic Laboratory, Cochin, in partial fulfillment of the requirement for the Ph. D. Degree of the Cochin University of Science & Technology, Cochin and that no part thereof has been previously formed the basis of the award of any degree, diploma or associateship in any University.

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CERTIFICATE

This is to certify that this thesis bound herewith is an authentic record of the research carried out by Shri. K. Srinivas, under my supervision and guidance at the Centre for Earth Science Studies, Trivandrum, in partial fulfilment of the requirement for the Ph. D. Degree of the Cochin University of Science & Technology and that no part thereof has previously formed the basis of the award of any degree, diploma or associateship in any university.

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ACKNOWLEDGEMENTS

I wish to place on record my deep sense of gratitude to my Research Guide, Dr. R. R. Rao, Scientist- F, Naval Physical and Oceanographic Laboratory (NPOL), Cochin, for suggesting the topic of study, and for the guidance and advice given during the course of the investigation.

I am very much grateful to the Director, Centre for Earth Science Studies (CESS), Trivandrum for kindly permitting me to work at the centre and for encouragement and facilities given for carrying out the study. I owe very much to Dr. K. Premchand and Dr. C.M. Harish, Scientists, CESS with whom I was associated earlier and to Dr. M. Baba (the then Head, Marine Sciences Division and presently Director, CESS) for the encouragement given to me while carrying out my work at CESS.

I wish to express my profound indebtedness to the Director, National Institute of Oceanography (NIO), Goa and the Scientist-in-Charge, Regional Centre, Cochin. I have been greatly benefited by discussion with some of the Scientists of the Institute. I am particularly indebted to Drs. V.N. Sankaranarayanan. V. Kesava Das, V. Josanto and K.K.C. Nair. I wish to express my gratitude to Dr. P. Udaya Varma, Scientist (Retd.), NIO, Cochin for his constant encouragement and suggestions on the manuscript.

I am grateful to the Marine Surveyor's Office, Cochin Port Trust, Cochin; Hydrographic Surveyor's Office, Beypore Harbour, Beypore and Meteorological Office, Naval Air Station, Cochin for kindly providing me the data that was used in this study.

I am also grateful to the Permanent Service for Mean Sea Level, United Kingdom, for monthly mean sea level data. My profound thanks to Dr. Patrick Caldwell, University of Hawaii, for the software.

I also wish to thank the Directors of the following organisations - NPOL, Cochin; CMFRI, Cochin and School of Marine Sciences, CUSAT, Cochin for permitting me to make use of the respective library facilities. I am also thankful to many Scientists and Teachers of these institutes for their help and encouragement.

I wish to thank the Administrative Sections of CESS, Trivandrum and CUSAT, Cochin for timely guidance and advice regarding administrative formalities in connection with the present study.

Not mentioned are the names of many friends, colleagues and well-wishers who helped and encouraged me on various occasions. I am very much thankful to each one of them.

I am highly thankful to the Council of Scientific & Industrial Research, New Delhi for providing a fellowship under the tenure of which the present work was carried out.

CONTENTS

PREFACE

The interesting aspect of studying sea level variability on different time scales can be attributed to the diversity of its applications. There are many scientific and practical reasons to have a knowledge of the sea level variability, as it manifests itself in the dynamics of the ocean and atmosphere. Sea level has a controlling influence on many oceanographic (physical, chemical, biological and geological) and meteorological processes. Marine transport, coastal protection, harbour development, coastal pollution, design of coastal structures, fisheries, climate change and energy are some examples, which require information on sea level variability on different time scales.

Study of tides could perhaps be the oldest branch of physical oceanography. The measurement of sea level has also seen vast changes - from the most simple oceanographic measurement, using graduated staff, to the most advanced, using satellite altimetry involving complicated measuring techniques with a variety of corrections. Earlier, tide poles (vertically mounted graduated staffs) which are cheap and are easy to instal, have been used. Even today, these are often the best choice for short term surveys. A variety of gauges - stilling well gauges, pressure mounted systems, reflection-time gauges, and for deep sea use - open sea pressure gauges are still being used. The last one can be deployed for periods of nearly a year at depths around 4000m. Satellite altimetry is an answer to the many of the problems that these gauges have, generating enormous quantities of data over large areas. The satellite altimetric data have its own limitations - it is of limited accuracy and a variety of corrections are to be applied. The GEOSAT data (4.5 years) were of limited accuracy and the subsequent TOPEX/POSEIDON data (1992-continuing) are of much better accuracy after the corrections are applied. It is, however, to be emphasised that whatever may be the status of the satellite techniques, traditional techniques will continue to be important. The traditional processing techniques have also seen a lot of change. Earlier, the data were digitised from the marigrams, usually at half hourly or hourly intervals and occasionally at finer intervals (say, 10 minutes). Nowadays, the tidal information is recorded on the computer and one has the choice of recording information at time intervals of a minute or less. Processing software has also improved considerably and it is possible to make a good tidal analysis immediately after any specified period of data is collected - a fortnight, a month or a year.

The tide gauges along the Indian coastline have been installed exclusively for one purpose only - providing information on tides for navigational purposes in connection with the shipping activities. These gauges have been installed mostly in bays, gulfs, lagoons and estuaries.

Many of the tide gauge locations have become main centres of commercial activity and have been experiencing rapid industrialisation, urbanisation and population pressures. Many man-made changes are seen in the near vicinity, and at times at distances in the alongshore, offshore and in the downstream and upstream directions. Some of these man-made changes include - construction of dams, barrages, bunds, coastal protection measures, change in the prevailing bathymetry and coastline by dredging and land reclaiming. Indiscriminate deforestation in the catchment areas of rivers, removal of vegetation along the river banks and sand mining are some of the far field effects that have caused heavy siltation in estuaries. These change the flow patterns of water, upsetting ecological balance by changing tidal flow patterns and the long term seasonal sea level patterns.

Because of the complex nature of tidal wave propagation, a detailed study at each water body is required. The non-tidal sea level is also a function of a variety of oceanographical, meteorological and hydrological forcings. The tidal and non-tidal effects seen on the sea level could be due to a range of factors from seiches to changes associated with climate changes. Because of the interaction of so many variables, it is difficult to make generalisations on the characteristics. Detailed studies are required to understand the phenomenon.

In this thesis, the results of the studies on sea level variability at Cochin (southwest coast of India) are presented for the important time scales- tidal, seasonal and interannual, by making use of data compiled by different organistations. These data have been collected at different but regular time intervals using a variety of instruments. The seasonal and interannual variability of sea level at Cochin has been compared with that at 15 other stations along the Indian Subcontinent.

The thesis is presented in seven chapters. The first chapter gives, apart from a general introduction, a survey of literature on sea level variability on different time scales - tidal, seasonal and interannual (geological scales excluded), with particular emphasis on the work carried out in the Indian waters. The second chapter is devoted to the study of observed tides at Cochin on seasonal and interannual time scales using hourly water level data for the period 1988-1993. The third chapter describes the long-term climatology of some important surface oceanographic and meteorological parameters (at Cochin) which are supposed to affect the sea level. The fourth chapter addresses the problem of seasonal forecasting of the meteorological and oceanographic parameters at Cochin using autoregressive, sinusoidal and exponentially weighted moving average techniques and testing their accuracy with the observed data for the period 1991-1993. The fifth chapter describes the seasonal cycles of sea level and the driving forces at 16 stations along the Indian subcontinent. It also addresses the observed interannual variability of sea level at 15 stations using available multi-annual data sets. The sixth chapter deals with the problem of coastal trapped waves between Cochin and Beypore off the Kerala coast using sea level and atmospheric pressure data sets for the year 1977. The seventh and the last chapter contains the summary and conclusions and future outlook based on this study.

CHAPTER 1

CHAPTER 1

INTRODUCTION AND LITERATURE SURVEY

1.1. INTRODUCTION

International maritime trade has increased phenomenally in recent years. The economic survival of many nations has come to depend on their trade with other nations. Many large vessels, carrying crude oil from the Middle East, industrial products from the west, raw materials from developing nations, sail across the vast oceans playing a key role in this activity. In the wake of this growth in maritime activity, some nations had to open up new ports, while upgrading and modernising the existing ones. Thus a scientific approach to the port based activities has become the need of the hour. Sea level in the port area is one of the important environmental factors to be considered in this respect. A proper knowledge of sea level and the causes behind its variation are important for the construction of ports and to manage the port traffic.

Sea level has important bearing on other environmental aspects as well. The effects of an increase in mean sea level on an estuarine ecosystem are many. The mean water level of a river may increase as a result of rise in mean sea level, such an increase extending to many tens of kilometers upstream, depending on local conditions, river gradient and the magnitude of the rise. As a result of sea level rise, the tide will propagate further inland. If the river bed does not build up, salt intrusion will increase, causing problems for water for human consumption, agriculture and industries. Increased mean sea level will lead to increased mean wave height and wave related effects (e.g., erosion). These effects in the estuary could lead to habitat shifts in estuarine flora and fauna.

The estimates of global mean sea level change during the last 100 years, based on tide gauge records, indicate a rate of rise of about 1.0-2.0 mm/yr. Factors contributing to the trends include: 1. Vertical land motions (a) natural and (b) anthropogenic (e.g. dam-building, ground water, gas, and/or oil withdrawl) 2. 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. The global air and sea water temperatures have increased because of the increased use of fossil fuels, industrialisation, deforestation, etc. Because of the global warming due to greenhouse effect, thermal expansion of sea water is taking place causing sea level to rise. This, combined with the melting of polar ice caps (also related to global warming) has also increased the sea level. These factors (1 and 2) vary widely in their effects on recorded relative sea levels. Atmospheric and oceanographic processes, however, produce a large fraction of the seasonal and interannual variability in sea level records.

1.2. SEA LEVEL VARIABILITY - TIME SCALES

Sea level studies cover a wide range of time and space scales of interest, and a large number of associated measurement techniques. The sea level changes (of interest to oceanographic and meteorological applications) vary from approximately hourly to decadal time scales.

Excellent reviews on the topic of sea level include that of Lisitzin (1963, 1972) and recently that of Pugh (1987), Emery and Aubrey (1991) and Woodworth (1993). The latter includes survey on studies based on satellite altimetric data and modelling of oceanic processes wherein sea level data have been incorporated.

1.2.1. TIDES

The tides, which manifest as a rhythmic rise and fall of water level seen along the coast, are very important to navigation, harbour development, fisheries and are also a source of energy (Godin, 1972; Foreman et al., 1994; Pugh, 1987). There is often a requirement to remove the tidal oscillations in a time series of water level changes to avoid contamination in the study of non-tidal signals. This de-tiding process can be problematic depending both on the nature of the time series and tide (Foreman et al., 1994). Normally a digital filter is used for removing energy at semi-diurnal and diurnal periods (Godin, 1972; Breaker, 1986; Emery and Thomson, 1998)

1.2.2. SEA LEVEL AND ATMOSPHERIC PRESSURE

Another important process which affects sea level, especially at higher latitudes, is the "inverse barometer" effect which causes the sea level to depress by 1 cm for every 1 mb increase of atmospheric pressure at sea level (Lisitzin, 1974; Pugh, 1987). Over seasonal time scales, a second order effect arises from the seasonal cycle in average air pressure over the world oceans, varying from approximately 1012 mb in December to 1014 mb in July, due mainly to a shift in air mass towards Siberia in winter (Pattullo et al., 1955; Lisitzin, 1974). No correction would be required if the annual changes in pressure were uniform over all the oceans. The inverse barometer effect breaks down on time scales shorter than two days (Wunsch, 1972). The phase of the annual cycle, at least at higher latitudes, relates to summer and winter in each hemisphere, i.e., lower air pressure in winter implies higher sea level. According to Wyrtki and Leslie (1980), atmospheric pressure and the temperature in the upper layers of the ocean are the two parameters having the largest effect on the annual variation in sea level. Air pressure changes and winds are important driving forces in shallow waters (Heaps, 1983) and in deep oceans (Wunsch, 1991). In the Arctic regions, atmospheric pressure is mainly responsible for the observed variations in sea level.

1.2.3. SEA LEVEL AND RAINFALL

Hydrological contributions to the observed sea level variability is also important, because of large scale runoff from rivers in the vicinity of tide gauge stations (Banse, 1968; Lisitzin, 1974; Woodworth, 1993; Cui et al., 1995). Rainfall in a particular coastal area raises the sea level considerably at that location. To assess the impact of rainfall on sea level variations, one should consider a large area and a series of long duration. Rainfall along with runoff from rivers affects the sea level, particularly when tide gauges are installed in constructed harbours (Ramanadham and Varadarajulu, 1964).

Palumbo and Mazzarella (1985) in their study on the mean sea level variation in the Mediterranean Sea, reported that major portion of the sea level variance, concentrated at annual (12 months) and semi-annual (6 months) periods, is dominated by evaporation (effect of rainfall is less than the effect of evaporation).

1.2.4. SEA LEVEL AND WINDS (AND WAVES)

Air flow over the water surface is responsible for the drift currents because of the friction at the boundary of the two media (Lisitzin, 1974). Wind is an important meteorological parameter which affects the sea level directly by piling up of water near the coast (Miller, 1958; Rama Raju and Hariharan, 1967; Pugh, 1987). Miller (1958) studied the response of the sea level to the wind setup along the Atlantic coast of the United States of America and concluded that the sea level is affected by local wind force, direction, fetch length and local topography, the relative importance of which varies with different conditions. Rama Raju and Hariharan (1967) concluded from their study that wind blowing from west-southwest direction is most favourable for rise of sea level at Cochin.

Wave setup in small harbours may also contribute to the observed seasonal cycle of sea level (Cubit et al., 1986; Mehta, 1990; Woodworth, 1993; and Cui et al., 1995).

1.2.5. SEA LEVEL AND THERMAL PARAMETERS

The apparent relationship between the slope of the isotherms and the slope of the sea surface has been used frequently to estimate geostrophic flow (Wyrtki and Kendall, 1967). The need to document the relationships between sea level, thermocline depth, heat content and dynamic depth in the tropical ocean has been highlighted by a number of workers (Chaen and Wyrtki, 1981; Rebert et al., 1985; Wyrtki, 1985). These relationships will again depend on how closely the ocean resembles a two layer system (Rebert et al., 1985). Changes in the temperature and salinity of the surface layer and steepness of the thermocline will adversely affect the relationships. The steeper the thermocline, the better is the relationship.

A number of workers have investigated the relationships between sea level, isotherm depth, heat content and dynamic height in the upper ocean. Rebert et al. (1985) have reported that the sea level fluctuations in the tropical Pacific between about 15°N and 15°S allow the determination of changes of upper layer volume, and that sea level is a good measure of the heat content. They concluded that a combination of bathythermograph and sea level observations will allow a better mapping of the changes of thermocline topography, heat content and dynamic height for the monitoring of climatic changes in the tropical

Pacific Ocean. Chaen and Wyrtki (1981) related sea level and isotherm depth at Truk and found a good positive correlation for monthly mean values. Studies by Pattullo et al. (1955) suggested a strong relationship between sea level and heat content in the open ocean.

Local surface heating steric effects are important in the mid-latitude open oceans (Gill and Niiler, 1973). The large-scale advected steric changes (due to the variability of the tropical ocean circulation) are also important (Tsimplis and Woodworth, 1994).

1.2.5.1. SEA LEVEL AND THERMOCLINE

The depth of the thermocline (typically represented by the depth of the 20°C isotherm) is a measure of the amount of upper layer water present at a location. If variations of the thermocline are related to variations in sea level, fluctuations in upper layer volume can be monitored continuously by sea level observations. This relationship would enable monitoring of the volume of the tropical warm water pools, which are of great relevance to climate studies (Niiler and Stevenson, 1982). Wyrtki (1985) reported that the relationship between sea level and 20°C isotherm depth is maintained in the equatorial regions. Away from the equator, the 20°C isotherm is much deeper than in the equatorial belt, and the thermocline is much weaker and no longer resembles a two-layer system.

1.2.5.2. SEA LEVEL AND HEAT CONTENT

Rebert et al. (1985) have defined the heat content as the mean temperature of the upper 300 m of the ocean. Information regarding the changes of the oceanic heat content is of great importance for climatic studies. Sea level serves as an indirect measure of heat content, which is an integral of the thermal structure (Chambers et al., 1997). Fluctuations in heat content are mainly determined by fluctuations in the depth of the thermocline rather than by changes in the temperature of the mixed layer. If the heat content is related to sea level and its fluctuations can be monitored by sea level observations, the direct observations of heat content along XBT routes could be supplemented by indirect determinations of heat content at sea level stations. This would allow to estimate the heat content changes with satellite-derived sea level data on a basin scale domain. In the subtropics, the seasonal sea level fluctuations are due to seasonal variation in heat storage induced by local heating. In the tropics, the fluctuations are the largest during the solstices and seem to be due to variations in the heat content.

1.3. IMPORTANCE OF SEASONAL VARIABILITY OF SEA LEVEL

Outside the semi-diurnal and diurnal tidal bands, one of the most prominent components of sea level time series is its seasonal cycle. In some parts of the world, the annual ranges of the monthly mean sea level are comparable to daily tidal ranges, and they are consequently of utmost importance in the studies of coastline development (Kibria, 1983; Woodworth, 1993). The changes in the salinity and temperature (which in turn affect density structure) are brought about by a number of factors such as heating, cooling, precipitation, runoff, evaporation, mixing by winds and currents.

A number of investigators e.g. Montgomery (1938), Jacobs (1939), La Fond (1939), Pattullo et al. (1955), Lisitzin and Pattullo (1961), Pugh (1987) and Woodworth (1993) have pointed out that the seasonal cycle occurs from meteorological, oceanographic and hydrological forcings and that the gravitational contribution is negligible. The forcings on the seasonal fluctuations in sea level have been discussed theoretically by Gill and Niiler (1973).

The most important forcing mechanisms for the seasonal fluctuations of sea level, according to Woodworth (1993), are air pressure at high latitudes, wind setup in coastal areas, local surface heating, steric effects in the mid-latitude open ocean, and large non-local steric changes in the tropics. The amplitude of the annual cycle of sea level is typically 50-100 mm at most northern hemispheric locations and 25-50 mm in the southern hemisphere, although amplitudes of the order of a metre can be observed at some locations where runoff plays a major role (Woodworth 1984, 1993). It is essential that prior to any discussion on interannual variability and long term trends, we must have a thorough understanding of the average seasonal cycle of sea level and the various forcing mechanisms which drive the observed seasonal cycle (IPCC, 1990; Woodworth, 1993).

Several studies on seasonal cycle of sea level have been presented by a number of workers (Pattullo et al., 1955; Lisitzin, 1974; Wyrtki and Leslie, 1980; Woodworth, 1984; Tsimplis and Woodworth, 1994). Pattullo et al. (1955) made a detailed study of the seasonal cycle of sea level on a global scale. They reported that the recorded and steric departures agree remarkably well in low and temperate latitudes. Wyrtki and Leslie (1980) made a detailed study of the annual variation of the sea level in the Pacific Ocean by means of harmonic analysis. Woodworth (1984) documented the seasonal variability of sea level at 390 stations distributed throughout the globe and presented the first and second harmonic parameters of the seasonal cycle in a tabular form. In a recent study, Tsimplis and Woodworth (1994) mapped the global distribution of the mean seasonal cycle harmonic parameters viz. the amplitude and phase of the annual cycle and the semi-annual cycle, using 1043 tide gauges around the world.

Estimates of amplitudes and phases of the seasonal cycle based on analysis of individual years demonstrate the presence of interannual varaibility (Wyrtki and Leslie, 1980; Woodworth, 1984). This variability includes, for e.g., the effects of El-Nino (Mitchum and Wyrtki, 1988) and in some areas, the 14-month pole tide or quasi-pole tide (Trupin and Wahr, 1990) and the seasonal monsoons in the monsoon dominated regions of Asia (Longhurst and Wooster, 1990). Woodworth (1984) found the seasonal parameters for "El-Nino" and "non El-Nino" years to be similar at San Francisco.

Tsimplis and Woodworth (1994) concluded from their study that the seasonal cycle of mean sea level of coastal waters exhibits greater spatial coherence when viewed globally, but considerable spatial complexity at a regional level. The seasonal cycle of the mean sea level along coastlines is spatially complex, reflecting the effect of local meteorology, oceanography and hydrology of each region. Seasonal changes of sea level are mostly about 20 cm or less. In March, sea level is generally lower in the northern hemisphere and higher in the southern hemisphere, with reverse pattern in September (Pattullo et al., 1955).

1.4. INTERANNUAL VARIABILITY OF SEA LEVEL

Most of the tide gauge records are approximately 20 years long and few are longer than a century (Woodworth, 1991). Their spectra are essentially "red" making it difficult to extract unambiguous signals of a centimeter or less, with periods of a decade. Trupin and Wahr (1990) by employing "global stacks" of tide gauge data, detected the presence of the 18.6 year period nodal tide. By using "global stacking" procedure, the signal to noise ratio is significantly improved for long period cycles, compared with results obtained from single station records. Fluctuations of approximately 11 year period present in many tide gauge records have been attributed to the variability in forcing from solar radiation at "sunspot" time scales (Woodworth, 1985). Woodworth (1993), however, opined that the significance of the 11 year cycle has not so far been conclusively proved and no causal climatological link with solar activity has been convincingly demonstrated in the case of sea level records.

1.4.1. EL NINO

El Nino ("The Christ Child" - in Spanish) event is a climatic fluctuation centered in the Pacific, that occurs every 2 to 10 years (Enfield, 1989; Bearman, 1995; Lutgens and Tarbuck, 1995; Glantz, 1996; Horel and Geisler, 1997; Scorer, 1997; Wells, 1997). The most obvious sign that an El Nino is underway is the appearance of unusually warm water off the coast of Ecuador and Peru, which generally occurs during Christmas time and hence the name. These occasional invasions of warm surface water from the western equatorial Pacific to the eastern equatorial Pacific, cause a rise in sea level, higher sea surface temperatures, reduced offshore flow, reduced primary productivity and a depressed thermocline in the eastern equatorial Pacific (Philander, 1990; Glantz 1992, 1996). El Nino events are perturbations of the ocean-atmosphere system. There are indications that anomalous climatic conditions outside the Pacific basin, are also in some way linked with El Nino events.

During the 1982-'83 El Nino event, one of the strongest ones reported during the present century, a modest research effort was mounted to examine the effects of the event on meteorology and oceanography - physical and biological (e.g., Rasmusson, 1985; Wooster and Fluharty, 1985; Glantz 1992, 1996; Lavaniegos et al., 1998). The recent El Nino event in 1997, is the most severe one reported for this century. It surpassed the 1982-'83 event (De and Mukhopadhyay, 1998)

The effects of El Nino have been well studied, especially for the Pacific and Atlantic Oceans (Wyrtki, 1978; Enfield and Allen, 1980; Chelton and Davis, 1982; Barber and Chavez, 1983; Cane, 1983; Breaker et al., 1984; Breaker and Lewis, 1985; Breaker and Mooers, 1986; Breaker and Broenkow, 1994; WMO, 1995). In the Indian Ocean, minimum transport through the Indonesian throughflow occurs during El Nino episodes (Meyers, 1996; Potemra et al., 1997).

The largest non-tidal changes of sea level evident in the Pacific Ocean are due to El Nino-Southern Oscillation (ENSO) events. During these ENSO events, approximately 1 metre of water is transferred from the western equatorial Pacific to the South American coast, with the changes clearly observed in tide gauge records (Enfield and Allen, 1980; Wyrtki, 1985) and in satellite altimetry (Miller et al., 1988).

The literature on sea level contains several compilations on the subject of sea level and ENSO connections (Hickey, 1975; Enfield and Allen, 1980; Thomson and Tabata, 1981; Chelton and Davis, 1982; Meyers, 1982; Huyer and Smith, 1985; Mitchum and Wyrtki, 1988; Clarke and Liu, 1994; Clarke and Van Gorder, 1994; Kawabe, 1994; Burrage et al., 1995; Bell and Goring, 1998).

1.4.2. SOUTHERN OSCILLATION

The Southern Oscillation (or Walker Circulation) is an important mode of the tropical atmosphere, generally characterized by the exchange of air between the eastern (predominantly land) and western (predominantly water) hemispheres. Walker (1924) discovered one of the most important oscillations of the planetary atmospheric pressure field, widely known as the Southern Oscillation (SO). It basically describes a see-saw effect in the sea level pressure oscillation between the equatorial Indian Ocean and the south eastern Pacific Ocean. This is generally considered as a shift in the distribution of air masses between the southeast Pacific sub-tropical High and the Indian Ocean Equatorial Low (Mohanty and Ramesh, 1993). Walker and Bliss (1932) reported that when the pressure is high in the Pacific Ocean, it tends to be low in the Indian Ocean from Africa to Australia. These conditions are associated with low temperatures in both these areas, and rainfall varies in the opposite direction to pressure.

A number of workers have given different combinations of meteorological stations and meteorological variables to compute the Southern Oscillation Index (SOI) (Philander, 1990; Glantz, 1996). A parameter which measures the above mentioned see-saw effect is the difference of pressure between the two core regions represented by the stations - Tahiti (17.5°S, 149.6°W) and Darwin (12.4°S, 130.9°E), and is used as an index of the Southern Oscillation (Chen, 1982; Parthasarathy and Pant, 1985; Bray et al., 1996; McGregor and Nieuwolt, 1998). These two regions experience the greatest variation of pressure on interannual time scales. The SOI series (used in the present study) is the standardized pressure difference between Tahiti and Darwin and is determined as follows:

X = mean sea level pressure difference between Tahiti and Darwin (Tahiti minus Darwin) for each month

SOI = (X - MEANX) / SDX

where MEANX is the long term mean and SDX is the long term standard deviation of X.

The extreme values of SOI have received attention because a strong negative value has been associated with the occurrence of El Nino events and a strong positive value with La Nina events.

The effect of the ENSO events in meteorology have also been well studied (Rasmusson and Carpenter, 1982; Gill and Rasmusson, 1983; Rasmusson and Wallace, 1983; Namias and Cayan, 1984; Rasmusson and Arkin, 1985; Philander, 1990; Rasmusson, 1991; Das, 1993; WMO, 1995; Glantz, 1996).

1.4.3. ENSO EFFECTS IN THE INDIAN CONTEXT

The Indian summer monsoon, which provides 75 to 90 percent of the total annual rainfall over the country during June-September, is vital to the national economy. Food production, power generation and drinking water are all dependent on the monsoon rainfall, which has a crucial bearing on the national economy. Owing to the great socio-economic importance of the Indian monsoon rainfall, there has been a growing interest and effort to develop improved understanding of fluctuations in monsoon rainfall in relation to changes and fluctuations of large scale atmospheric and ocean circulation features. It is in this context that many workers have examined the relationship between the rainfall over the Indian region and ENSO events (Mooley and Parthasarathy, 1983; Parthasarathy and Pant, 1985; Mohanty and Ramesh, 1993; Mooley and Munot, 1993; Mooley, 1997 and Rao, 1998). The general conclusion from these studies is that Indian monsoon rainfall and ENSO phenomena 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) in the Indian Ocean has been reported (Cadet and Diehl, 1984; Cadet, 1985; Ramesh Kumar and Sastry, 1990; Babu and Joseph, 1998). These studies cover data sets of 2 to 3 decades, but the 1982-'83 event is not covered.

The upper ocean transport anomalies (modelled data) computed at four sections along the east coast of India indicated large interannual variability (Behera et al., 1998). The model upper layer transports along some sections showed a periodicity of 5-6 years. This periodicity conforms to that of the ENSO phenomenon.

Although the first half of the 1990s also witnessed strong ENSO episodes, these are small in intensity compared to the 1982-'83 event (Goddard and Graham, 1997). ENSO events were earlier reported to have a periodicity of approximately 5 years, but from recent studies, it is becoming increasingly evident that they are occurring much more frequently (Glantz, 1996).

From the above descriptions, it is clear that information on sea level-ENSO interactions are lacking in the Indian Ocean and we require to have some idea of these interactions using long time series observations (the presently available satellite data are insufficient for this purpose).

1.5. SATELLITE ALTIMETRY

With the advent of satellite altimetry, it has been possible to study large scale sea level variability which was not possible earlier (Fu et al., 1988; Jacobs et al., 1992; Harangozo et al., 1993). Satellite altimetric data at land-ocean boundary is bound to be less accurate as compared to that in the deep sea, and therefore, tide gauge data will continue to remain invaluable. Another use of the tide gauge data is for validation of the altimetric data (Le Provost, 1992; Mitchum, 1994; Chambers et al., 1998) and also for very accurate information on time scales smaller than a day (Woodworth, 1993).

When the time series of sea level is recorded with an instrument that is moving (e.g., satellite altimeter), the analysis and subsequent removal of the tidal signal is much more difficult because variations in the signal can arise not only from periodic temporal evolution of each constituent, but also from the movement through spatially varying fields of amplitudes and phases making the analysis a serious problem (Foreman et al., 1994). Hence, observed tide gauge data will continue to be important for accurate analysis.

1.6. SOME OTHER RECENT STUDIES ON SEA LEVEL

Noble and Gelfenbaum (1992) reported that changes in sea level (corrected for the effects of atmospheric pressure, wind stress and temperature) on the South Carolina shelf were seasonal and associated with seasonal changes in the transport of the Gulf Stream.

Yuce and Alpar (1994) identified non-tidal and tidal period oscillations in one year water level records from the southern coasts of Turkey.

Sultan et al. (1996) in their study of mean sea level variations at Port Sudan, Red Sea, found that the annual variations are induced by prevailing wind regime while the semi-annual variation was associated with the evaporation rate.

Abdelrahman (1997) showed that the seasonal changes of sea level are highly correlated with steric effects, evaporation rates and long-shore wind stress component at Gizan, Red Sea.

The study of Eid et al. (1997) showed that the seasonal sea level variations at the two ends of the Suez Canal are opposite in nature.

Tsimplis and Spencer (1997) found that the annual and semi-annual cycles and the longer term variability are consistent in the Mediterranean and Black Sea.

Wang et al. (1997) investigated the seasonal response of sea level in San Francisco Bay to atmospheric forcing during 1980.

Yuce and Alpar (1997) showed high spatial correlation in sea level, barometric pressure and winds over the Sea of Marmara region.

Alpar and Yuce (1998) found that the seasonal sea level fluctuations in the Black Sea, are in tune with the hydrological cycle of the region.

Stumpf and Haines (1998) examined the relationship between mean sea level and mean high water in describing water level changes in the Gulf of Mexico.

1.7. SEA LEVEL STUDIES IN THE INDIAN CONTEXT

Defant (1961) and Dronkers (1964) published some information regarding the tides at Cochin. Both gave the amplitudes and phases of the most important harmonic components viz. K_1, O_1, M_2 and S_2.

Ramanadham and Varadarajulu (1964) studied the variations in mean sea level at Visakhapatnam with regard to different meteorological parameters viz. rainfall, river runoff, wind field, atmospheric pressure, as also with oceanographic factors such as upwelling, sinking, and currents. They concluded that the variations can be attributed to heavy and concentrated rainfall, and winds blowing persistently in one particular direction which bring about changes in the oceanic circulation.

Ramanadham and Varadarajulu (1965) studied the effect of tropical cyclonic storms and depressions in the Bay of Bengal on the sea level at Visakhapatnam. They concluded that the sea level is maximum or minimum, a day after the wind attains its maximum speed. Another result reported by them is that the magnitude of the storm tide depends primarily upon the wind direction rather than the wind speed.

Rama Raju and Hariharan (1967) made a study of the diurnal and seasonal variation of sea level at Cochin during 1958 and 1959. They reported that the short period fluctuations in sea level, observed during southwest monsoon period, bear a close relationship with the rainfall during the season .

Janardhan (1967) studied the storm induced sea level changes at Sagar Island. He reported that the sea level at Sagar Island is not significantly affected by freshet discharges of river Hooghly.

Based on the mean sea level data, Banse (1968) suggested that during southwest monsoon season, cool subsurface water is always present on the entire shelf between Cochin and Karachi.

Josanto (1971) discussed the tidal ranges at Cochin for 1969 and 1970, and reported that the maximum frequency is in the class interval of 0.80 to 0.90 m with the lowest frequency in the class interval of 1.10 to 1.20 m. The maximum tidal range of 1.18 m was recorded in December for both the years. He also reported that the tidal range progressively diminishes northward, and southward from the Cochin Gut region.

With a view to understand the coastal processes along Madras coast in relation to sea level and waves, the seasonal characteristics of the same have been studied by Varadarajulu and Dhanalakshmi (1975). They concluded that fluctuations in the monthly and annual sea level could be attributed to the physical properties and climate in the neighbourhood of Madras.

Sharma (1978) discussed the upwelling off the southwest coast of India in relation to the time variation of the density structure, horizontal divergence of surface current vectors, wind stress components, thermal structure and sea level. He concluded that upwelling causes lowering of the sea level.

Kesava Das (1979), based on monthly mean sea level data at Mormugao, concluded that the predominant factors controlling the seasonal variation in mean sea level appeared to be coastal currents and water density. Another result reported by him was that the direct effect of the wind appeared to be relatively insignificant.

Varadarajulu et al. (1982) examined the monthly mean sea level variations at Paradip (on the east coast of India) and found them to be primarily related to variations in heating and cooling during summer and winter, respectively.

Varadarajulu and Bangarupapa (1984) explained the seasonal changes of sea level at Port Blair in relation to climatic factors which alter the density structure of the surface layers in the Bay of Bengal.

Woodworth (1984) presented the amplitude and phase of the annual and semi-annual cycles of the sea level for 390 stations throughout the globe. He concluded that there is no clear evidence for the astronomical contribution to the seasonal cycle observed in sea level records.

Woodworth (1985) concluded that there is no clear cut evidence for an 11 year component in the mean sea level records along the Indian coastline.

Shetye and Almeida (1985) examined the monthly mean sea level data at selected stations along the coastline of India. They concluded that, in general, the effect of atmospheric pressure on monthly mean sea level is significant. They found an excellent correlation between the atmospheric pressure corrected sea level and the alongshore component of current. They suggested that the sea level records at these stations could be used for long term monitoring of the surface geostrophic currents along the coast.

Emery and Aubrey (1989) based on trend analysis at 5 stations along the Indian coastline (west coast - 3, east coast - 2), concluded that there is no clear evidence as to whether the records document real sinking of land or real eustatic rise of sea level.

Shetye et al. (1990a) examined the vulnerability of the Indian coastal region to the consequences of the estimated sea level rise (0.67 mm/yr) due to the greenhouse effect.

Longhurst and Wooster (1990), in a study on upwelling along the southwest coast of India with regard to abundance of oil sardines, concluded that the sea level just prior to the onset of the monsoon is remotely forced in contrast to the wind driven upwelling that occurs during the southwest monsoon.

Das and Radhakrishna (1991) analysed the sea level records at Bombay, Madras, Cochin and Visakhapatnam and concluded that all the stations show long period cycles (50-60 year period), with shorter period cycles of 4.5 to 5.7 years riding on them.

Das and Radhakrishna (1993) studied tide gauge records from stations on the Indian coastline and also those at Karachi and Aden. Their analysis of the monthly records revealed evidence on the pole tide and annual cycle. Coherence analysis between monthly rainfall and relative sea level fluctuations for Bombay, revealed that the coherence is low.

Clarke and Liu (1993) showed that semi-annual sea levels along the eastern equatorial Indian Ocean are similar over a distance of more than 4000 km, whereas the annual sea level signals vary strongly along the coast in both amplitude and phase.

Tsimplis and Woodworth (1994) made a detailed study of records from 1043 tide gauges around the world to map the global distribution of the seasonal cycle of mean sea level at the continental coastlines and at ocean islands, making it the most exhaustive study of the seasonal cycle of sea level on a global basis, surpassing the data covered by Pattullo et al. (1955) and Woodworth (1984). Eventhough they covered the Indian coastline, they have not attempted to explain the meteorological or oceanographic influences that bring about the observed variability in the seasonal sea level. They concluded that the seasonal cycle of the sea level in the coastal waters exhibits considerable spatial complexity at a regional level but shows a greater spatial coherence when viewed globally.

Perigaud and Delecluse (1992) have discussed Indian Ocean sea level variability using Geosat altimeter data of 4.5 years duration. In the southern tropical Indian Ocean, they have shown the signature of the Rossby waves west of Indo-Pacific throughflow region.

Clarke and Liu (1994) studied the sea level records available for India and Pakistan to examine interannual sea level variability in the northern Indian Ocean. Their model study suggested that the interannual sea level signal occurs along more than 8000 Km of Indian Ocean coastline extending from Bombay to southern Java and is generated remotely by zonal interannual winds blowing along the equator.

Kalyani Devasena et al. (1996) determined that the sea level variability was high during a good monsoon year as compared to a bad monsoon year in the Indian Ocean. They also compared tide gauge data and Geosat altimeter data at a few selected stations in the Indian Ocean and further, observed that the sea level along the Arabian coast during the monsoon season was mainly influenced by the Somali Current.

Indira et al. (1996) based on fractal analysis of sea level variations along the Indian coastline, inferred that the long term behaviour of sea level changes can be modelled by a nonlinear dynamical system, having a small number of variables.

Shankar and Shetye (1997), in a modelling study, depicted the Lakshadweep High (centered near 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 during southwest monsoon) and subsequently propagates offshore.

Ali and Rashmi Sharma (1998) estimated mixed layer depth from Geosat derived sea level in the equatorial Indian Ocean.

Ali et al. (1998) located several cyclonic and anticyclonic eddies in the Bay of Bengal from in situ and altimeter observations.

Bruce et al. (1998) hypothesized that in addition to local and remote seasonal forcing, the Laccadive High region (an anticyclonic circulation feature that forms off the southwest coast of India during the northeast monsoon) is influenced by an intraseasonal signal that originates in the Bay of Bengal.

Pal and Ali (1998) simulated the sea surface heights in the Arabian Sea using a reduced gravity, primitive equation thermodynamic model.

Prasanna Kumar et al. (1998), using satellite altimeter data, reported that the large scale sea surface height variability reflects the dominant seasonal signal such as coastal currents and the upwelling zones along Somalia, Arabia and west coast of India.

Rashmi Sharma et al. (1998) reported that long wavelength Rossby waves are present in the Arabian Sea at latitudes between 10°N and 16°N.

1.8. BACKGROUND OF THE PRESENT STUDY

Cochin (9° 58'N; 76° 15'E) (also known as Kochi), a growing city located on the southwest coast of India, is the main port of Kerala State (South India). It is also one of the major ports of the country. The hinterland of the port includes the whole of Kerala state and parts of Tamil Nadu and Karnataka states of South India. With a strategic location, it holds a commanding position at the cross roads of East-West ocean trade. Its proximity to the international sea route between Europe on one hand and Far East and Australia on the other, enhances its importance. This port is located on the western side of Vembanad lake and is surrounded by a number of islands, the most important ones being Vallarpadom, Vypeen and Bolghatty in the north, and Nettor, Kumbalam and Panangad in the south. Periyar and Muvattupuzha are the two important rivers, besides others, discharging into the Vembanad estuary, which is the life-line for the inhabitants of this area. The Cochin estuarine complex consisting of Vembanad estuary, the rivers flowing into the estuary and the surrounding islands, is a very important and integral part of the estuarine ecosystem in this part of the country (Fig. 1.1). Thus, Cochin is well known as a port and also for its ecosystem.

The estuarine systems are highly sensitive to changing climatic variables such as river discharge of water and sediments, temperature rise, rainfall, wind and wave climate (Dyer, 1995; Psuty, 1995; Houghton et al., 1998). Further, sea level is also well known to be controlled by the astronomical tidal forcings (this is perceptible at most coastal sites and met-oceanic forcings such as atmospheric pressure, wind field, oceanic circulation, density of sea water, rainfall and river discharge in the area. All these point out the need for an integrated approach to the study of variability in sea level and related meteorological and oceanographic parameters. From this point of view, it was felt that a study on the effect of some of these climatic variables on the Cochin estuarine system, which is a complex system into which 5 rivers debouch, should be carried out. This system has been experiencing many anthropogenic and natural changes. In view of its importance as a port city also, an understanding of the effect of sea level variations in relation to other meteorological and oceanographic parameters was felt necessary for Cochin. Accordingly the study was undertaken, and the results of the study form the subject matter of the subsequent chapters. The findings of the study as also some other related aspects are included in these chapters. As a part of this study, the sea level variations at Cochin have been compared with those of sixteen other stations along the Indian subcontinent (Fig. 1.2). These findings, it is hoped, will pave way for a better understanding of the ecological changes being brought about by the developmental activities taking place in and around Cochin.

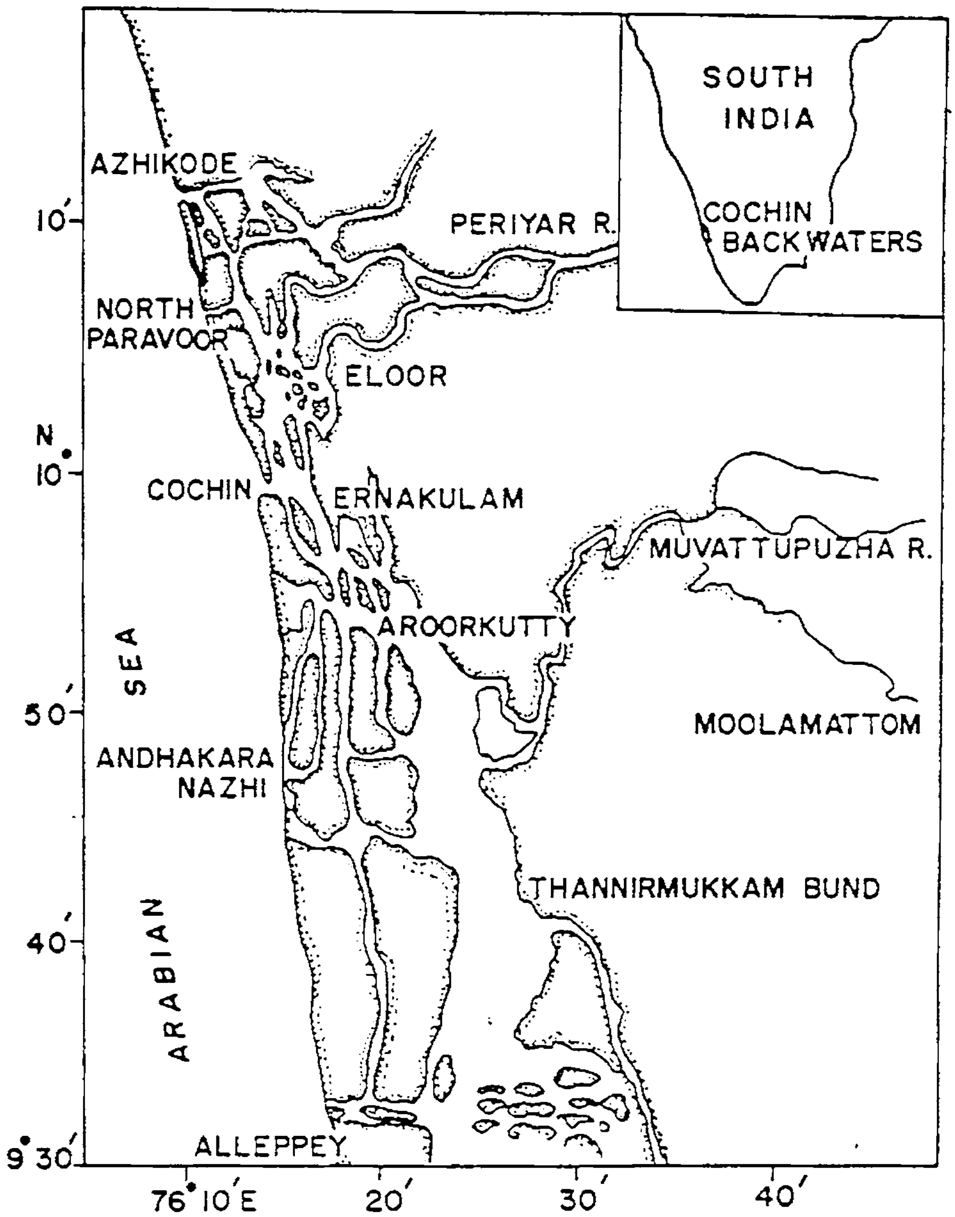


Fig. 1.1. Vembanad Lake system.

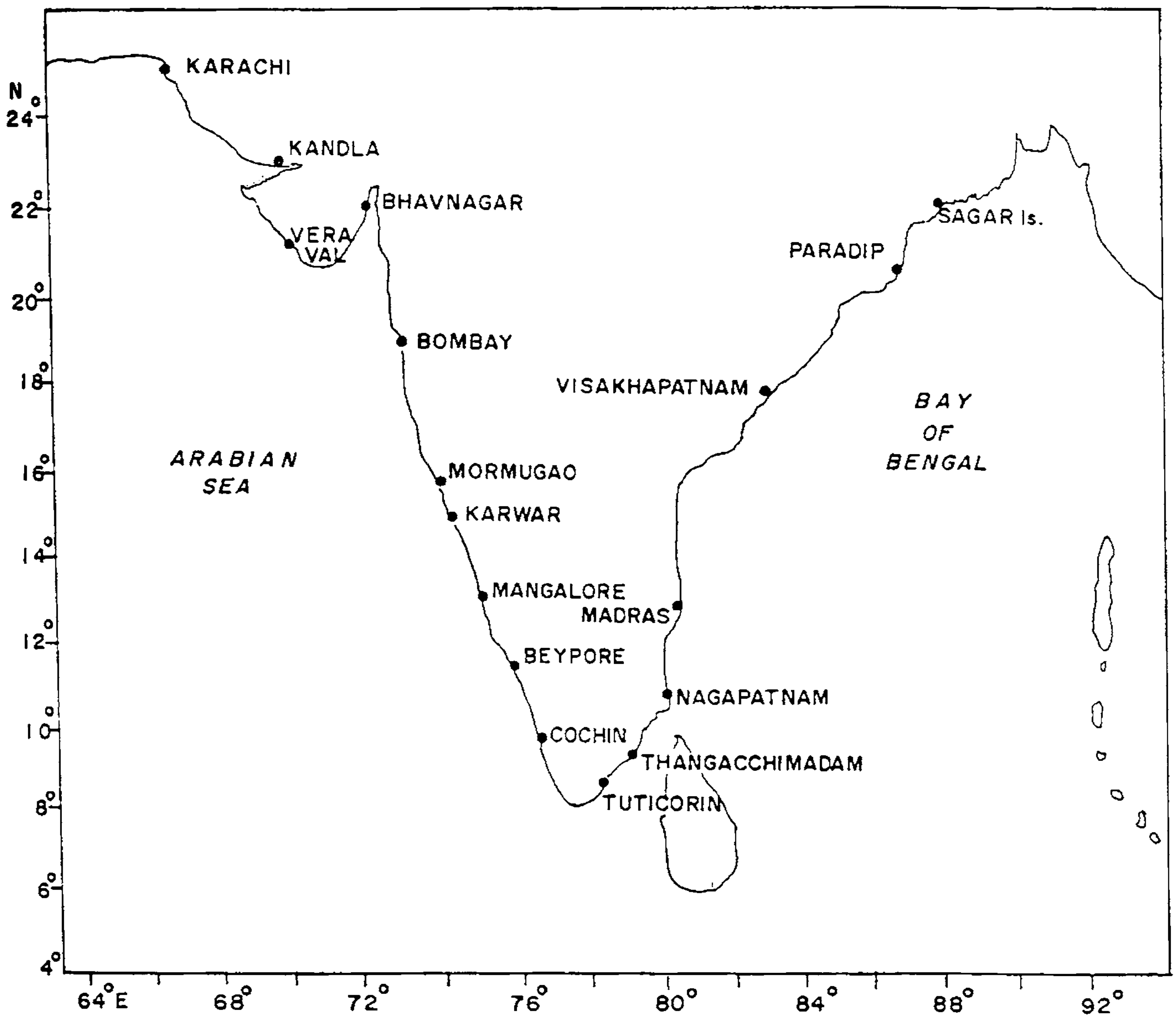


Fig. 1·2. STATION LOCATION MAP.

CHAPTER 2

CHAPTER 2

HARMONIC ANALYSIS OF TIDES AT COCHIN

2.1. INTRODUCTION

Tides form one of the oldest branches of physical oceanography. It is the most perceptible form of sea level variation. The gravitational forces of the sun and moon, acting on a rotating and orbiting earth, are responsible for the tides observed on the earth (Pugh, 1987; Godin, 1988; Foreman, 1993; Carter, 1995; Wells, 1997). These tides manifesting as regular water movements (seen as both vertical rise and fall, and the to and fro movement of associated water currents) are a feature in all the oceans and the adjacent seas (Pugh, 1987; Bearman, 1994). Because of the proximity of the earth to the moon, the lunar contribution is prominent in the observed tides on the earth. The sun's tide generating force is about 46% that of the moon. The tidal response of the ocean due to forcings of the sun and moon is very complicated and the two main tidal features - range and period, vary greatly from one location to another. Tides have a controlling influence on many marine biological and geological processes (King, 1972; Komar, 1976; Dyer, 1986; Carter, 1995; Kvale et al., 1995; Power, 1997). A proper knowledge of the tidal dynamics is necessary to understand many general oceanographic phenomena at any station.

2.1.1. EFFECT OF SOLAR AND LUNAR MOVEMENTS ON THE TIDES

During Vernal Equinox (21 March), the sun is directly above the equator and moves from the southern hemisphere to the northern hemisphere. By about 21 June (Summer Solstice), the sun reaches its maximum northerly point in the sky i.e. Tropic of Cancer (23.5^{o}N latitude). The Summer Solstice marks the beginning of summer in the northern hemisphere and the beginning of winter in the southern hemisphere. The sun then starts moving southward and by about 23 September (Autumnal Equinox) it is directly above the equator again. The southern movement continues and by about 22 December (Winter Solstice), it reaches its maximum southerly point in the sky i.e. Tropic of Capricorn (23.5^{o}S latitude). The Winter Solstice marks the beginning of the winter in the northern hemisphere and the beginning of summer in the southern hemisphere. The tides occurring at the times of equinoxes are called "equinoctial tides". The tides occurring at the times of solstices are called "solstitial tides". There is a tendency for an increase in the diurnal range during solstices. Tides occurring semimonthly near the times of maximum north or south declination of the moon are called "tropic tides". The tropic range - the difference in height between higher high water and lower low water during the times of moon's maximum declination, may be expected to be large during these times. The semimonthly tides, occurring when the moon is over the equator, are called "equatorial tides". The diurnal inequality in the tide is a minimum at this time. The moon moves through a declinational cycle in 27.21 mean solar days whereas the sun moves through a declinational cycle once a year. The solar declination varies between 23.5°N and 23.5°S and the cycles of lunar declination vary in amplitude over an 18.6 year period from 28.5° to 18.5° (Pugh, 1987).

2.1.2. TYPES OF TIDES

The harmonic tidal constituents which enable us to recognise the characteristic features of tides at a particular location are M_2, S_2, N_2, K_2 and K_1, O_1, P_1 (Defant, 1961). When the phase of M_2 and S_2 tides are the same, the amplitudes of M_2 and S_2 tides are added, which results in the range $2(M_2+S_2)$. This occurs during spring tide and the process repeats itself 14.77 days later. In the mean time, a moment occurs when the amplitudes of both tides result in (M_2-S_2). This occurs during neap tide, giving a neap range of $2(M_2-S_2)$. The amplitude of S_2 thus determines the fortnightly inequality (Defant, 1961; Bowden, 1983; Wells, 1997).

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

i) DIURNAL TIDE: Only one high water occurs daily. At neap tide, when the moon has crossed the equatorial plane, two high waters may occur. The mean range of the spring tide is $2(K_1+O_1)$.

ii) MIXED, PREDOMINANTLY DIURNAL TIDE: At times only one high water occurs per day namely, after the extremes of the moon's declination. When the moon has passed over the equator, the two high waters per day show large inequalities in range and time. The mean range of the spring tides is $2(K_1+O_1)$.

iii) MIXED, PREDOMINANTLY SEMI-DIURNAL TIDE: Two high and two low waters occur daily with large inequalities in range and time. The maxima in inequalities occur whenever the moon's declination has passed its maximum values. The mean range of the spring tide is $2(M_2+S_2)$.

iv) SEMI-DIURNAL TIDE: Two high and two low waters of nearly same height occur daily. The time of high water follows at approximately equal interval after transit of moon at that location. The mean range at spring tide is given by $2(M_2+S_2)$.

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

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

where HK_1, HO_1, HM_2 and HS_2 are the amplitudes of the K_1, O_1, M_2 and S_2 tides.

With the aid of this Form Number, F, which describes the form of a tidal curve during one day, the tides may be broadly classified as follows:

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

Over-tides (which are produced during the propagation of the tide into shallow waters) may change the shape of the tide but cannot change the type of tide.

2.1.2.1. MIXED TIDES

During part of the lunar month at the time when the moon crosses the equator (declination is small), the tide is mainly semi-diurnal. When the moon's declination is nearly maximum, the diurnal components may be sufficient to produce one high and one low water. It is evident that at places where the tides can be considered semi-diurnal, the diurnal components may be noticeable when the declination of the moon is large. Conversely, when the moon's declination is zero, tides which are usually diurnal can become semi-diurnal. The mixed tide may have characteristics of both semi-diurnal and diurnal tides. The diurnal inequality is a characteristic of this tide, as successive high tides and/or low tides will have significantly different heights. Mixed tides commonly have a period of 12 hr 25 min, which is a semi-diurnal characteristic, but may also possess diurnal periods. This is the tide that is most common throughout the world. Diurnal inequalities are greatest when the moon is at its maximum declination, and such tides are called tropical tides because the moon is over one of the tropic regions.

In a mixed tide with very large diurnal inequality, the higher low water (or lower high water) frequently becomes indistinct (or vanishes) at the time of extreme declinations. During these periods, the diurnal tide has such overriding dominance that the semi-diurnal, although still present, cannot be seen on the tidal curve. This condition is often referred to as the vanishing tide.

In the case of mixed tides, the magnitude of the diurnal tides is similar to that of semi-diurnal tides. In this composite type of tidal regime, the relative importance of the semi-diurnal and diurnal components keeps changing throughout the month. The diurnal tides have large magnitudes when the moon's declination is greatest but reduce to low values when the moon is passing through the equatorial plane. Semi-diurnal tides are most important after full and new moon and are only partly reduced during the period of neap tides.

In view of the importance of tides with reference to sea level, an analysis of observed tidal data has been carried out for Cochin and the results form subject matter of this chapter. Some aspects of the important partial tides are given in Appendix-I.

2.2. MATERIALS AND METHODS

The hourly sea level data recorded by a tide gauge at Cochin for the period 1988-'93 (Figs. 2.1 - 2.6) were utilised for this purpose. The instrument for recording the tide is the Automatic Tide Gauge Recorder installed by the Survey of India, Dehra Dun. The tide curve is recorded on a chart paper, which is replaced at 10.10 AM every day. The accuracy of the instrument is ± 2cm. The occasional gaps in the data were interpolated using cubic spline algorithm. The important lunar phases are also indicated in each figure to appreciate their forcings on the tides.

Harmonic analysis of observed sea level provides the basis for the prediction of tides (Wong, 1986; Chettiar and Ullah, 1988; Fernandes et al., 1991; Emery and Thomson, 1998). Tide filtering is necessary to study non-tidal signals, and harmonic analysis provides a basis for computing the residuals (Denes and Caffrey, 1988). This is important as the tidal signal is strong in most of the coastal regions. The procedure of harmonic analysis involves calculation of the amplitudes and phases of a finite number of constituents that best fit a given time series (Appendix-I). Subsequent to this, a new time series comprising of only tides has to be constructed and the time series has to be de-tided by subtraction (Foreman et al., 1994). A thorough discussion of harmonic analysis methods is given by Godin (1972), Pugh (1987), Godin (1988) and Emery and Thomson (1998).

Accuracy of the estimates of harmonic tidal constituents (components) is highly dependent on the record length, total number of harmonic constituents sought and variance of the non-tidal signal in the record (Aubrey and Speer, 1985; Pugh, 1987; Reid, 1990; DiMarco and Reid, 1998; Kantha et al., 1998).

2.2.1. SPECIES DETAILS

Table 2.1 gives the number of constituents (total 68, including mean sea level) in each of the nine species, that were resolved using the least squares method on hourly data of 365 days (or 366 days for leap years) for the period of study (1988-1993). The respective lower and upper limits of the periods are also given against the species number. The periods for which the amplitudes and phases were determined varied between 0.1294 days to 365.2728 days. The sum of the amplitudes of the diurnal and semi-diurnal species contributed about 40% each of the total amplitude. The sum of amplitudes of the long period species contributed about 14% to 19% of the total sum. The sum of amplitudes of the third to eighth diurnal species was generally much less than 3% of the total amplitude.

2.3. RESULTS AND DISCUSSION

2.3.1. ACCURACY OF TIDAL CONSTITUENTS

When presenting the results of a tidal analysis, it is usual to refer to tidal "constituents" rather than tidal "constants". The constituents may have slight changes if a different period of data is analysed for the same place. However, analysis of individual months of the tidal data for the same place invariably shows small variations in the tidal constituents about some mean value (Defant, 1961; Pugh, 1987). Reasons for the variability include inconsistencies in the measuring instruments, analysis limitations due to non-tidal energy at tidal frequencies and real oceanographic modulations of the tidal behaviour. Pugh (1987) opined that for monthly analyses, there remains a real oceanographic signal, which is not due to variations in the astronomical forcing functions, as these variations persist no matter how fully the forces are represented.

2.3.2. TIDAL CONSTITUENTS

The harmonic constituents (amplitudes and phases) estimated from the hourly data for each year for the period 1988-1993 for the observed data are presented in Tables 2.2 and 2.3. From the tables, it is evident that there is year to year variability in the amplitudes and phases of the constituents. The year to year changes are less in the case of the principal tidal constituents. This is in accordance with the observations made by a number of workers at other locations (Defant, 1961; Cheng and Gartner, 1985; Pugh, 1987 and Godin, 1995). From Table 2.4, in which some statistics of the tidal amplitudes are presented, it is clear that the important constituents M_2, S_2, N_2, K_2, K_1, O_1 and P_1 have smaller coefficients of variation, which show that they manifest smaller variability as compared to the other constituents. The shallow water constituents showed a high degree of variability and this also varied from component to component. The M_2 constituent showed the maximum amplitude (20.4 cm), followed by K_1, O_1, S_a, S_2, P_1, N_2, S_{sa}, Q_1 and K_2 (2.2 cm), etc.

The relative amplitudes of the two smaller constituents (S_2 and N_2) to M_2 are about 0.37 and 0.22, indicating a large spring-neap variation $((M_2+S_2)/(M_2-S_2) = 2.2)$ and monthly variation $((M_2+S_2+N_2)/(M_2-S_2-N_2) = 3.9)$ in the semi-diurnal forcing. A similar analysis for the tides on the Amozonian shelf, reported by Beardsley et al. (1995) gave a value of 1.9 for the spring-neap variation and 3.2 for the monthly variation in the semi-diurnal forcing.

2.3.3. PRINCIPAL TIDAL CONSTITUENTS

The amplitudes as well as phases displayed a more or less constant value for the seasonal as well as annual analysis, pointing out remarkable stability of these constituents viz. K_1, O_1, M_2 and S_2 (Table 2.5).

The amplitudes based on the annual analysis showed a change, whose magnitude was less than 5% of its seasonal value (Table 2.6). The phases based on the annual analysis showed a change, whose magnitude was less than 2% of its seasonal value (Table 2.6).

The seasonal variation of the amplitude of the most important harmonic constituents namely M_2, S_2, K_1 and O_1 are presented in Fig. 2.7a. It may be noted that the components O_1 and M_2 show very little variation whereas K_1 and S_2 show comparatively higher variation. The seasonal cycle of K_1 is more or less the mirror image of that of S_2 with the maxima of K_1 corresponding with the minima of S_2 and vice-versa. The contribution of the K_1 component is conspicuously more during June and December and less during March and September whereas it is exactly opposite for S_2.

The seasonal variation of the phases of the constituents M_2, S_2, K_1 and O_1 are presented in Fig. 2.7b. The phases of the O_1 and M_2 constituents show very little variation whereas K_1 and S_2 components show comparatively higher variation. The seasonal march of the phases of the K_1 and S_2 constituents show a more or less similar pattern.

K_1 and P_1 have the same phase at the time of summer and winter solstices when both the tides reinforce each other, whereas at the equinoxes, the two components counteract each other. The P_1 tide thus causes the diurnal contribution to have a maximum at solstices and not at the equinoxes (Defant, 1961; Pugh, 1987). Pugh (1987) discussed the month to month variability of the tidal constituents, and showed that there exists usually a consistent regional pattern in these variations. These irregular variations are likely to be caused by shallow-water interactions between tides and surges, as a result of more energy being lost from tides and surges travelling together (Amin, 1982). Pugh and Vassie (1976) reported that there is a seasonal modulation of the M_2 constituent amplitude which varies between 1% and 2 % in the North Sea. A part of such modulations is directly due to astronomical effects such as the influence of the sun on the lunar orbit, but the rest of the variability could probably be due to tide-surge interaction. Because surges are larger during winter, the winter amplitudes of M_2 should be less than the amplitudes obtained during quieter summer months, and the observations were consistent with the expected behaviour (Pugh, 1987). Seasonal variation of tides has been reported elsewhere (Ahmad, 1972; Lisitzin, 1974; Godin, 1987; Foreman et al., 1995; Kang et al., 1995).

2.3.4. SPRING AND NEAP TIDAL RANGES

The seasonal mean of the spring tidal range was 56.8 cm, with a standard deviation (SD) of 2.5 cm (which is 4.4% of the mean) and the seasonal mean of the neap tidal range was 25.3 cm, with a SD of 4.6 cm (which is about 18.2% of the mean). It was thus seen that the mean neap tidal range exhibited a higher degree of variability as compared to the mean spring tidal range over the long-term seasonal cycle (Fig. 2.8a).

2.3.5. FORM NUMBERS

The Form Numbers for the annual analysis for the period 1988-1993 varied from 0.94 to 1.02, indicating that the tide is of mixed, predominantly semi-diurnal form during each year (Table 2.7). This result is in good agreement with those of Defant (1961) and Dronkers (1964) who reported 0.91 and 0.90 for Cochin, respectively. The sum of the amplitudes of K_1, O_1, M_2 and S_2 accounted for roughly 45% to 55% of the sum of all amplitudes and this increased to 55% to 65% with the inclusion of the K_2, N_2, and P_1 amplitudes. Dietrich (1963) had mentioned that for annual analysis, the four principal tidal components K_1, O_1, M_2 and S_2 dominate the tidal phenomena and their amplitudes contribute about 70% of all the amplitudes. He considered about 27 partial tides only for the annual analysis, whereas in this study 67 components were considered. The sum of the amplitudes also varied from 50 cm to 60 cm for the principal tidal components, but Defant (1961) reported a value of 57.6 cm, which could be due to the interannual fluctuations in the constituent amplitudes.

Dronkers (1964) classified the tides at Cochin to be of mixed type, with the Form Number equal to 0.90. He also brought out the variation of the daily inequality with the moon's declination as well as the variation in range with the phases of the moon. This can be seen in Figs. 2.1-2.6, in which the lunar phases are displayed.

The Form Numbers, based on mean monthly data on the amplitudes of M_2, S_2, K_1 and O_1 were generated for the period 1988-1993 (Fig. 2.8b). This was to get a clear seasonal picture of the importance of diurnal and semi-diurnal components. The Form Numbers varied from 0.74 to 1.25. This shows that the tide is of mixed, predominantly semi-diurnal type. It is mixed, having higher diurnal contribution during June and December, and higher semi-diurnal contribution during March and September. This is in agreement with other observations reported elsewhere (Ahmad, 1972; Lisitzin, 1974; Pugh, 1987).

The seasonal variation of the tides at Cochin may be classified as mixed and predominantly semi-diurnal because the Form Number is between 0.25 and 1.50. The solar declination plays a very important role in this regard. The solar declination varies seasonally from 23.5° in June to -23.5° in December. During March and September the solar declination is zero and hence the total amplitude of the diurnal forcing is the least.

2.3.6. COMPARISON BETWEEN EARLIER RESULTS AND THE PRESENT RESULTS

To understand whether any changes have taken place in the amplitude and phase of the constituents (K_1, O_1, M_2 and S_2), data published by Defant (1961) and the data generated in this study (for the year 1993) have been compared (Table 2.8).

The amplitudes displayed a more or less constant value whereas the phases showed an increase over the three decade period. The increase in phase indicates delayed occurrence of the times of maxima which could be attributed to dredging and other hydraulic projects (Gopalan et al., 1983; Rasheed et al., 1995; Dinesh Kumar, 1997).

2.3.7. RADIATIONAL TIDES

In addition to the astronomical forcing, there are few harmonic constituents which are primarily due to periodic meteorological forcing - annual, semi-annual and the S_1, diurnal tide. They are called radiational tides because of their association with the cycles of solar radiation (Pugh, 1987). Among the long-period astronomical tides - S_a (solar annual) and S_{sa}(solar semi-annual) tides are strongly enhanced by seasonal climatic variations. The radiational tides (often referred to as meteorological tides) have their origin in daily or seasonal variations in the weather conditions which usually occur with some degree of periodicity. This definition, however, excludes changes in sea level due to meteorological changes that are random e.g. those due to storm surges. These periodic variations in sea level are forced by meteorological changes such as semi-diurnal cycle in barometric pressure, diurnal cycle of land and sea breezes and seasonal changes in temperature - all solar radiation induced. The principal meteorological constituents seen in observed tides are S_a, S_{sa} and S_1, of which the first two usually have much higher amplitudes than the last one.

The S_1 tide has its origin in diurnal meteorological forcing and may have amplitudes of a few centimeters in extreme cases (Pugh, 1987). The radiational S_1 component is probably generated by local diurnal land-sea breezes caused by the differential heating of the land and sea. Only in the tropical regions where the diurnal heating cycle is strong, large S_1 tidal amplitudes are found. Along the coast of the United States, the amplitude of S_1 is quite small, close to 0.01m (Pugh, 1987). The S_1 constituent may also be produced by instrument errors in a harmonic analysis. Temperature sensitive sea level recorders and incorrectly mounted chart drums have been known to introduce a spurious S_1 term into the data.

For the radiational tides at Cochin, the sum of the amplitudes of S_a, S_{sa} and S_1 contributed from around 12% to 15% of the sum of all amplitudes for each year during the period 1988 to 1993. The S_a constituent contributed maximum followed by the semiannual, and the least by S_1 constituent, for all the years (Table 2.9).

The amplitudes of the annual and semi-annual equilibrium tides at Cochin are 0.14 cm and 0.91 cm, respectively. These are very small compared to the amplitudes of the annual (8.95 cm) and semi-annual (3.83 cm) components of the sea level (Table 2.4). It is evident that the annual component in the observed sea level is almost entirely due to non-tidal influences, as indicated by the high ratio of observed to equilibrium tide amplitudes (of around 64). This arises because the annual solar cycle produces a weak astronomical tide, but generates the major climatic cycles such as those exhibited by seasonal atmospheric pressure, wind, rainfall, evaporation and sea temperature. In comparison, the ratio of the observed to the equilibrium tide amplitudes in the case of the semi-annual cycle is only about 4. Similar comparisons have been made elsewhere (Sultan et al., 1995a; Kjerfve et al., 1997; Bell and Goring, 1998).

2.3.8. SHALLOW WATER TIDES

Tidal ranges on relatively shallow continental shelves are usually larger than those in the open oceans. In some shallow regions, however, very small tidal ranges are observed, often accompanied by curious distortions of the normal tidal patterns. Pugh (1987) reported that at Courtown when the range is very small, careful examination showed that four tides occurred each day. These effects are due to the distorted tidal propagation in very shallow water. Shallow water tidal constituents arise from the distortion of the main constituent tidal oscillations. Shallow water distortions are also responsible for double high and double low waters in some places. In shallow water, the progression of the tidal wave is modified by bottom friction and other physical processes which depend on the square or higher powers of the tidal amplitude itself. These distortions can also be expressed as simple harmonic constituents with angular speeds which are multiples, sums or differences of the speeds of the major harmonic tidal constituents (Dronkers, 1964; Aubrey and Speer, 1985; Pugh, 1987; Bearman, 1994). In practice, a whole range of extra constituents is necessary to represent distortions in shallow water. Harmonic analysis of the observed tides shows that shallow-water terms in the odd-order bands (third, fifth, etc.) are less important than the fourth, sixth and higher even-order bands. However, the relative importance of the shallow-water terms and the number required to represent the observed tidal variations varies considerably from region to region depending on the physical processes and the severity of the interaction. Because the speed of propagation of a progressive wave is approximately proportional to the square root of the depth of the water in which it is travelling, shallow water has the effect of retarding the trough of a wave more than the crest. This distorts the original sinusoidal wave shape and introduces harmonic signals that are not predicted in tidal potential development. The shallow water constituents included in the present study are derived only from the largest main constituents, namely M_2, S_2, N_2, K_2, K_1 and O_1, using the lowest type of interactions.

In the present study, the sum of the amplitudes of 24 shallow water constituents shows a percentage contribution varying around 5% - 7% of the sum of all amplitudes. The percentage contribution to the total sum increased to 7% - 9% with the inclusion of long period shallow water tides.

2.3.9. DISTRIBUTION OF OBSERVED AND PREDICTED TIDES AND METEOROLOGICAL RESIDUALS

The regular and predictable tidal movements of the sea are continuously modified to a greater or lesser extent by the effects of the weather. Exchange of energy between the oceans and the atmosphere occurs within a wide range of space and time scales. The weather-driven movements with periods from several minutes to several days are the ones which are of interest. The relative importance of tidal and non-tidal movements depends on the time of the year and the local bathymetry. The non-tidal residual S(t), as the difference between the observed and predicted tides, is given by

$$S(t) = X(t) - Z_0(t) - T(t) \qquad (2.1)$$

where X(t) is the observed sea level (which varies with time)

$Z_0(t)$ is the mean sea level (which changes slowly with time)

T(t) is the tidal part of the variation

The non-tidal residual is also called the meteorological residual, set-up, or non-tidal component.

If the time series S(t) of the hourly residuals is computed according to equation (2.1), several useful statistics may be derived. The standard deviation of S(t) varies from values of a few centimeters at tropical oceanic islands, to tens of centimeters in areas of extensive shallow water subjected to stormy weather. At Mahe (in Seychelles) it has a very low standard deviation (0.05m) whereas at Southend in the southern North Sea, it has a relatively high value (0.25m). These figures may be used to derive confidence limits for tidal predictions, but are not "errors" in the predictions in the usual scientific sense. Even though tidal variations can be removed in the analysis, there could be energy in the tidal frequencies because of small timing errors in the gauge and weak interaction between the tides and the surges.

The time series of the meteorological residuals for the period 1988-1993 are presented in Figs. 2.9 to 2.14. The meteorological residuals are normally noisy due to nonlinear influences on the tides from shallow depth, interaction with river flow, irregular coastal and bottom geometry. Sometimes, periodic fluctuations seen riding on the residuals are caused by the ineffectiveness of the tidal predictions to resolve all the nonlinear harmonics in the tides. Tide gauge timing errors also cause a periodic component to be present in the meteorological residuals.

The distribution of the observed hourly tides and the meteorological residuals and some associated statistical parameters were estimated to understand the nature of these observations. These are discussed below.

2.3.9.1. OBSERVED TIDES

The mode was observed to be occurring in the class interval 70-80 cm. The kurtosis and skewness parameters showed that the distribution was largely platykurtic and that the skewness was negative (Table 2.10). The combined data for the entire period of study also showed the distribution to be platykurtic, with negative skewness (Fig. 2.15a). The mean sea level showed slight variations for the yearly data and the mean for the entire period of study was 66.8 cm. The standard deviation of the observed hourly values showed slight variability over the years, and for the whole period it was 24.4 cm. The average annual range (of the maximum observed hourly value and the minimum observed hourly value for each year) was around 137 cm for the 1988-1993 period.

2.3.9.2. PREDICTED TIDES

The kurtosis and skewness parameters showed that the distribution was largely platykurtic and that the skewness was negative (Table 2.10). The combined data for the entire period of study also showed the distribution to be platykurtic, with negative skewness (Fig. 2.15a). The mean sea level showed slight variations for the yearly data and the mean for the entire period of study was 66.8 cm. The standard deviation of the predicted hourly values showed slight variability over the years, and for the whole period it was 23.5 cm.

2.3.9.3. METEOROLOGICAL RESIDUALS

Distribution of the meteorological residuals (difference between the observed and predicted tides) and some statistical parameters were also worked out to understand the nature of the distribution (Table 2.10).

The distribution was found to be largely leptokurtic (kurtosis is positive) and skewed to the left (skewness is negative) for the individual years. The combined data for the entire period viz. 1988-1993 also showed kurtosis to be positive and skewness slightly negative (Fig. 2.15b). The standard deviation of the hourly residuals for individual years also showed slight variability and it was 6.46 cm for the entire period. The average annual range (based on the difference between maximum positive value and the minimum negative value for each individual year) for the residuals was found to be about 55 cm for the 1988-1993 period. The maximum percentage frequency was found to occur in the 0-5 cm class interval.

2.4. CONCLUSIONS

From the foregoing account, the following conclusions could be arrived at:

1. The constituents M_2, S_2, N_2, K_2, K_1, O_1 and P_1 have not shown significant variability over the period 1988-1993, indicating that these tidal components are more or less constant in amplitude and phase. Most of the other components, particularly the shallow water ones, showed higher degree of variability as brought out by the coefficient of variation in amplitude.

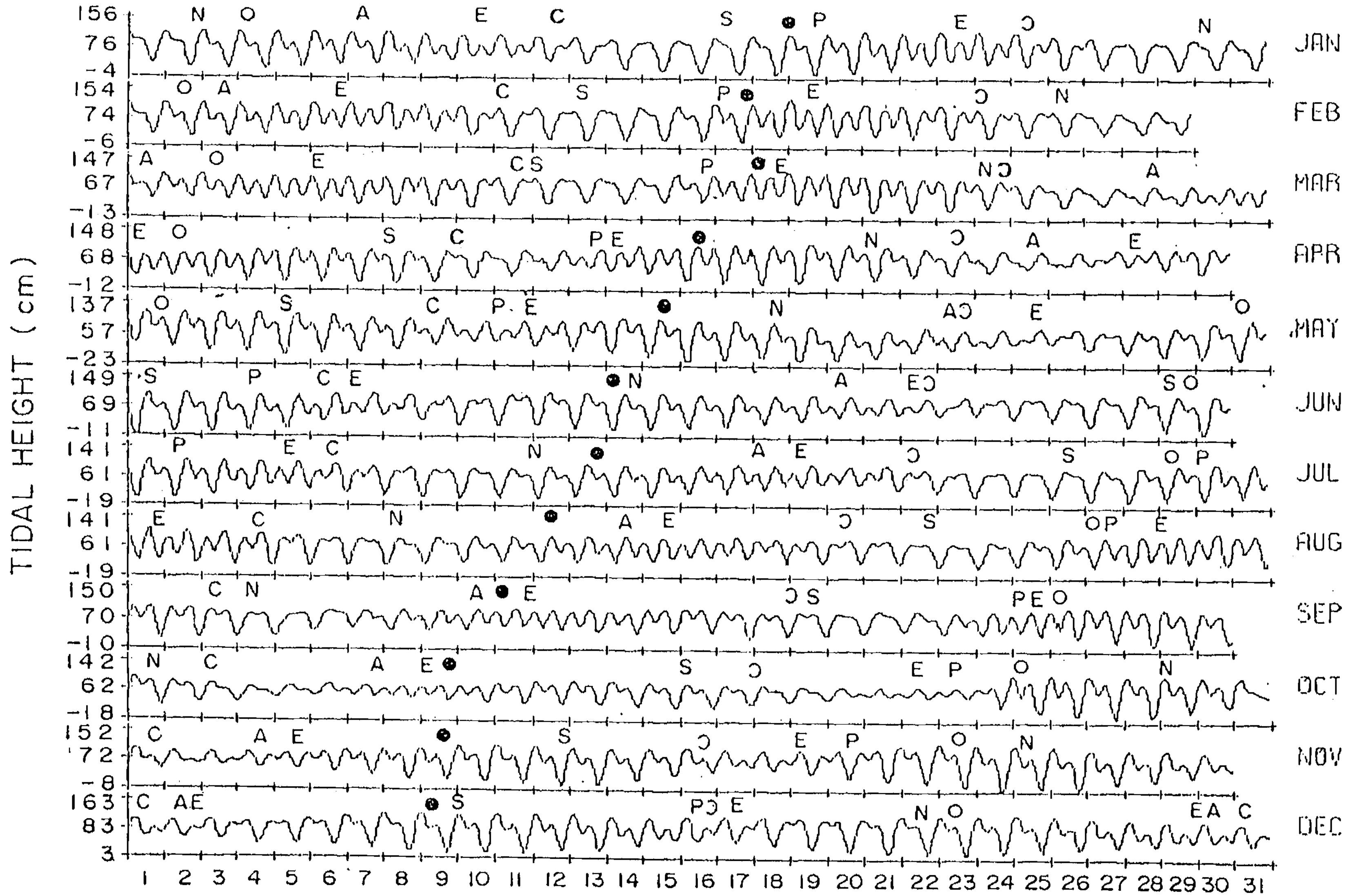
2. The seasonal variation of the most important constituents has shown that K_1 and S_2 are responsible for the observed seasonal cycle of tides at Cochin.

3. Form Numbers showed that the observed tide is of mixed, predominantly semi-diurnal type. However, it was seen that there was higher diurnal contribution during June and December, and higher semi-diurnal contribution during March and September.

4. The mean neap tidal range exhibited a higher degree of variability as compared to the mean spring tidal range over the long-term mean seasonal cycle.

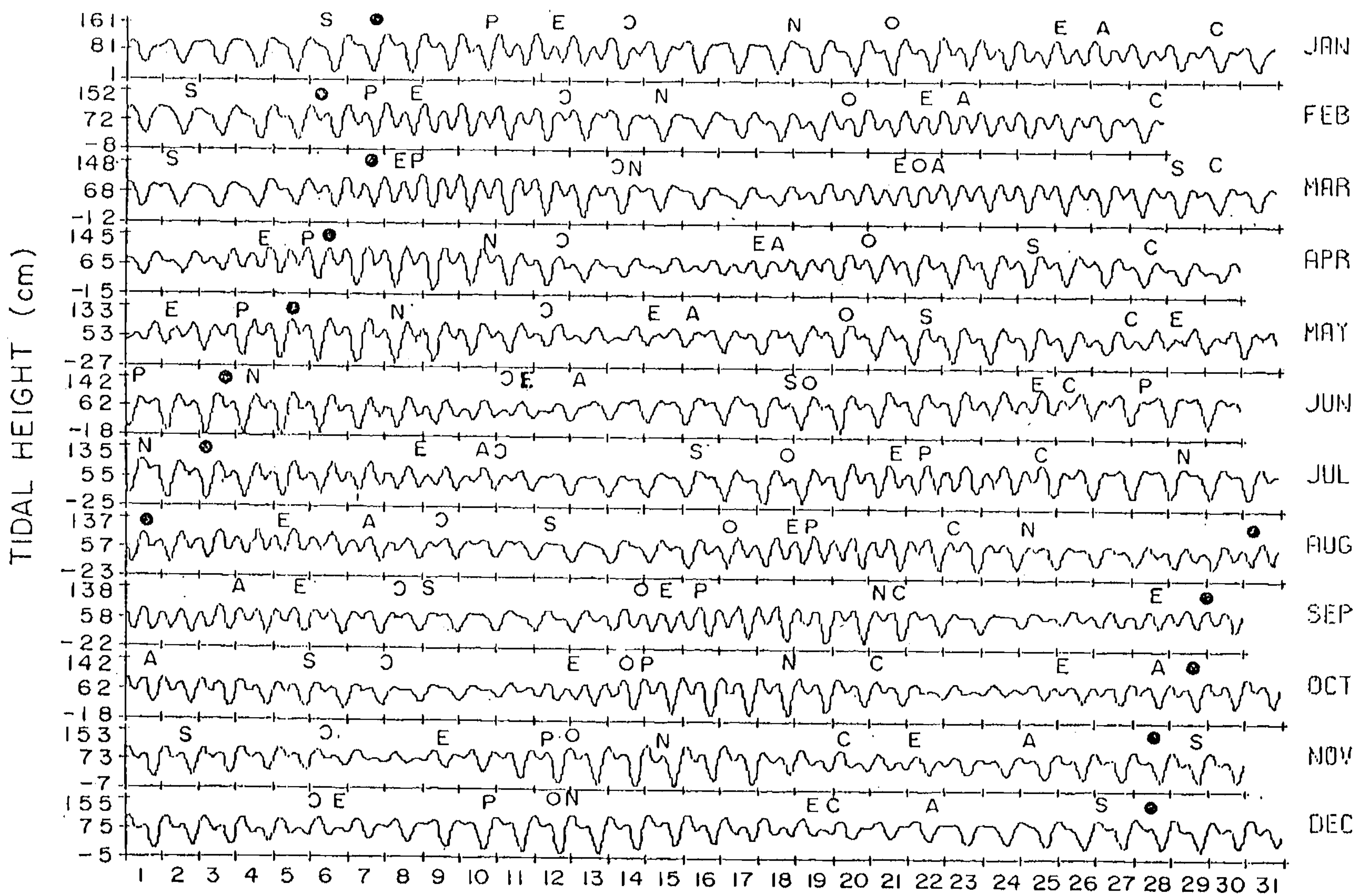
5. The standard deviation, skewness and kurtosis of the observed and predicted tides, and the meteorological residuals were worked out.

6. The RMS deviations based on the residuals between the observed and the predicted tides were, in general, small for the predictions based on the present analysis.



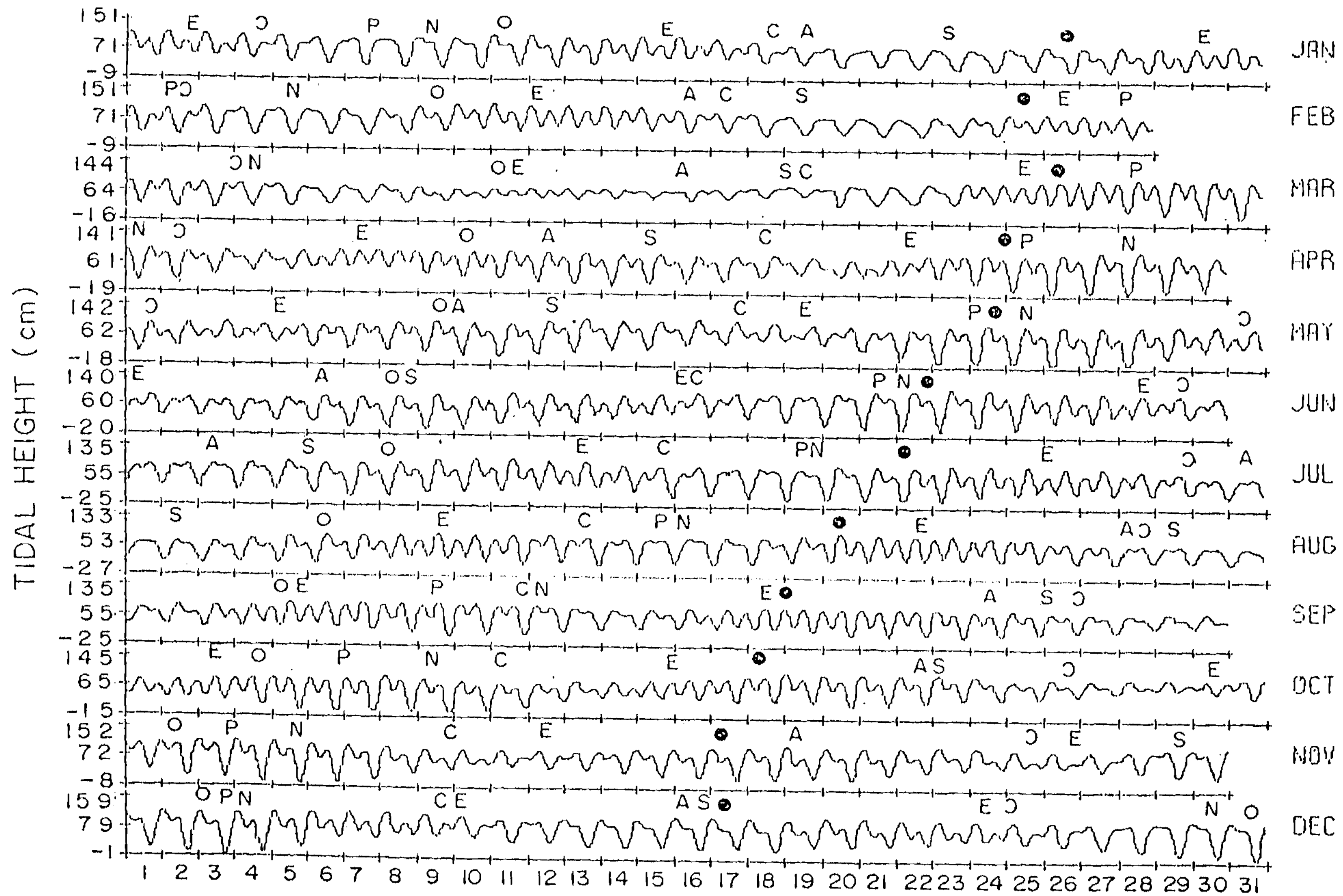
P = PERIGEE ; A = Apogee ; ● = NEW MOON ; Ɔ = First Quarter ; O = FULL MOON ; C = Last Quarter ; E = Moon on Equator ; N = MAXIMUM NORTH DECLINATION ; S = MAXIMUM SOUTH DECLINATION ; Lunar phenomena having a superior effect on tides are printed in CAPITALS.

Fig. 2·1 . Observed hourly tidal heights at Cochin during 1988.



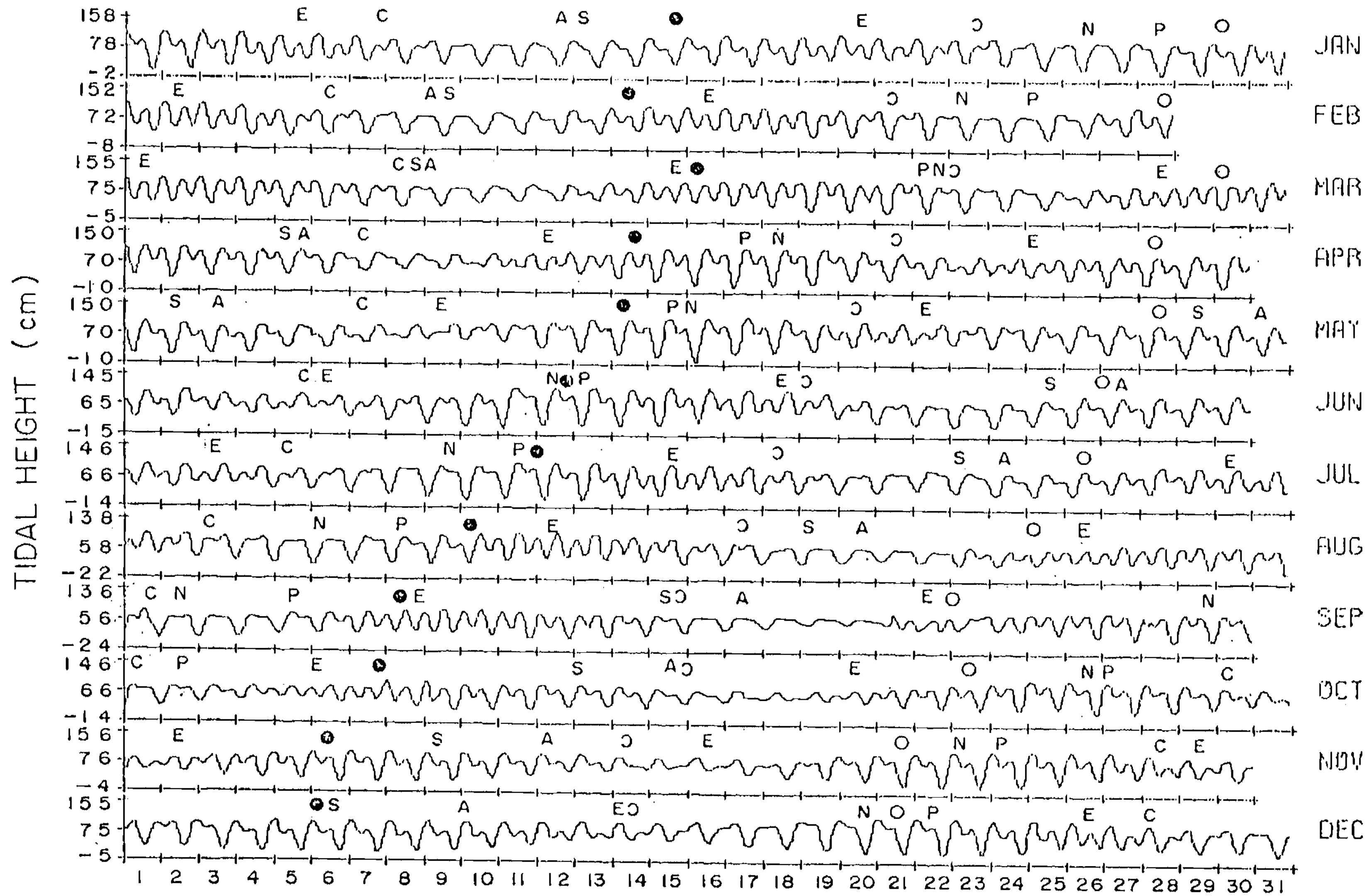
P = PERIGEE ; A = Apogee ; ● = NEW MOON ; ☽ = First Quarter ; O = FULL MOON ; C = Last Quarter ;
E = Moon on Equator ; N = MAXIMUM NORTH DECLINATION ; S = MAXIMUM SOUTH DECLINATION ;
Lunar phenomena having a superior effect on tides are printed in CAPITALS.

Fig. 2·2 . Observed hourly tidal heights at Cochin during 1989.



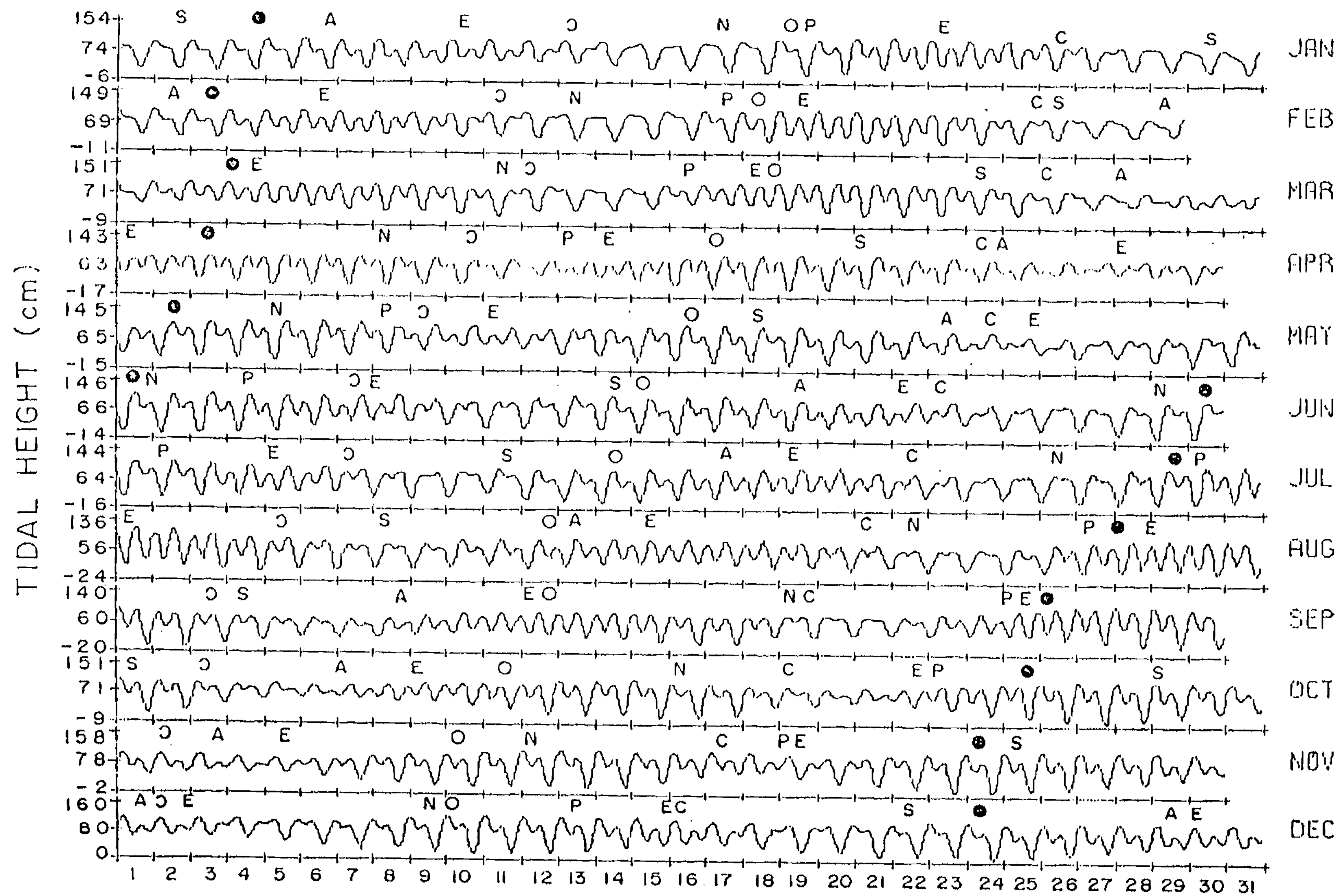
P = PERIGEE ; A = Apogee ; ● = NEW MOON ; ↄ = First Quarter ; O = FULL MOON ; C = Last Quarter ; E = Moon on Equator ; N – MAXIMUM NORTH DECLINATION ; S – MAXIMUM SOUTH DECLINATION ; Lunar phenomena having a superior effect on tides are printed in CAPITALS.

Fig. 2·3 . Observed hourly tidal heights at Cochin during 1990.



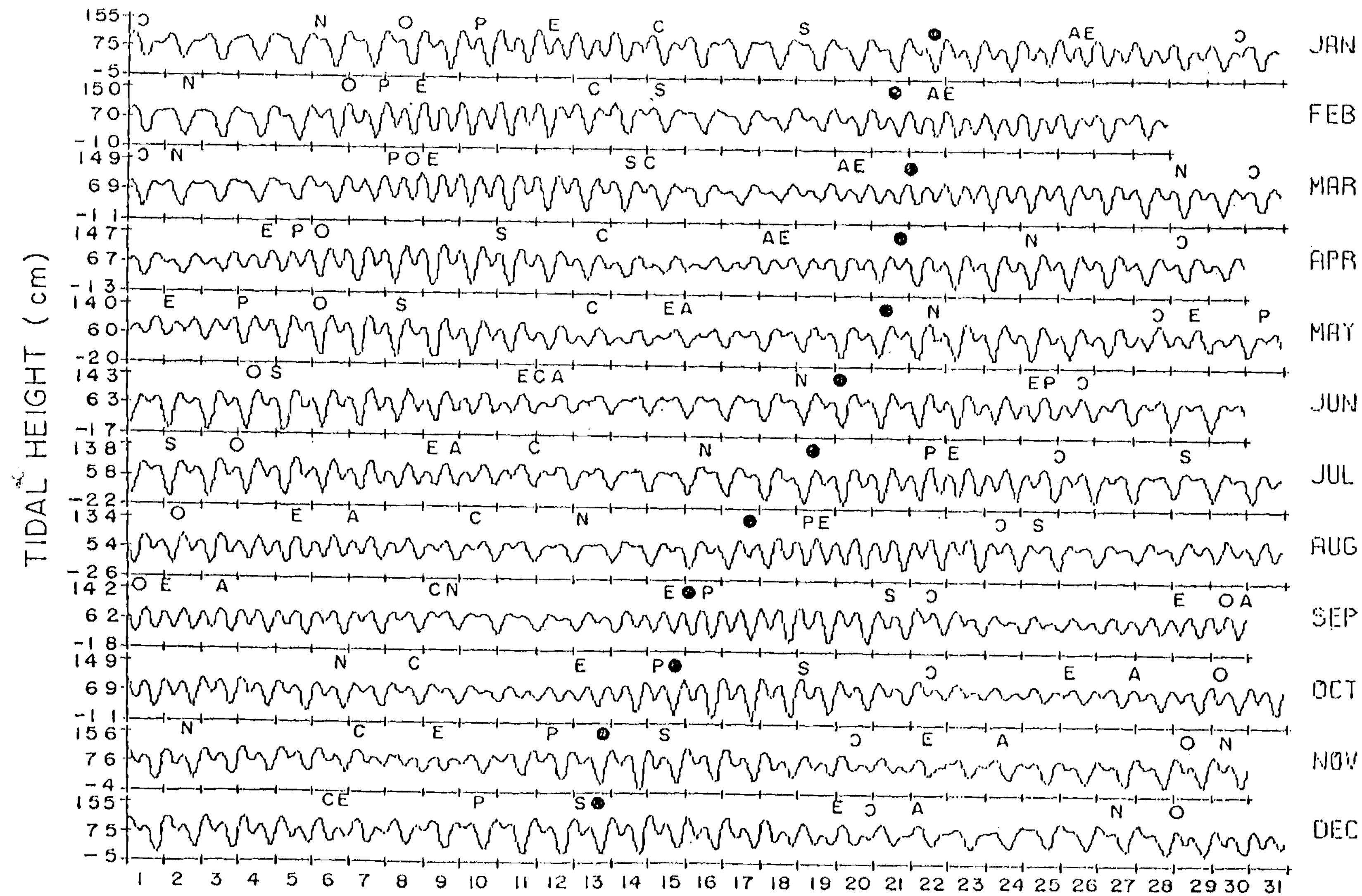
P = PERIGEE ; A = Apogee ; ● = NEW MOON ; Ɔ = First Quarter ; O = FULL MOON ; C = Last Quarter ; E = Moon on Equator ; N = MAXIMUM NORTH DECLINATION ; S = MAXIMUM SOUTH DECLINATION ; Lunar phenomena having a superior effect on tides are printed in CAPITALS.

Fig. 2·4 . Observed hourly tidal heights at Cochin during 1991.



P = PERIGEE ; A = Apogee ; ● = NEW MOON ; ◐ = First Quarter ; O = FULL MOON ; C = Last Quarter ; E = Moon on Equator ; N = MAXIMUM NORTH DECLINATION ; S = MAXIMUM SOUTH DECLINATION ; Lunar phenomena having a superior effect on tides are printed in CAPITALS.

Fig.2·5 . Observed hourly tidal heights at Cochin during 1992.



P = PERIGEE ; A = Apogee ; ● = NEW MOON ; Ɔ = First Quarter ; O = FULL MOON ; C = Last Quarter ; E = Moon on Equator ; N = MAXIMUM NORTH DECLINATION ; S = MAXIMUM SOUTH DECLINATION ; Lunar phenomena having a superior effect on tides are printed in CAPITALS.

Fig. 2·6 . Observed hourly tidal heights at Cochin during 1993.

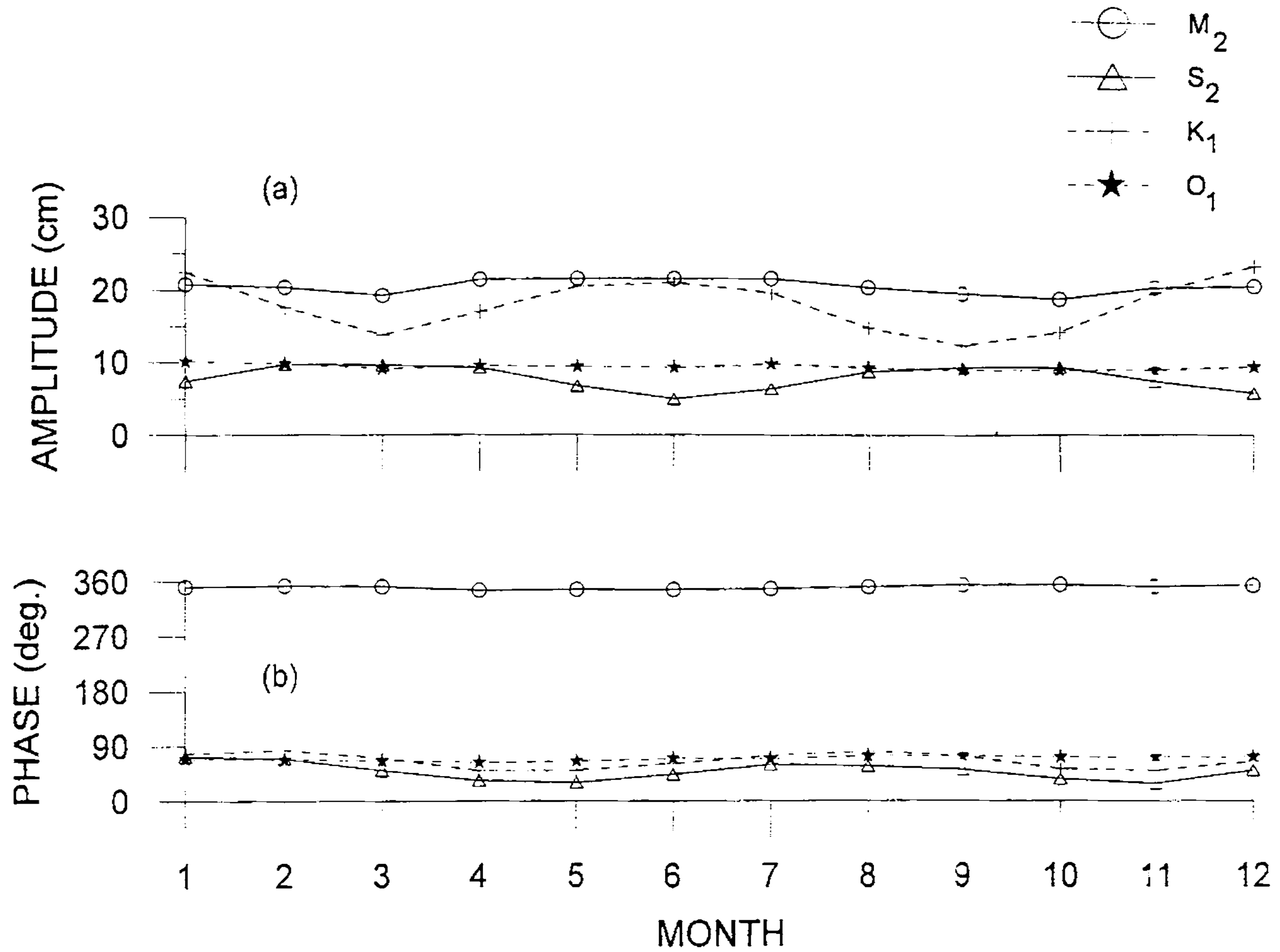


Fig. 2.7. Seasonal march of (a) amplitudes and (b phases of the M2, S2, K1 and O1 tidal constituents based on the mean monthly data for the period 1988-1993.

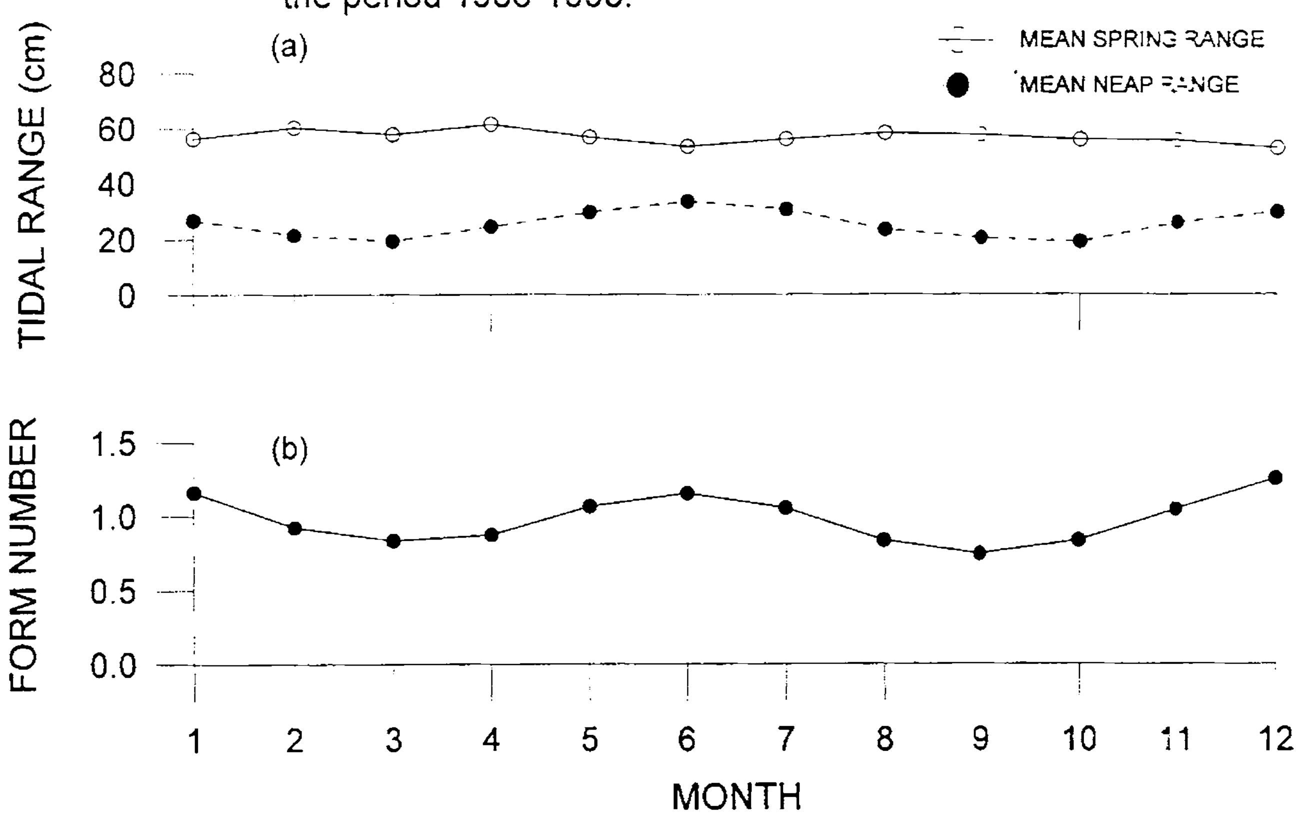


Fig. 2.8. Seasonal march of (a) mean spring and mean neap tidal range and (b) Form Number based on the mean monthly data for the

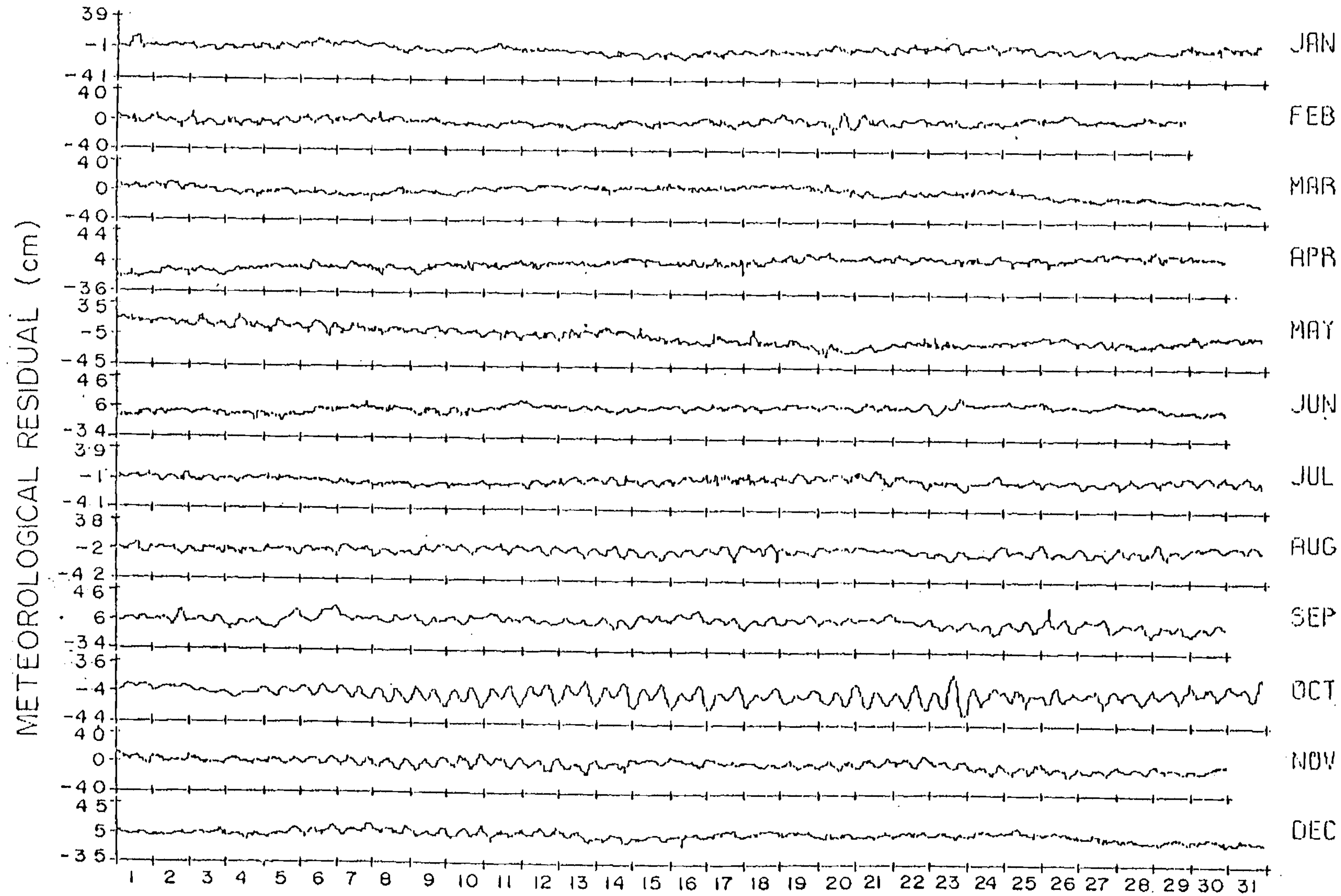


Fig. 2·9 . Hourly meteorological residuals at Cochin during 1988.

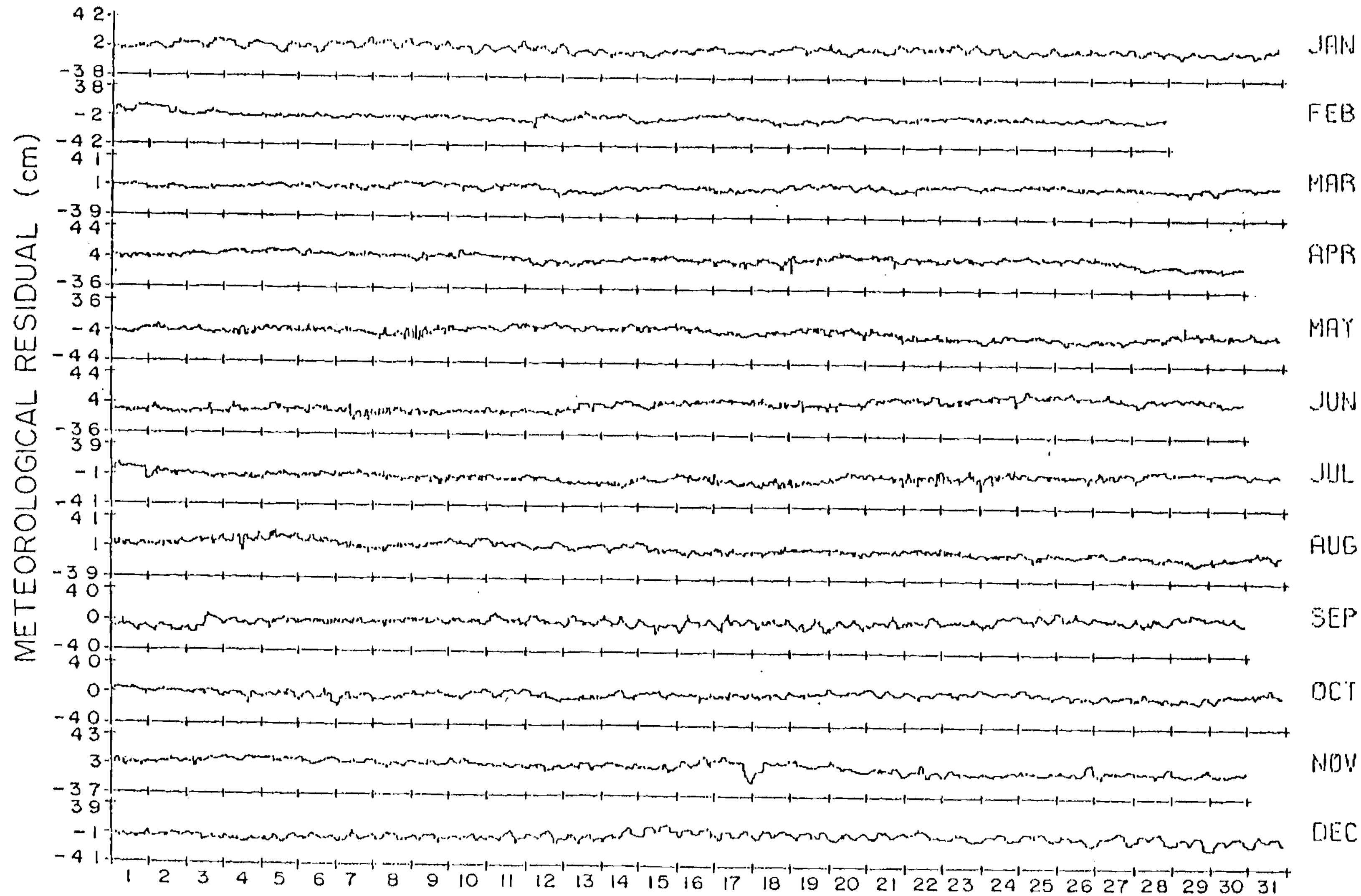


Fig. 2·10 . Hourly meteorological residuals at Cochin during 1989.

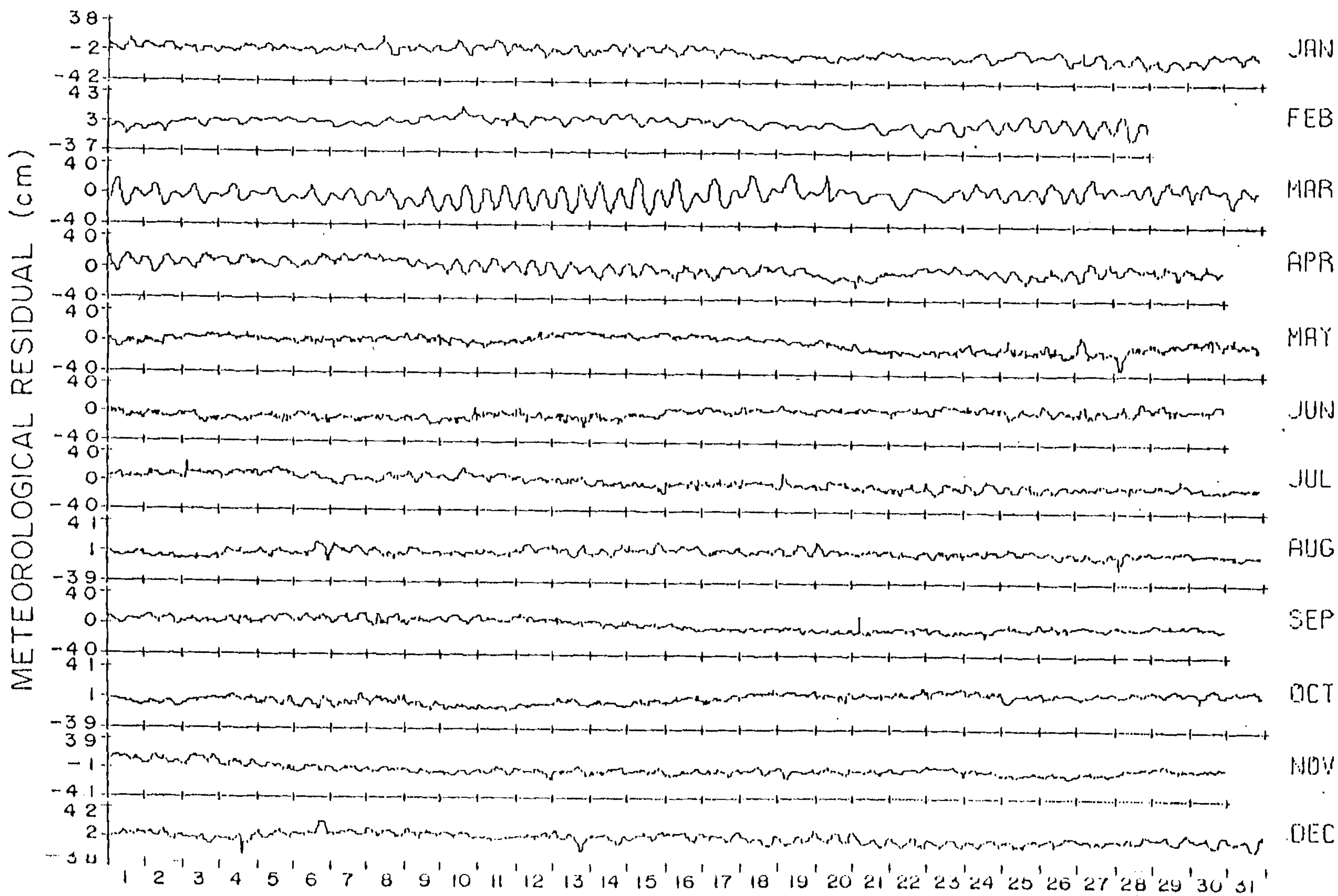


Fig. 2·11 . Hourly meteorological residuals at Cochin during 1990.

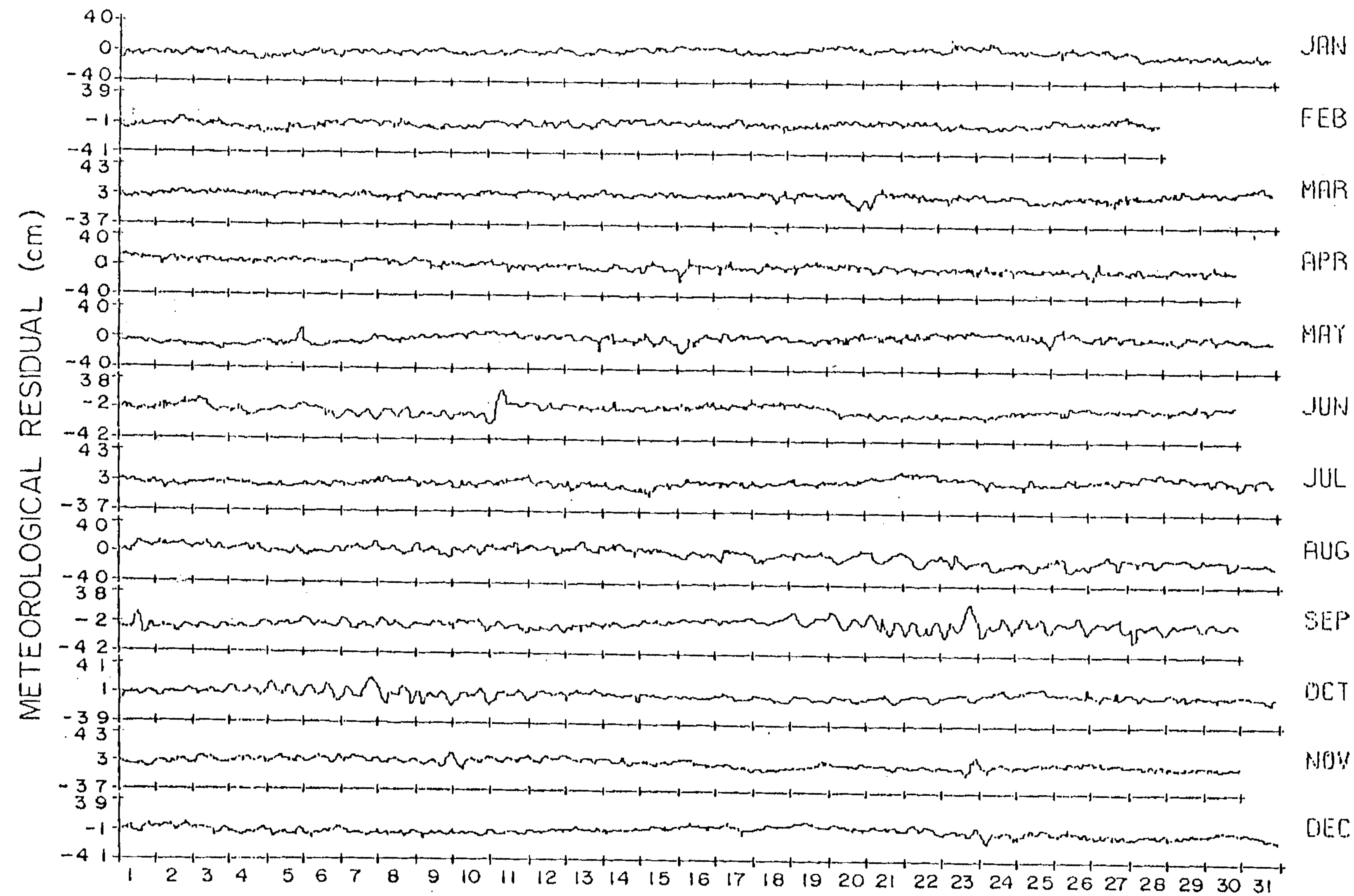


Fig. 2.12 . Hourly meteorological residuals at Cochin during 1991.

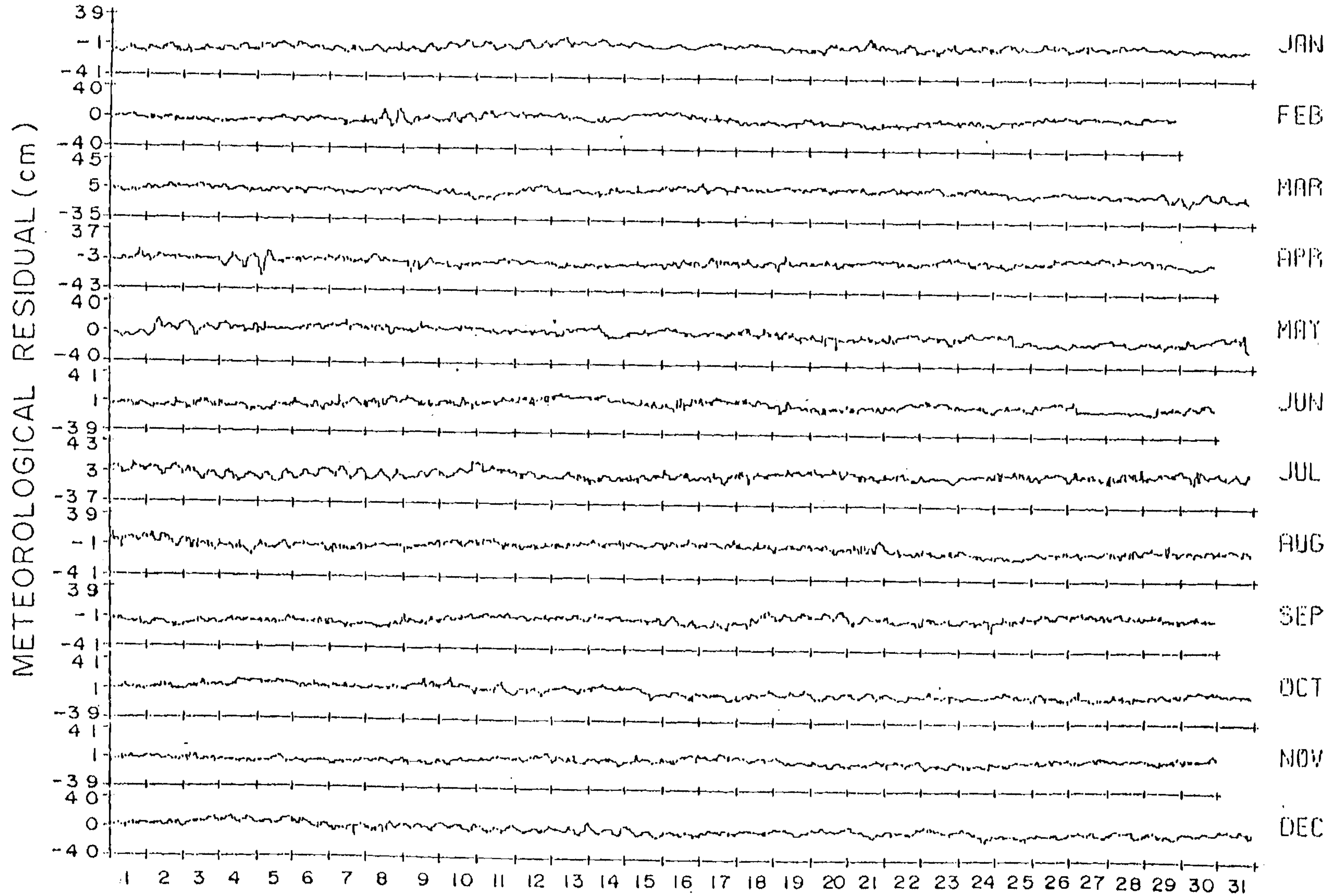


Fig. 2·13 . Hourly meteorological residuals at Cochin during 1992.

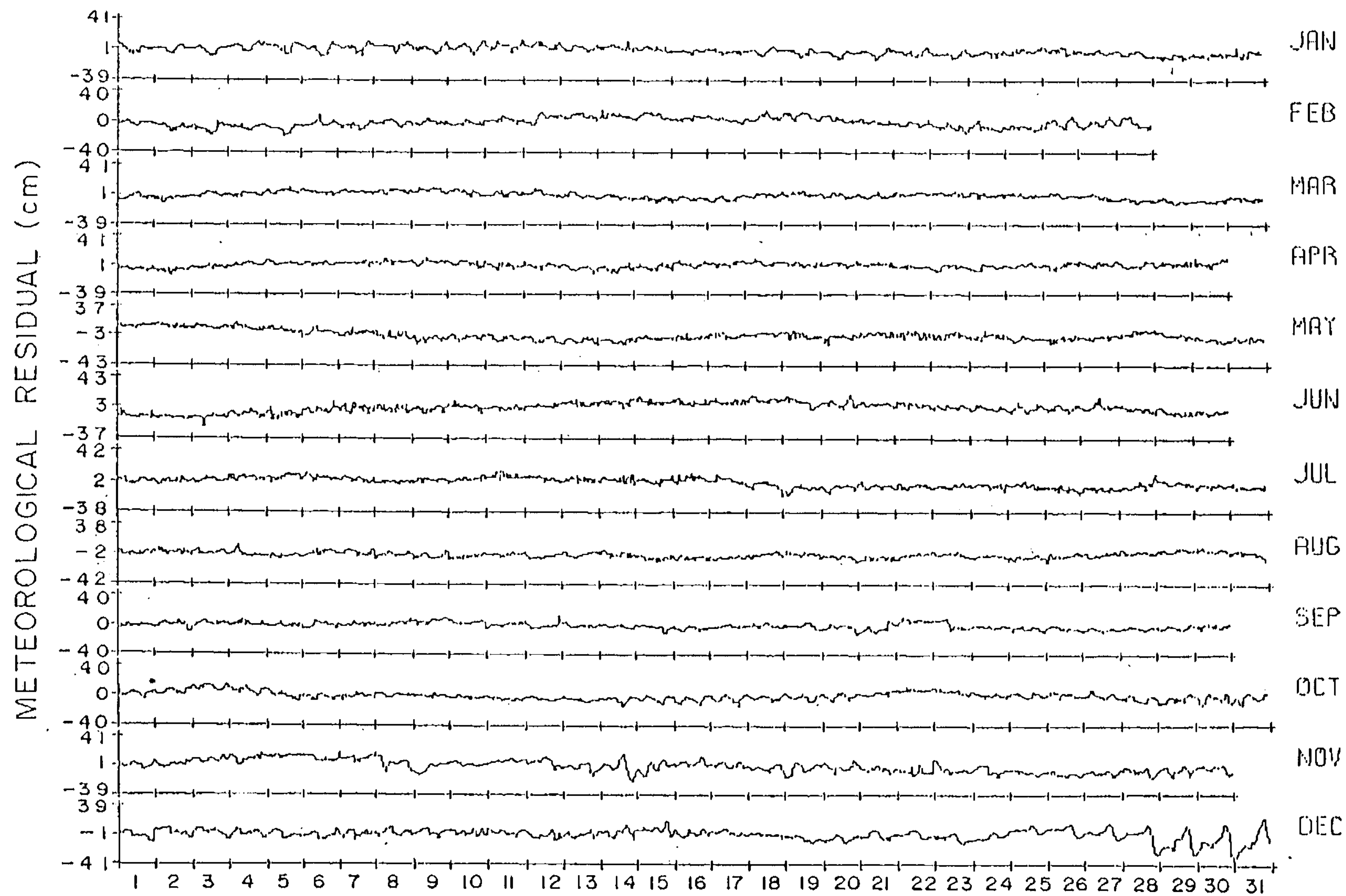


Fig. 2·14 . Hourly meteorological residuals at Cochin during 1993.

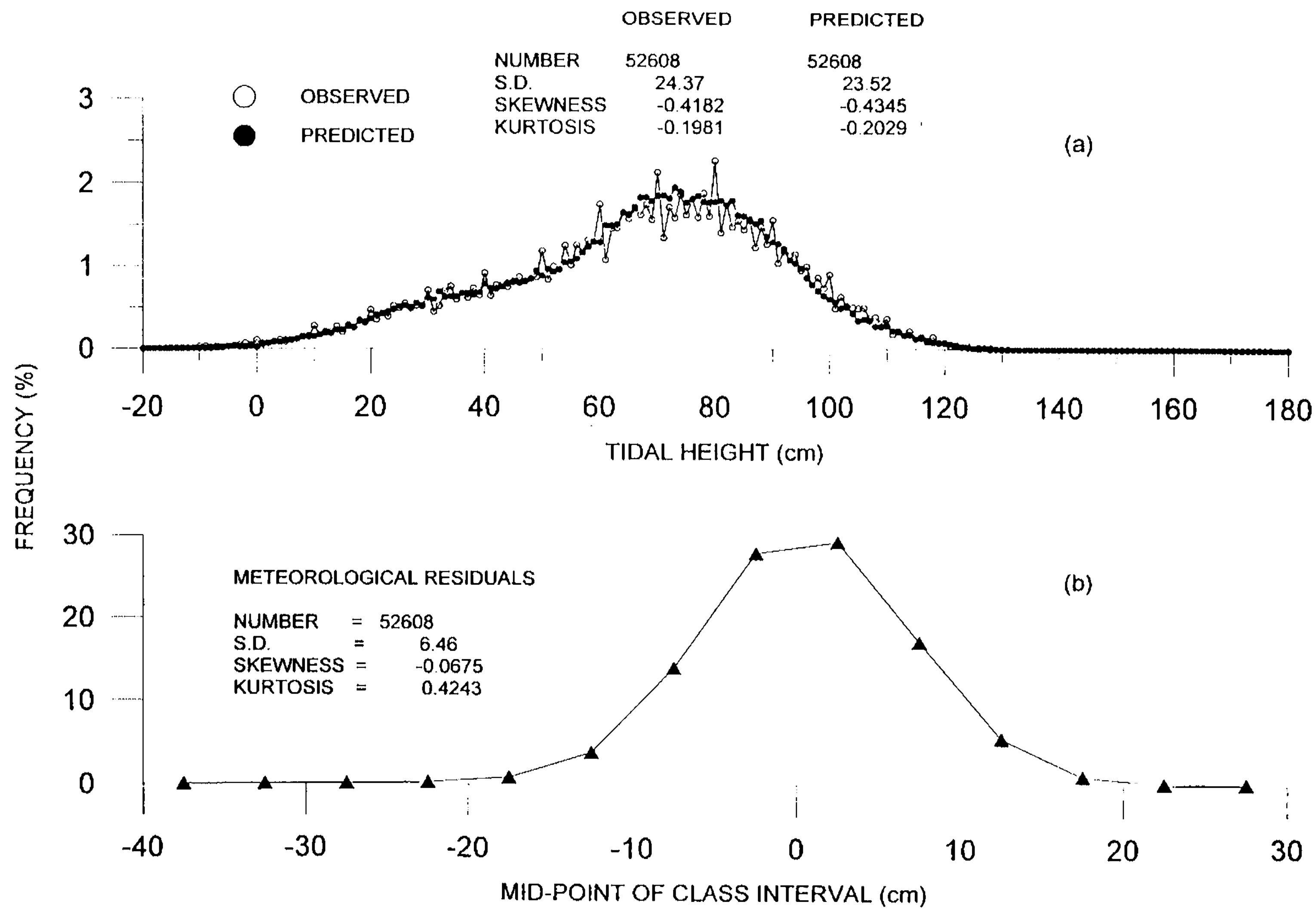


Fig. 2.15. Frequency distributions of hourly (a) observed & predicted tidal heights and (b) meteorological residuals at Cochin for the period 1988-1993.

Table 2.1. Species details of the 67 harmonic tidal constituents used in the present analysis.

SPECIES NUMBER	NUMBER OF CONSTITUENTS	PERIOD (DAYS)	Percentage contribution of each species 1988 (%)	1989 (%)	1990 (%)	1991 (%)	1992 (%)	1993 (%)
0	6	13.6608 - 365.2728	14.12	17.58	18.57	16.55	16.42	14.35
1	21	0.8991 - 1.2114	42.02	38.84	38.84	40.19	39.09	40.10
2	18	0.4898 - 0.5484	39.09	38.51	38.78	37.61	39.08	40.63
3	5	0.3330 - 0.3494	1.80	1.89	1.58	2.29	2.18	1.52
4	7	0.2497 - 0.2612	1.81	1.65	1.09	1.34	1.70	1.82
5	2	0.1999 - 0.2055	0.16	0.30	0.30	0.54	0.35	0.28
6	6	0.1684 - 0.1736	0.84	1.03	0.68	1.27	1.08	1.08
7	1	0.1471	0.04	0.09	0.06	0.12	0.06	0.05
8	1	0.1294	0.12	0.11	0.10	0.09	0.04	0.17

Table 2.2. Amplitude (cm) of the 67 harmonic tidal constituents at Cochin for the period 1988 - 1993. Z0 is the mean sea level.

CONSTITUENT	FREQUENCY (cph)	1988	1989	1990	1991	1992	1993
1 Z0	.00000000	68.1674	65.1794	63.9369	68.9116	68.1653	66.4389
2 SA	.00011407	7.5702	11.1566	9.8519	8.0881	7.9571	9.0840
3 SSA	.00022816	3.2665	3.3910	4.9040	3.9249	4.5621	2.9416
4 MSM	.00130978	.4924	.9960	2.1009	.8687	1.6019	.5154
5 MM	.00151215	.5878	1.1055	.6055	2.4057	1.3343	.9283
6 MSF	.00282193	.8368	.5373	.8069	1.2747	.5976	1.2055
7 MF	.00305009	3.0079	2.2929	3.0974	1.5373	2.2347	.6906
8 ALP1	.03439657	.0550	.0824	.0889	.0796	.1704	.1159
9 2Q1	.03570635	.3658	.2341	.3637	.4717	.4577	.2843
10 SIG1	.03590872	.2683	.2809	.2876	.0978	.4756	.3431
11 Q1	.03721850	2.1631	2.1488	2.1200	2.2669	2.3798	2.3486
12 RHO1	.03742087	.5083	.3245	.3162	.6061	.4207	.2973
13 O1	.03873065	9.4557	9.3446	8.9159	8.8596	9.7732	9.5892
14 TAU1	.03895881	.2628	.7747	.3799	.2197	.0810	.7252
15 BET1	.04004044	.3198	.1487	.1308	.3269	.1200	.3606
16 NO1	.04026860	.8929	.8003	.7463	.8420	.5478	.4161
17 CHI1	.04047097	.1678	.1586	.1563	.4540	.2323	.0335
18 PI1	.04143851	1.1661	.4796	1.1345	.5423	.4510	.2403
19 P1	.04155259	5.9329	4.8995	6.2276	5.3982	5.5611	4.8796
20 S1	.04166667	2.5140	.8803	2.1470	2.0241	.8787	.7090
21 K1	.04178075	18.1325	18.0838	16.4707	16.7048	18.2128	17.8917
22 PSI1	.04189482	1.2737	1.6517	1.3023	1.5516	.4815	1.6027
23 PHI1	.04200891	.6259	.3422	1.3394	.4836	.5174	.5939
24 THE1	.04309053	.3295	.0264	.1073	.2965	.2600	.2694
25 J1	.04329290	1.3481	1.4362	1.5313	1.5860	1.2001	1.0992
26 SO1	.04460268	.2133	.1066	.1970	.2302	.3684	.1741
27 OO1	.04483084	.7399	.7424	.6103	.6704	.7566	.8572
28 UPS1	.04634299	.0989	.0893	.0995	.2089	.2100	.1149
29 OQ2	.07597495	.2110	.0861	.1166	.0330	.0758	.0430
30 EPS2	.07617731	.1315	.1190	.0817	.1552	.2315	.1094
31 2N2	.07748710	.2384	.6303	.9076	.6722	.3760	.5161
32 MU2	.07768947	.5107	.5335	.5690	.8141	.7979	.3174
33 N2	.07899925	4.3997	4.5887	4.3582	4.3979	4.7239	4.7766
34 NU2	.07920162	.8560	.6196	1.0513	.7580	.8798	.7306

Contd..

Table 2.2 (continued)

STITUENT	FREQUENCY (cph)	1988	1989	1990	1991	1992	1993
35 H1	.08039733	2.0285	.9273	2.9217	1.9568	.9590	1.0377
36 M2	.08051140	21.0938	21.1327	18.8605	18.3227	21.3601	21.3761
37 H2	.08062547	1.4327	1.5107	2.0429	1.5677	1.1191	1.2118
38 MKS2	.08073956	.9481	.5184	1.1564	1.0757	.3338	.7228
39 LDA2	.08182118	.1271	.3451	.2380	.2487	.2464	.4505
40 L2	.08202355	.1223	.6114	.7451	.5287	.7376	.6359
41 T2	.08321926	.4381	.4222	1.7151	.5738	.8168	.4914
42 S2	.08333334	7.9370	7.7923	6.5429	6.8730	7.9639	7.9965
43 R2	.08344740	.5551	.5103	.9083	.7118	.5868	.6051
44 K2	.08356149	2.1739	2.1707	2.1940	2.0460	2.1603	2.2720
45 MSN2	.08484548	.2073	.0847	.0217	.2268	.1345	.1014
46 ETA2	.08507364	.1587	.0695	.1781	.1372	.0381	.1182
47 MO3	.11924210	.2960	.4665	.4539	.6925	.5750	.1469
48 M3	.12076710	.3433	.3488	.2778	.3091	.3435	.3030
49 SO3	.12206400	.4358	.2706	.4439	.4347	.6238	.2704
50 MK3	.12229210	.8279	.7991	.5634	.7965	.6276	.6998
51 SK3	.12511410	.0997	.2106	.0784	.2739	.2607	.2120
52 MN4	.15951060	.3128	.2874	.1813	.1490	.2705	.2740
53 M4	.16102280	.7848	.7213	.6417	.5530	.6854	.7040
54 SN4	.16233260	.0289	.0264	.0376	.0402	.1056	.0569
55 MS4	.16384470	.5880	.5310	.3312	.3992	.4645	.4768
56 MK4	.16407290	.0383	.0875	.0201	.1861	.1385	.1472
57 S4	.16666670	.1680	.1513	.0188	.1039	.1039	.1279
58 SK4	.16689480	.0955	.0231	.0236	.0307	.1302	.1655
59 2MK5	.20280360	.1471	.2284	.3015	.5344	.3708	.2284
60 2SK5	.20844740	.0277	.1015	.0399	.0515	.0159	.0760
61 2MN6	.24002200	.0709	.1718	.0996	.1260	.1174	.0833
62 M6	.24153420	.1387	.1545	.1469	.2881	.2485	.2450
63 2MS6	.24435610	.3461	.3673	.2790	.4527	.4107	.3538
64 2MK6	.24458430	.1119	.2028	.1241	.2149	.1801	.1680
65 2SM6	.24717810	.1433	.1399	.0424	.2072	.1059	.1160
66 MSK6	.24740620	.1236	.1047	.0922	.0968	.1429	.1914
67 3MK7	.28331490	.0410	.1040	.0678	.1262	.0659	.0562
68 M8	.32204560	.1353	.1205	.1135	.0987	.0501	.1776

Table 2.3. Phase (deg.) of the 67 harmonic tidal constituents at Coch for the period 1988 - 1993.

CONSTITUENT	FREQUENCY (cph)	1988	1989	1990	1991	1992	1993
1 Z0	.00000000	.00	.00	.00	.00	.00	.00
2 SA	.00011407	359.03	6.82	5.74	33.89	.16	.12
3 SSA	.00022816	209.44	212.79	151.00	153.49	143.14	117.93
4 MSM	.00130978	129.85	198.45	284.40	3.62	62.71	33.51
5 MM	.00151215	27.23	9.25	48.13	327.35	345.91	39.56
6 MSF	.00282193	246.51	132.43	176.88	74.17	178.73	194.06
7 MF	.00305009	37.27	13.13	353.84	344.01	333.25	5.75
8 ALP1	.03439657	315.84	9.83	94.13	54.06	43.96	137.42
9 2Q1	.03570635	56.01	45.21	41.71	81.97	70.97	56.32
10 SIG1	.03590872	29.83	23.59	54.25	345.99	350.87	55.38
11 Q1	.03721850	70.40	63.17	66.29	63.28	66.08	70.14
12 RHO1	.03742087	53.49	64.43	48.79	79.99	65.92	65.55
13 O1	.03873065	67.54	66.91	71.50	72.19	69.02	70.32
14 TAU1	.03895881	173.20	111.45	238.52	280.25	179.65	138.03
15 BET1	.04004044	166.76	100.25	3.70	81.39	112.21	110.88
16 NO1	.04026860	69.90	63.52	59.95	70.50	60.85	47.07
17 CHI1	.04047097	341.78	55.39	302.61	107.94	352.66	173.78
18 PI1	.04143851	57.96	29.09	43.48	60.61	78.54	357.26
19 P1	.04155259	54.09	59.58	66.84	61.77	63.00	63.78
20 S1	.04166667	18.11	34.66	139.24	338.20	68.69	24.68
21 K1	.04178075	64.24	62.64	66.71	69.81	63.31	65.01
22 PSI1	.04189482	84.74	121.44	190.60	102.11	151.21	120.66
23 PHI1	.04200891	125.71	325.91	105.82	134.94	64.84	349.88
24 THE1	.04309053	76.23	23.32	350.19	62.08	64.74	44.80
25 J1	.04329290	86.65	80.40	72.15	70.36	80.41	70.11
26 SO1	.04460268	111.58	121.68	63.41	141.39	89.78	129.29
27 OO1	.04483084	113.60	100.38	103.25	115.21	91.67	107.94
28 UPS1	.04634299	128.96	126.32	176.58	113.89	82.40	95.61
29 OQ2	.07597495	125.13	176.37	187.52	323.44	255.79	108.93
30 EPS2	.07617731	226.96	245.74	171.69	143.02	270.88	146.39
31 2N2	.07748710	252.95	247.27	268.50	286.10	290.91	272.88
32 MU2	.07768947	271.26	263.93	252.76	267.90	257.20	277.79
33 N2	.07899925	316.39	311.84	318.11	322.35	314.15	315.49
34 NU2	.07920162	321.71	313.62	308.76	328.04	326.86	315.14

Contd..

Table 2.3 (continued)

CONSTITUENT	FREQUENCY (cph)	1988	1989	1990	1991	1992	1993
35 H1	.08039733	56.53	326.83	275.90	52.38	251.96	341.50
36 M2	.08051140	348.72	343.51	351.97	358.64	347.97	348.89
37 H2	.08062547	.71	60.71	140.59	19.27	178.15	61.78
38 MKS2	.08073956	142.90	216.23	71.11	159.04	120.32	256.42
39 LDA2	.08182118	72.41	22.24	14.30	90.25	79.04	44.63
40 L2	.08202355	29.55	65.16	67.34	56.79	.85	25.96
41 T2	.08321926	330.25	87.99	137.07	305.97	77.84	88.80
42 S2	.08333334	49.47	43.30	49.60	58.39	44.39	47.67
43 R2	.08344740	261.88	303.46	52.40	246.09	48.80	318.13
44 K2	.08356149	60.20	41.73	61.60	67.17	48.48	39.45
45 MSN2	.08484548	73.80	297.74	77.54	66.70	278.36	95.64
46 ETA2	.08507364	93.23	33.75	49.48	43.65	44.31	263.68
47 MO3	.11924210	225.33	218.35	208.19	212.07	198.66	200.52
48 M3	.12076710	241.46	226.15	229.60	202.36	177.17	159.68
49 SO3	.12206400	173.75	189.55	220.60	227.87	218.72	190.85
50 MK3	.12229210	193.15	203.06	197.81	231.25	197.57	214.39
51 SK3	.12511410	290.99	265.14	334.67	313.28	305.41	345.32
52 MN4	.15951060	65.15	42.43	64.49	72.52	48.87	82.73
53 M4	.16102280	124.95	108.39	133.04	151.49	129.99	141.74
54 SN4	.16233260	289.95	41.31	291.95	132.06	253.58	334.30
55 MS4	.16384470	194.95	173.02	226.71	215.86	179.31	215.07
56 MK4	.16407290	268.68	76.48	224.59	95.40	91.68	120.73
57 S4	.16666670	208.13	160.32	199.26	164.41	223.97	218.79
58 SK4	.16689480	191.47	195.47	141.40	270.86	191.85	253.26
59 2MK5	.20280360	128.17	162.03	152.49	194.05	156.50	144.19
60 2SK5	.20844740	77.32	143.89	204.74	132.96	281.11	193.84
61 2MN6	.24002200	12.03	29.29	70.59	75.00	28.20	359.11
62 M6	.24153420	126.39	92.29	87.61	132.86	104.82	118.04
63 2MS6	.24435610	251.96	225.58	214.08	238.52	224.54	232.03
64 2MK6	.24458430	200.80	188.92	207.87	184.97	184.90	191.04
65 2SM6	.24717810	337.97	340.28	240.43	326.12	313.11	304.91
66 MSK6	.24740620	319.13	278.03	285.50	254.59	272.27	305.09
67 3MK7	.28331490	258.40	261.36	285.74	342.42	298.85	278.04
68 M8	.32204560	54.12	351.95	288.21	343.02	350.28	358.82

Table 2.4. Maximum, minimum, standard deviation(SD) and the coefficient of variation(CV) of the amplitudes of the 67 harmonic tidal constituents for the period 1988 - 1993.

	NAME	FREQUENCY (cph)	AVERAGE (cm)	SD (cm)	MAXIMUM (cm)	MINIMUM (cm)	CV (%)
	1 Z0	.00000000	66.7999	1.7864	68.9116	63.9369	2.67
	2 SA	.00011407	8.9513	1.2472	11.1566	7.5702	13.93
	3 SSA	.00022816	3.8317	.7069	4.9040	2.9416	18.45
**	4 MSM	.00130978	1.0959	.5815	2.1009	.4924	53.06
	5 MM	.00151215	1.1612	.6156	2.4057	.5878	53.01
**	6 MSF	.00282193	.8765	.2787	1.2747	.5373	31.80
	7 MF	.00305009	2.1435	.8333	3.0974	.6906	38.88
	8 ALP1	.03439657	.0987	.0367	.1704	.0550	37.16
	9 2Q1	.03570635	.3629	.0852	.4717	.2341	23.49
	10 SIG1	.03590872	.2922	.1116	.4756	.0978	38.19
	11 Q1	.03721850	2.2379	.1006	2.3798	2.1200	4.49
	12 RHO1	.03742087	.4122	.1133	.6061	.2973	27.49
	13 O1	.03873065	9.3230	.3347	9.7732	8.8596	3.59
	14 TAU1	.03895881	.4072	.2580	.7747	.0810	63.35
	15 BET1	.04004044	.2345	.1024	.3606	.1200	43.68
	16 NO1	.04026860	.7076	.1698	.8929	.4161	24.00
	17 CHI1	.04047097	.2004	.1278	.4540	.0335	63.75
	18 PI1	.04143851	.6690	.3529	1.1661	.2403	52.75
	19 P1	.04155259	5.4832	.4958	6.2276	4.8796	9.04
	20 S1	.04166667	1.5255	.7203	2.5140	.7090	47.22
	21 K1	.04178075	17.5827	.7133	18.2128	16.4707	4.06
	22 PSI1	.04189482	1.3106	.3976	1.6517	.4815	30.34
	23 PHI1	.04200891	.6504	.3212	1.3394	.3422	49.38
	24 THE1	.04309053	.2148	.1095	.3295	.0264	50.95
	25 J1	.04329290	1.3668	.1730	1.5860	1.0992	12.66
*	26 SO1	.04460268	.2149	.0791	.3684	.1066	36.79
	27 OO1	.04483084	.7295	.0764	.8572	.6103	10.47
	28 UPS1	.04634299	.1369	.0518	.2100	.0893	37.86
	29 OQ2	.07597495	.0943	.0590	.2110	.0330	62.64
	30 EPS2	.07617731	.1381	.0473	.2315	.0817	34.27
	31 2N2	.07748710	.5568	.2151	.9076	.2384	38.63
	32 MU2	.07768947	.5904	.1721	.8141	.3174	29.15
	33 N2	.07899925	4.5408	.1659	4.7766	4.3582	3.65
	34 NU2	.07920162	.8159	.1356	1.0513	.6196	16.62

Contd..

Table 2.4 (continued)

	NAME	FREQUENCY (cph)	AVERAGE (cm)	SD (cm)	MAXIMUM (cm)	MINIMUM (cm)	CV (%)
	35 H1	.08039733	1.6385	.7335	2.9217	.9273	44.77
	36 M2	.08051140	20.3576	1.2628	21.3761	18.3227	6.20
	37 H2	.08062547	1.4808	.2972	2.0429	1.1191	20.07
*	38 MKS2	.08073956	.7925	.2964	1.1564	.3338	37.40
	39 LDA2	.08182118	.2760	.1004	.4505	.1271	36.38
	40 L2	.08202355	.5635	.2108	.7451	.1223	37.41
	41 T2	.08321926	.7429	.4543	1.7151	.4222	61.15
	42 S2	.08333334	7.5176	.5839	7.9965	6.5429	7.77
	43 R2	.08344740	.6462	.1323	.9083	.5103	20.47
	44 K2	.08356149	2.1695	.0664	2.2720	2.0460	3.06
*	45 MSN2	.08484548	.1294	.0707	.2268	.0217	54.61
	46 ETA2	.08507364	.1166	.0489	.1781	.0381	41.95
*	47 MO3	.11924210	.4385	.1777	.6925	.1469	40.53
	48 M3	.12076710	.3209	.0262	.3488	.2778	8.15
*	49 SO3	.12206400	.4132	.1204	.6238	.2704	29.14
*	50 MK3	.12229210	.7190	.0977	.8279	.5634	13.58
*	51 SK3	.12511410	.1892	.0748	.2739	.0784	39.52
*	52 MN4	.15951060	.2458	.0594	.3128	.1490	24.15
*	53 M4	.16102280	.6817	.0717	.7848	.5530	10.52
*	54 SN4	.16233260	.0493	.0270	.1056	.0264	54.89
*	55 MS4	.16384470	.4651	.0835	.5880	.3312	17.96
*	56 MK4	.16407290	.1030	.0597	.1861	.0201	58.03
*	57 S4	.16666670	.1123	.0479	.1680	.0188	42.63
*	58 SK4	.16689480	.0781	.0561	.1655	.0231	71.86
*	59 2MK5	.20280360	.3018	.1249	.5344	.1471	41.38
*	60 2SK5	.20844740	.0521	.0291	.1015	.0159	55.79
*	61 2MN6	.24002200	.1115	.0328	.1718	.0709	29.44
*	62 M6	.24153420	.2036	.0587	.2881	.1387	28.85
*	63 2MS6	.24435610	.3683	.0542	.4527	.2790	14.71
*	64 2MK6	.24458430	.1670	.0379	.2149	.1119	22.71
*	65 2SM6	.24717810	.1258	.0493	.2072	.0424	39.19
*	66 MSK6	.24740620	.1253	.0342	.1914	.0922	27.29
*	67 3MK7	.28331490	.0769	.0291	.1262	.0410	37.89
*	68 M8	.32204560	.1160	.0384	.1776	.0501	33.10

* - Short period shallow water constituents (24 Nos.)
** - Long period shallow water constituents (2 Nos.)

Table 2.5. Comparison between the seasonal and annual data on K_1, O_1, M_2, S_2 generated for the period 1988-1993.

	SEASONAL DATA				ANNUAL DATA			
	AMPLITUDE		PHASE		AMPLITUDE		PHASE	
ponent	MEAN (cm)	SD (cm)	MEAN (deg.)	SD (deg.)	MEAN (cm)	SD (cm)	MEAN (deg.)	SD (deg.)
K_1	18.02	3.49	66.01	12.02	17.58	0.71	65.29	2.40
O_1	9.37	0.37	69.80	3.23	9.32	0.33	69.58	1.94
M_2	20.51	0.95	350.51	3.15	20.36	1.26	349.95	4.61
S_2	7.87	1.58	48.85	13.91	7.52	0.58	48.80	4.90

Table 2.6. Percentage increase or decrease in amplitude and phase of the above constituents between the seasonal and annual data.

Component	Increase or decrease in amplitude (%)	Increase or decrease in phase (%)
K_1	-2.44	-1.09
O_1	-0.53	-0.32
M_2	-0.73	-0.16
S_2	-4.45	-0.10

Table 2.7. Percentage contribution of the amplitudes of some important constituents to the total for the annual analysis for the years 1988 - 1993.

YEAR	1988	1989	1990	1991	1992	1993
FORM NUMBER	0.95	0.95	1.00	1.02	0.95	0.94
A	50.8	50.9	44.2	46.4	51.4	53.1
B	62.0	61.4	55.3	57.3	62.6	64.2
C	5.7	5.4	4.8	6.8	5.9	5.6
D	6.9	6.8	7.3	8.7	7.8	7.2

A Percentage contribution of (M_2+S_2+K_1+O_1) to total amplitude (67 constituents)

B Percentage contribution of (M_2+S_2+K_2+N_2+K_1+O_1+P_1) to total amplitude

C Percentage contribution of 24 short period shallow water constituents to the total amplitude (Table 2.4)

D Percentage contribution of 24 short period shallow water constituents and two long period shallow water constituents to the total amplitude (Table 2.4)

Table 2.8. Present results (year - 1993) compared with those published by Defant (1961).

Component	Defant (1961) AMP (cm)	Defant (1961) PHA (deg.)	Present study (1993) AMP (cm)	Present study (1993) PHA (deg.)
K_1	18.0	52	17.9	65.0
O_1	9.4	58	9.6	70.3
M_2	22.2	332	21.4	348.9
S_2	8.0	29	8.0	47.7

Component	Increase or decrease in amplitude (%)	Increase or decrease in phase (%)
K_1	-0.55	25.00
O_1	2.13	21.21
M_2	-3.60	5.09
S_2	0.00	64.48

Table 2.9. The contribution of radiational tides to the total amplitude (67 constituents) at Cochin.

YEAR	S_a (%)	S_{sa} (%)	S_1 (%)	TOTAL (%)
1988	6.79	2.93	2.26	11.98
1989	10.07	3.06	0.79	13.92
1990	8.56	4.26	1.87	14.69
1991	7.40	3.59	1.85	12.84
1992	7.14	4.09	0.79	12.02
1993	8.48	2.75	0.66	11.89

Table 2.10. Skewness, kurtosis, standard deviation and mean of the observed, predicted and residual sea level.

OBSERVED SEA LEVEL (cm)

YEAR	KURTOSIS	SKEWNESS	STANDARD DEVIATION	MEAN
1988	-0.21497	-0.40185	25.34	68.15
1989	-0.17125	-0.40216	25.39	65.11
1990	-0.06693	-0.46331	23.97	63.99
1991	-0.39190	-0.34465	22.62	68.95
1992	-0.31158	-0.43745	24.39	68.11
1993	-0.24176	-0.43766	24.02	66.40

PREDICTED SEA LEVEL (cm)

YEAR	KURTOSIS	SKEWNESS	STANDARD DEVIATION	MEAN
1988	-0.19391	-0.42141	24.22	68.16
1989	-0.14296	-0.41026	24.61	65.11
1990	-0.07011	-0.51834	22.88	63.99
1991	-0.37257	-0.33256	21.81	68.95
1992	-0.30733	-0.45954	23.75	68.12
1993	-0.35986	-0.44579	23.31	66.41

RESIDUAL SEA LEVEL (cm)

YEAR	KURTOSIS	SKEWNESS	STANDARD DEVIATION
1988	0.29791	-0.22569	7.50
1989	0.18810	0.26408	6.32
1990	0.12917	-0.05407	7.24
1991	0.36043	-0.14804	6.00
1992	-0.10240	-0.02881	5.60
1993	0.75679	-0.11248	5.86

CHAPTER 3

CHAPTER 3

SEASONAL AND INTERANNUAL VARIABILITY OF SEA LEVEL AT COCHIN

3.1. INTRODUCTION

The aim of this chapter is to describe and explain the observed seasonal and interannual variability of sea level and the associated oceanographic and surface meteorological parameters using long time series observations collected at Cochin. An attempt is also made to describe and explain the forcings related to ENSO cycles on the oceanographic and surface meteorological parameters.

Seasonal variability has been defined as a movement in a time series during a particular time of the year that repeats year after year. Seasonality of any parameter is better understood through a fit of the data to annual and semi-annual harmonics (Ripa. 1997). Further, for climate monitoring purposes, the sub-seasonal (annual and semi-annual) periods together give most of the information (Rao et al., 1989; Maul et al., 1990; Rao, 1995; Emery and Thomson, 1998).

3.2. MATERIALS AND METHODS

The meteorological and oceanographic data used for the present study are presented in Table 3.1.

The data on parameters serial numbered 1,6 and 7 were obtained from the Marine Surveyor's Office, Cochin Port Trust, Cochin and those of serial numbered 2, 3 and 5 from the Indian

Daily Weather Reports, published by the India Meteorological Department, Pune. The wind data at three hourly intervals were obtained from the Naval Air Station, Cochin. The Southern Oscillation Indices (SOI) data were obtained from the National Climatic Data Center, North Carolina, USA. The data on parameters 1,2,3 and 6 were obtained at 0830 hrs. Data on parameter 3 was obtained at 1730 hrs also. The rainfall data is the total ending at 0830 hrs on the day of observation. The sea level data were obtained at hourly intervals.

The data on wind speed and direction were used to resolve the cross-shore (offshore-onshore) and along-shore (poleward-equatorward) components along an angle of 339° 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 that due to Hsu (1988) - with onshore and poleward wind as positive, and offshore and equatorward wind as negative. The wind data are presented in m/s.

The relative density (specific gravity) value used in the present discussion is defined as follows and is used for computational ease :

σ_t ~~relative density~~ = (relative density -1.0)*1000

In the description of the seasonal cycle of the parameters (section 3.3.1), 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 (in cm) were obtained.

The seasonal cycle parameters (amplitude and phase of the annual, semi-annual and ter-annual cycles) were computed using the techniques described in Appendix II. In the present study, the ter-annual (4 month) cycle has also been included, enabling us to obtain additional information on the environmental parameters that are known to force sea level variability on seasonal time scales.

Some earlier workers have pointed out the importance of year-to-year variability of the seasonal cycle of sea level (Lisitzin, 1974; Woodworth, 1984; Ekman and Stigebrandt, 1990; Tsimplis and Woodworth, 1994; Bell and Goring, 1998; Wroblewski, 1998). The data on sea level along with the other associated parameters were, therefore, subjected to this analysis.

Measures of seasonal and interannual variability are provided by standard deviations of the variable 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 monthly departures 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.

Comparison between the seasonal signal and the interannual signal for each of the calendar months is obtained by computing the ratio of seasonal SD (of the climatological mean seasonal cycle) to the long-term SD of each of the 12 individual calendar months. If the value is less than unity, the month is dominated by interannual signal and if greater than unity, the seasonal signal dominates.

3.3. RESULTS AND DISCUSSION

3.3.1. SEASONAL MARCH OF THE PARAMETERS

The sea surface temperature (SST) shows a bimodal structure with the primary maximum in April (30.9°C) and with primary minimum in August (27.8°C) (Fig. 3.1a). The range of the SST was 3.1°C. The high temperature during April is due to high incident solar radiation and low surface heat losses, and the low value during August is due to coastal upwelling, overcast skies, evaporation and rainfall (Johanessen et al., 1981; Pillai et al., 1997). The maximum interannual variability was during the summer monsoon season (Fig. 3.1b).

The time series of air temperature also shows a bimodal pattern (Fig. 3.1c). The maximum air temperature of 29.0°C occurred during April, while 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. This is in conformity with the observations made by other workers (Ananthakrishnan et al., 1979; Ramesh Kumar and Ananthakrishnan, 1986). The rise from January to April and the drop from April to July were quite sharp. The annual range of the air temperature was about 4.2°C. The variability of the air temperature is higher than that of water, because of its lesser specific heat capacity (Ashizawa and Cole, 1994). Another notable feature is the fairly sharp drop from April to July, which could be attributed to the summer monsoonal effects (such as cloudy skies, rainfall and winds). The drop from the premonsoon high to summer monsoon low is particularly sharp in the case of the air temperature. The maximum interannual variability was during the onset time of the summer monsoon (Fig. 3.1d).

The seasonal march of the atmospheric pressure shows a roughly concave pattern, with low values during May and high values during the premonsoon and postmonsoon months (Fig. 3.1e). The highest atmospheric pressure occurred during January (1013.4 mb) and the lowest during May (1009.3 mb). The seasonal cycle of atmospheric pressure clearly indicated a sharp drop from January to May, and a gradual increase from May to December. This is in conformity with the observations made by other workers (Ananthakrishnan et al., 1979; Ramesh Kumar and Ananthakrishnan, 1986). The drop was quite sharp as compared to the rise. The range was about 4.1 mb. 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 maximum interannual variability was during February (Fig. 3.1f).

The seasonal march of the scalar wind speed shows a convex shape with high values during April - September (Fig. 3.1g). 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 of 1.6 m/s during November, showing an annual range of 0.9 m/s. The observed wind speed, however, 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). These high values must be due to the site being close to the open sea, with minimal frictional effects (Hsu, 1988). The general low-level air flow is directed from the sea to land during summer monsoon months and from land to sea during winter monsoon months (Ananthakrishnan et al., 1979). The maximum interannual variability was during the summer monsoon months (Fig. 3.1h).

The seasonal march of the cross-shore component of wind shows a largely convex shape (Fig. 3.2a). The maximum westerly value occurred in June (1.0 m/s) and the minimum westerly value during December (0.2 m/s) giving an annual range of 0.8 m/s. The cross-shore wind was directed towards the shore throughout the year. The interannual variability was maximum during the summer monsoon (Fig. 3.2b).

The along-shore component of wind shows a concave shape with a small decrease during June (Fig. 3.2c). The maximum value occurred during August (-1.5 m/s) and minimum during November (-0.2 m/s) giving an annual range of 1.3 m/s. The drop from August to November was quite sharp. The along-shore component was northerly throughout the year. The least interannual variability was during November-December-January (Fig. 3.2d).

The seasonal variations of the along-shore and offshore winds are interlinked with the seasonal variations in the pressure distribution, which in turn are coupled with the seasonal variation in the temperature field, pointing out the relationship between these parameters. In general, the seasonal variation of these parameters is less at southern latitudes as compared to those at northern latitudes (Ananthakrishnan et al., 1979).

The seasonal cycle of rainfall shows a weak bimodal pattern with a sharp rise from April to June, and then a gradual drop to Septmber (Fig. 3.2e). The primary peak occurred during June and the secondary peak during October. The range of the monthly totals was about 81 cm. The rise was sharp compared to the drop. The maximum rainfall of 83 cm was recorded during June, while the minimum of 2 cm was recorded in January. The southwest monsoon months accounted for as much as 68% of the annual total. This is in conformity with the observations made by other workers (Ananthakrishnan et al., 1979; Ramesh Kumar and Ananthakrishnan, 1986). The Western Ghats at the eastern boundary of Kerala, which have an average elevation of 1 km, provide orographic lifting of the southwest monsoon winds, resulting in heavy precipitation over the western slopes and good rainfall over the midlands and lowlands. The maximum interannual variability of the rainfall was during the summer monsoon months (Fig. 3.2f).

The seasonal cycle of relative density shows a very interesting pattern (Fig. 3.2g). The relative density was more or less constant at 20 units from January to April. A sharp drop of 19 units from April to July, and a gradual rise upto December were noticed. The drop from April to July was very sharp as compared to the rise from July to December. The range of the relative density was about 19 units. The 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. The months of May-June showed the maximum interannual variability, and July the least (Fig. 3.2h).

The monthly march of the observed sea level shows a concave type of distribution (Fig. 3.3a). The mild peak noticed during June is attributed to peak summer monsoon rainfall. The maximum sea level (75 cm) occurred during December and the lowest value (57 cm) during August-September period. The range of the sea level was about 18 cm. The interannual variability for each month is presented in Fig. 3.3b.

The corrected sea levels, corrected for the atmospheric pressure over the global oceans (CSL-G) and for the local atmospheric pressure (CSL-L) were considered next (Appendix-II).

The seasonal march of CSL(G) shows a concave shape with a slight peak during June (Fig. 3.3c). The maximum sea level of 77 cm occurred during December and the minimum of 55 cm during July. The annual range of CSL-G was about 22 cm. The interannual variability for each month is presented in Fig. 3.3d.

The seasonal cycle of CSL(L) shows a concave shape with a slight peak during June (Fig. 3.3e). The maximum sea level of 88 cm occurred during December and the minimum of 68 cm during August. The annual range of CSL-L was about 20 cm. The interannual variability for each month is presented in Fig. 3.3f.

There is no significant difference between the seasonal march of the observed sea level and corrected sea levels, CSL(G) and CSL(L), pointing out that the "inverted barometer effect" is not an important factor for seasonal time scales at Cochin. The range is, however, marginally higher in the case of the corrected sea levels as compared to the observed sea level. The maximum interannual variability in the case of the observed sea level, CSL(G) and CSL(L) occurred during the months of November-December (Figs. 3.3 b,d,f).

The seasonal cycle parameters (amplitude and phase of the annual, semi-annual and ter-annual components) of the data are presented in Table 3.2. 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 the rainfall and cross-shore wind. The first three cycles explained more than 96% of the total variance in all the cases. The RMS deviations clearly indicate that the modelled series using annual, semi-annual and ter-annual harmonics closely approximate the original series than the one modelled using annual and semi-annual harmonics.

The seasonal amplitudes of the meteorological parameters at the southern stations are generally lower than the corresponding ones at the northern stations, particularly for air temperature, winds, atmospheric pressure, etc. whereas it is higher for the rainfall (Ananthakrishnan et al., 1979).

3.3.2. YEAR-TO-YEAR VARIABILITY OF THE SEASONAL CYCLE AMPLITUDES

The analysis indicated that the mean of the annual cycle amplitudes was the largest, followed by that of the semi-annual or ter-annual amplitudes, except for air temperature (Table 3.3). The standard deviations of the annual cycle amplitudes were greater than those of the semi-annual or ter-annual amplitudes for all the parameters. The coefficients of variation were high for the ter-annual amplitudes, as compared to the annual or semi-annual amplitudes, except for relative density. It is thus clear that there exists year-to-year variability in the seasonal cycle amplitudes of the elements. The amplitudes based on the climatological mean cycle were all less than the long-term mean amplitudes derived from individual years (Tables 3.2 and 3.3).

3.3.3. WIND DIRECTION AND STEADINESS AT COCHIN

The wind direction data at Cochin for the period 1982-'93 was examined to determine the most predominant direction (Table 3.4). The data indicated that the percentage of observations in the class interval 270° - 300° is 35.5% and that for the class interval 300° - 330° is 17.2%. In other words, 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 more or less in agreement with the orientation of the Western Ghats.

The steadiness parameter gives information on how steady the wind is with respect to its direction (Howarth and Huthnance, 1984; Tolmazin, 1985; Rao et al., 1995). It is the ratio of vector wind to the scalar wind (in percentage). The seasonal cycle of this parameter indicated a roughly convex shape (Fig. 3.3g). The highest steadiness of 88% was recorded during August and the lowest of 46% during December. This result is in accordance with that reported earlier (Anon., 1959).

3.3.4. SEASONAL VERSUS INTERANNUAL VARIABILITY

The data show that the cross-shore wind followed by the scalar wind speed has strong interannual variability whereas relative density and air temperature have strong seasonal variability (Table 3.5).

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). The percentage of variance contained in the seasonal component is given by :-

$$100(1- VAR_{RES}/ VAR_{OBS})$$

where VAR_{RES} is the variance of the residual time series (i.e. anomalies) and VAR_{OBS} is the variance of the original time series. The seasonal variances contained in the various elements are presented in Table 3.5.

From the table, it is clear that the cross-shore wind showed the least (33.7%) and the relative density showed the maximum (83.5%) seasonal signal. The observed sea level and the corrected sea levels showed that with the application of the pressure corrections, the seasonal signal in the series improved slightly.

3.3.5. LONG TERM SEASONAL VARIABILITY

For understanding the seasonal variation, the data collected at Cochin were stratified into three seasons, each comprising of four months viz. premonsoon (February-May), summer monsoon (June-September) and postmonsoon (October-January), and are presented in Table 3.6. This categorisation of the seasons is in accordance with that reported by a number of workers for the Cochin estuary (e.g., Sankaranarayanan and Qasim, 1969; Rasheed et al., 1995).

From the table, it is clear that the seasonal characteristics of the data on relative density, sea surface temperature, air temperature, wind speed, rainfall, atmospheric pressure and sea level showed wide variability. The changes brought about by the summer monsoon were particularly conspicuous as compared to the premonsoon and postmonsoon seasons in the case of most of the parameters.

3.3.6. SEA LEVEL - INTERANNUAL CORRELATION

For the following discussion, the data were first detrended, and then the monthly anomalies were generated giving the non-seasonal time series. These anomalies were then correlated with the sea level (Table 3.7).

The fitted regression line between the SST and observed sea level gave a slope of 1.39±1.31 cm per °C. This positive association between sea level and SST, is in accordance with many studies (La Fond, 1939; Moursy, 1996; Bell and Goring, 1998).

The data on air temperature revealed no significant relationship with the observed sea level (hence, not presented in the table). The sea with its large specific heat capacity, has more thermal inertia than the atmosphere (Pugh, 1987; Ashizawa and Cole, 1994). The random variations are larger in the air temperature than in the SST.

The fitted regression line between the observed sea level and the atmospheric pressure gave a slope of -1.52±0.82 cm mb^{-1}. The theoretical "inverted barometer" response is -1 cm mb^{-1}. The fitted regression line between the observed sea level and the atmospheric pressure gave a slope of -1.27 cm mb^{-1} at Newlyn and -0.44 cm mb^{-1} at Southend (both stations in the United Kingdom, Pugh, 1987). Sultan et al. (1995a) obtained a nearly perfect regression coefficient of -1 cm mb^{-1} at Rastanura and Safaniya in the Arabian Gulf. The result obtained in this study, does not vary much from the above mentioned observations. 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; Sultan et al., 1995a). The more random changes may also be due to interannual oceanographic changes.

The regression of scalar, cross-shore and along-shore wind on the observed sea level individually gave regression coefficients of -3.19±2.19, 3.85±1.91 and 6.12±1.83 cm per m/s, respectively. The relationship reveals that with increase in scalar wind speed of 1 m/s, the sea level decreases and the decrease is about 3.19±2.19 cm. This could be due to enhanced evaporation associated with increased wind speed. The cross-shore wind reveals that with an onshore increase of wind of 1 m/s, the sea level should rise by 3.85±1.91 cm and vice-versa, which is to be expected because of land boundary (piling up). The along-shore wind, on the other hand, reveals that with an increase of poleward wind of 1 m/s, the sea level should rise by 6.12±1.83 cm and 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. Ekman transport is 90° cum sole of the wind direction (Bakun, 1973; Thadathil et al., 1997). The most offshore transport of surface water and hence the most upwelling, occurs in response to along-shore equatorward winds, not offshore winds (Bearman, 1995). This could probably explain the higher regression coefficients for the along-shore wind than the offshore wind, in their relationship with sea level. Such a relationship has been shown (Jacobs, 1939; Sultan et al., 1995b; Bell and Goring, 1998). 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 (Pattullo et al., 1955; Hsieh and Hamon, 1991; Bell and Goring, 1998).

The regression of rainfall data on non-seasonal observed sea level revealed that for an increase of 1 cm of rainfall, the corresponding increase in sea level is 0.10±0.04 cm. This is attributed to the local addition of mass of water.

The regression of data on relative density with the observed sea level revealed that with an increase of 1 unit in the relative density, the sea level depresses by -0.34±0.19 cm. This is to be expected as denser waters depress the water level Bell and Goring, 1998).

The circulation off the southwest coast of India during the southwest monsoon, though weak, is dynamically similar to the wind-forced eastern boundary currents found elsewhere in the oceans (Shetye et al., 1990b; Madhupratap et al., 1994). These wind-induced changes in ocean circulation can significantly affect the eastern boundary sea level (Thompson, 1990; Longhurst and Wooster, 1990; Bearman, 1995).

The detrended and deseasonalised data were smoothened with a 13 point moving average and then the correlations between sea level and various elements were determined. This procedure involves a loss of 12 data points but helps to remove random fluctuations in the time series and brings out prominent relationships between the two parameters. The results of this correlation study are presented in Table 3.8. The relationship between the observed sea level and the air temperature, which was not found to be significant in the above study, revealed itself 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.

3.3.7. EL NINO EFFECTS

In the follwing description, two approaches have been adopted to show the year-to-year variations in the oceanographic and surface meteorological parameters in connection with ENSO cycles. In the first section, the means and medians have been utilised to highlight the variability for the period 1981 to 1984. In the second section, for the interannual time series correlation study - SOI series and the anomalies of the oceanographic and surface meteorological parameters have been used.

3.3.7.1. ANNUAL MEANS (1981-1984)

The daily data at Cochin for the parameters of relative density, SST, air temperature, atmospheric pressure and winds were subjected to statistical analysis, i.e. by estimating means and medians (Table 3.9) to identify anomalous conditions during 1981-1984. The 1982-'83 El Nino event is the strongest one reported during the last 100 years (Philander, 1990; Glantz, 1996). The data for 1981 and 1984 are also presented to show normal existing conditions.

From the above results, it is clear that some parameters showed anomalous values for the 1982-1983 period and that the nature of these anomalies is in general agreement with that reported for coastal stations in the Pacific and Indian Oceans (Rasmusson and Carpenter, 1982; Cadet and Diehl, 1984; Wyrtki, 1985; Enfield, 1989). These anomalies are larger than normal relative densities, higher air temperatures and sea surface temperatures, lower sea levels and higher atmospheric pressures during 1982-'83 as compared to 1981 and 1984. The rainfall and wind data, however, did not show much differences during 1982-'83 period as compared to 1981 and 1984.

3.3.7.2. INTERANNUAL CORRELATION WITH SOUTHERN OSCILLATION INDICES

To understand whether there is any relationship between these parameters at Cochin and the SOI (an indicator of the El Nino phenomenon), the data were subjected to a correlation study. The SOI data were detrended and smoothened with a 13 point moving average. The meteorological and oceanographic data were first detrended, and then the monthly anomalies were determined and the resulting anomalies were smoothened with a 13 point moving average and then the correlations with the SOI series were determined. This procedure involves the loss of 12 data points. The results are presented in Table 3.10.

The data on SST, air temperature, atmospheric pressure and relative density showed a highly significant negative relationship with the SOI series. This means, that during the El Nino periods, the SST, air temperature, atmospheric pressure and the relative density are expected to increase. 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, and CSL-L showed a positive relationship (at 95% significance level) with the SOI series. The observed sea level and CSL-G series,however, showed a highly significant relationship (at 99% significance level) with the SOI series. This means that during the El Nino periods, more northerly winds and lower sea levels are to be expected.

3.4. CONCLUSIONS

1. The seasonal cycle of the surface oceanographic and meteorological parameters at Cochin are well defined. The parameters showed interannual variability during the 18 year period considered in this study.

2. There is no significant difference between the seasonal cycles of the observed and corrected sea levels.

3. The Western Ghats have a profound influence on the wind direction at Cochin. For over 50% of the time, the direction is from 270°-330° pointing out to the influence of the Western Ghats.

4. The wind is remarkably steady during the southwest monsoon months whereas during winter months it is least steady.

5. The seasonal variability was found to be stronger than the interannual variability for sea level (with and without pressure corrections), rainfall, air temperature, atmospheric pressure and relative density. However, in the case of cross-shore wind and scalar wind, the seasonal signal was found to be more or less same as the interannual variability.

6. The data, when stratified into premonsoon, monsoon and postmonsoon seasons, clearly showed sharp changes during the southwest monsoon season.

7. The nonseasonal data on SST, air temperature, atmospheric pressure, scalar wind, cross-shore and along-shore winds, rainfall and relative density showed significant correlations with observed sea level, CSL(G) and CSL(L). The influence of the along-shore and cross-shore winds was particularly strong.

8. The influence of El Nino was seen in some of the parameters. The influence was strong in the atmospheric pressure followed by relative density. The sharp changes brought about by the 1982-'83 El Nino were clearly seen in most of the meteorological and oceanographic observations.

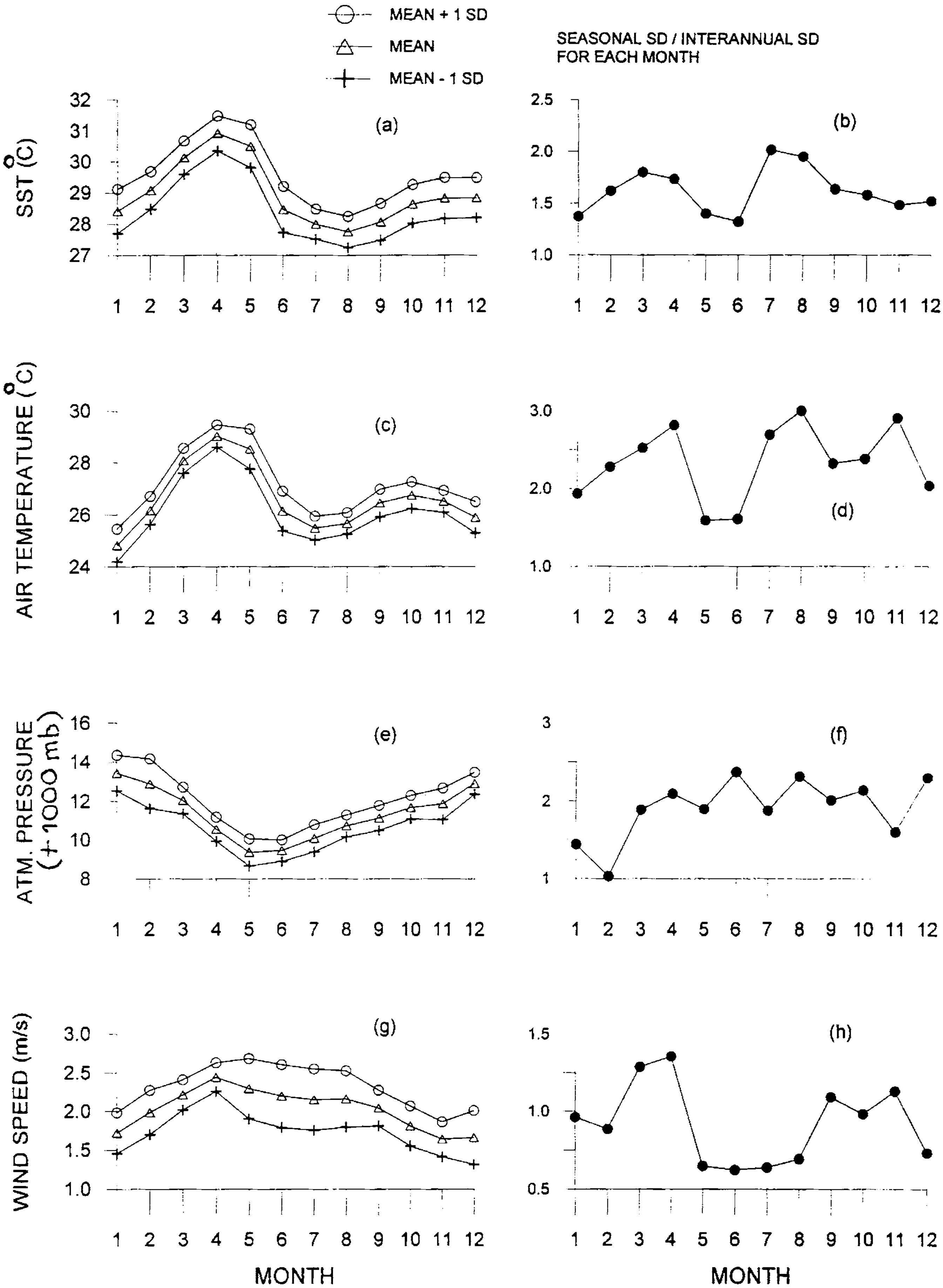


Fig. 3.1. Seasonal march of (a) SST (c) air temperature (e) atmospheric pressure and (g) wind speed. Interannual variability for each month for (b) SST (d) air temperature (f) atmospheric pressure and (h) wind speed.

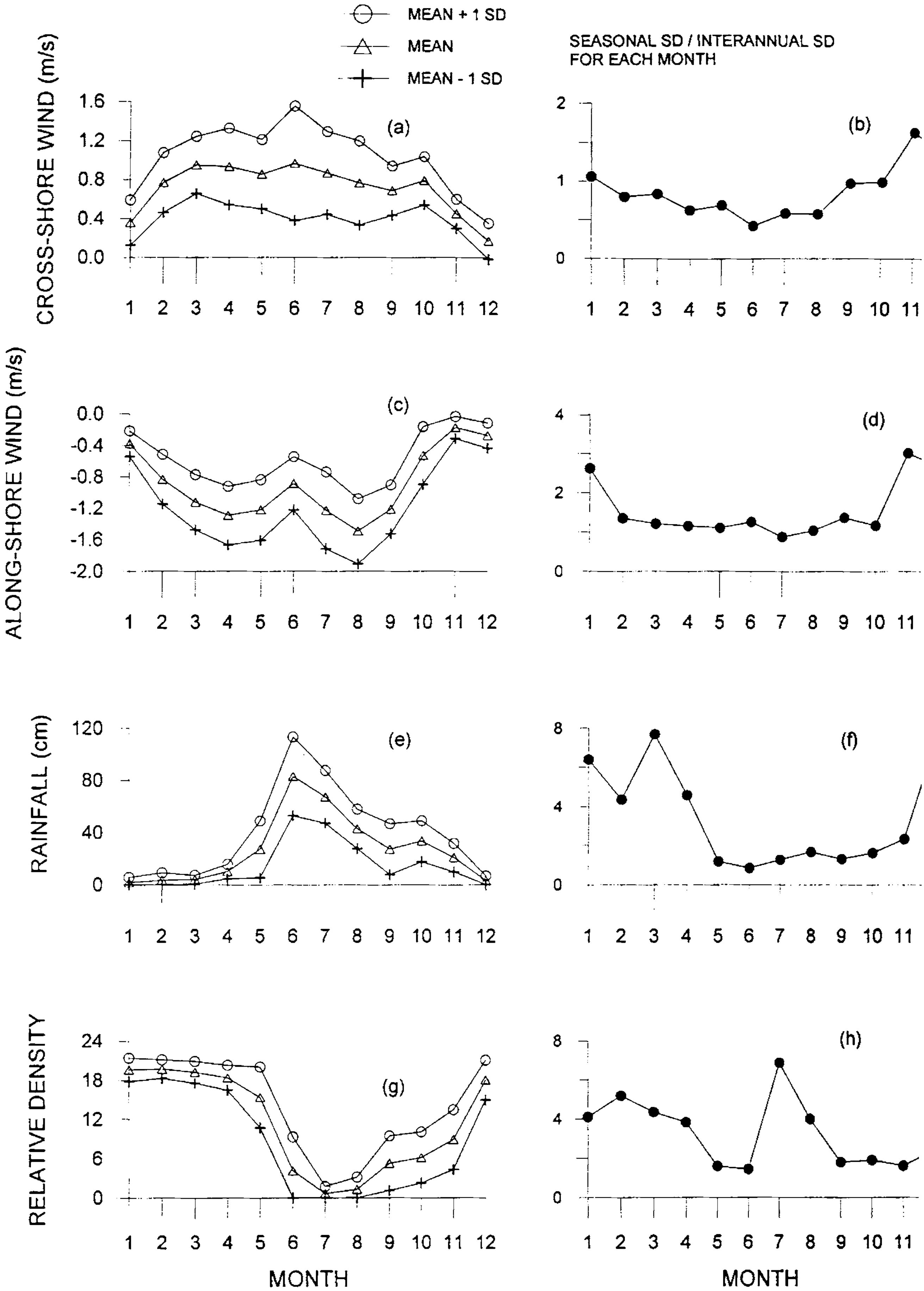


Fig. 3.2. Seasonal march of (a) cross-shore wind (c) along-shore wind (e) rainfall and (g) relative density. Interannual variability for each month for (b) cross-shore wind (d) along-shore wind (f) rainfall and (h) relative density.

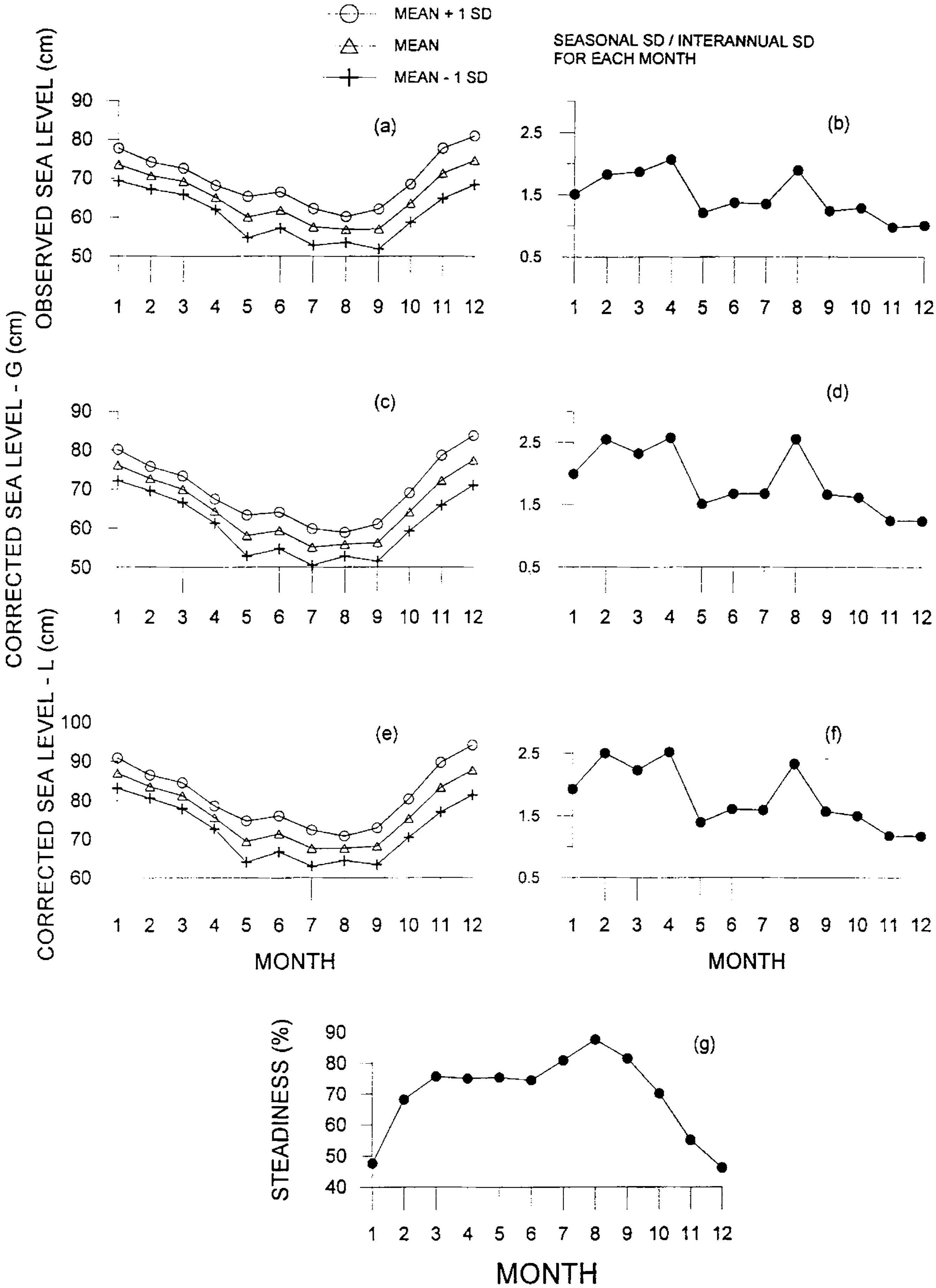


Fig. 3.3. Seasonal march of (a) observed sea level (c) corrected sea level - G and (e) corrected sea level - L. Interannual variability for each month for (b) observed sea level (d) corrected sea level - G and (f) corrected sea level - L. Seasonal march of (g) steadiness of the wind

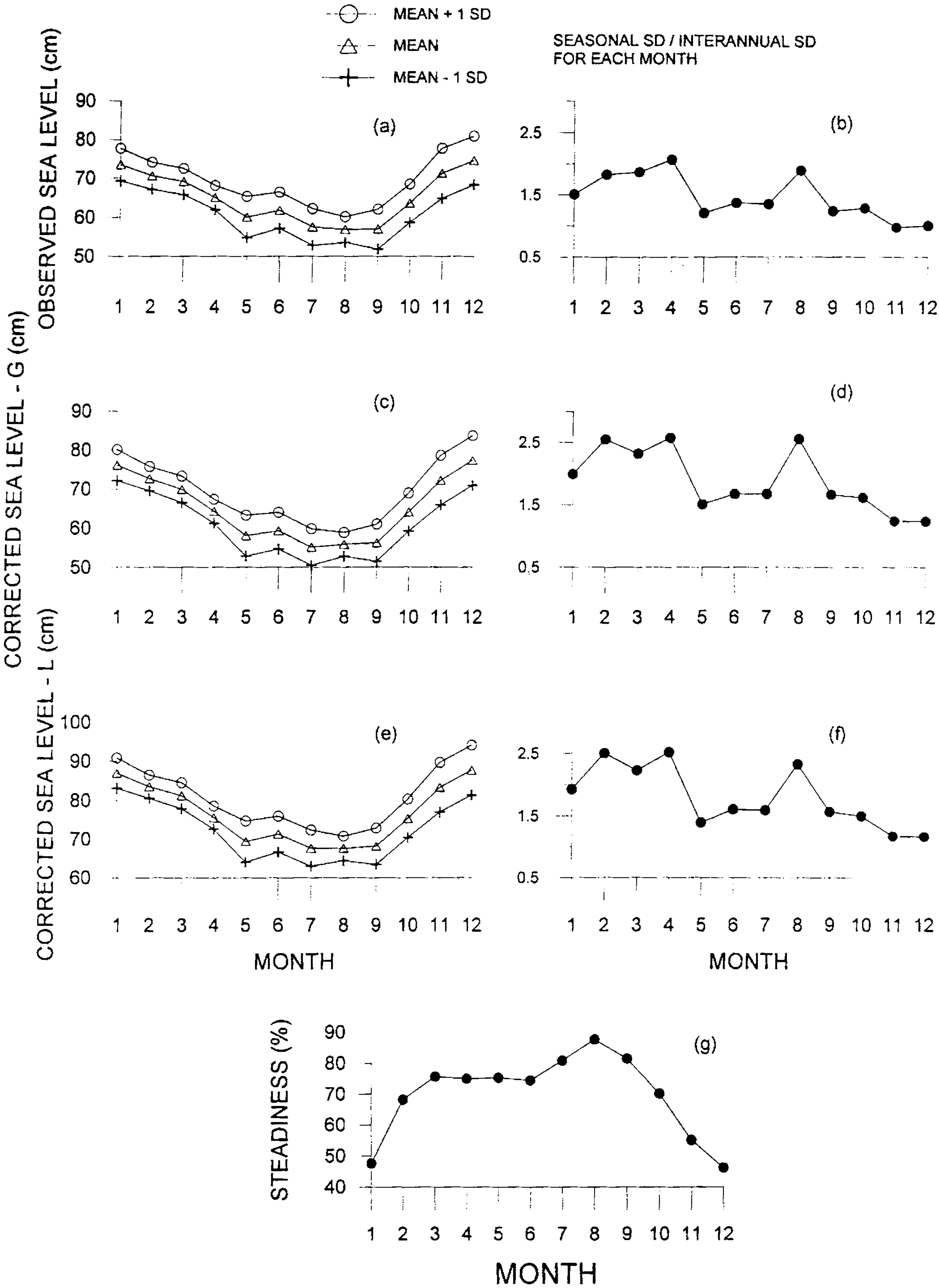


Fig. 3.3. Seasonal march of (a) observed sea level (c) corrected sea level - G and (e) corrected sea level - L . Interannual variability for each month for (b) observed sea level (d) corrected sea level - G and (f) corrected sea level - L. Seasonal march of (g) steadiness of the wind

Table 3.1. Details of the oceanographic & surface meteorological data collected at Cochin (1976 - 1993).

	PARAMETER	PERIOD (YEARS) START END		ACCURACY
1.	SST	1976 - 1988		0.1 °C
2.	AIR TEMPERATURE	1976 - 1993		0.1 °C
3.	ATMOSPHERIC PRESSURE	1976 - 1993		0.1 mb
4.	WIND	1982 - 1993	SPEED	0.5 kt
			DIRECTION	5.0 °
5.	RAINFALL	1976 - 1993		1.0 mm
6.	RELATIVE DENSITY	1976 - 1993		0.001
7.	SEA LEVEL	1976 - 1993		2.0 cm
8.	SOI	1976 - 1993		-----

Table 3.2. Results of harmonic analysis of the oceanographic and surface **meteorological** parameters (climatological means) at Cochin.

›ARAMETER	1	2	3	4	5	6	7	8	9	10	11	12	13
;ST	0.95	58.32	37.18	2.55	98.06	1.06	0.84	0.22	2.85	9.77	11.51	0.2071	0.1362
ιir temperature	1.50	31.71	64.25	2.27	98.23	0.98	1.39	0.26	3.71	9.57	11.39	0.2463	0.1632
.tm. Pressure	1.70	89.30	9.91	0.02	99.23	1.74	0.58	0.03	11.92	1.38	11.28	0.1162	0.1144
:calar wind	0.06	86.64	10.90	1.68	99.22	0.33	0.12	0.05	4.84	8.70	11.61	0.0397	0.0223
:ross-shore wind	0.06	66.99	18.48	13.06	98.53	0.28	0.15	0.13	5.10	8.75	9.83	0.0937	0.0298
.long-shore wind	0.18	66.85	26.12	5.67	98.63	0.50	0.31	0.14	11.43	11.18	9.72	0.1136	0.0501
.ainfall	638.01	73.82	11.28	11.62	96.72	30.69	12.00	12.18	6.68	11.78	9.83	9.7520	4.5769
.elative density	54.05	92.71	1.28	4.92	98.91	10.01	1.18	2.31	1.58	9.59	0.12	1.8017	0.7664
bserved sea level	40.04	89.95	6.53	1.99	98.47	8.49	2.29	1.26	0.59	11.40	10.54	1.1871	0.7821
SL-G	62.39	94.07	3.69	1.08	98.84	10.83	2.15	1.16	0.48	11.56	10.63	1.1817	0.8509
SL-L	55.06	93.37	3.90	1.48	98.74	10.14	2.07	1.28	0.48	11.64	10.56	1.2268	0.8318

1 - Variance of the 12 monthly values (in their respective units)
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 (cm)
7 - Amplitude of the semi-annual cycle (cm)
8 - Amplitude of the ter-annual cycle (cm)
9 - Phase of the annual cycle: in months centered to mid-month
0 - Phase of the semi-annual cycle: in months centered to mid-month
1 - Phase of the ter-annual cycle: in months centered to mid-month
2 - RMS deviation of the observed minus that calculated using annual and semi-annual cycle parameters
3 - RMS deviation of the observed minus that calculated using annual

Table 3.3. Year to year variability of the seasonal cycle amplitudes of the different oceanographic and surface meteorological parameters at Cochin.

		ANNUAL			SEMI-ANNUAL			TER-ANNUAL		
PARAMETERS	YEARS	MEAN	SD	CV	MEAN	SD	CV	MEAN	SD	CV
SST	13	1.09	0.34	31.22	0.86	0.17	19.21	0.26	0.15	58.35
AIR TEMPERATURE	18	1.01	0.28	27.65	1.41	0.17	12.30	0.33	0.15	44.21
ATMOSPHERIC PRESSURE	18	1.79	0.33	18.17	0.67	0.23	34.63	0.28	0.17	59.35
SCALAR WIND	12	0.38	0.14	38.05	0.18	0.08	41.81	0.14	0.06	44.08
CROSS-SHORE WIND	12	0.34	0.16	47.63	0.20	0.09	42.24	0.15	0.11	73.03
ALONG-SHORE WIND	12	0.53	0.16	29.93	0.35	0.09	25.44	0.19	0.10	48.94
RAINFALL	18	31.27	6.90	22.07	14.06	4.87	34.63	14.29	6.23	43.57
RELATIVE DENSITY	18	10.27	1.01	9.79	2.13	0.91	42.87	2.69	0.80	29.62
OBSERVED SEA LEVEL	18	8.97	1.65	18.35	3.17	1.03	32.49	2.05	1.08	52.67
CSL-G	18	11.14	1.53	13.76	3.07	0.94	30.71	2.07	1.04	50.40
CSL-L	18	10.47	1.51	14.43	3.02	0.95	31.38	2.13	1.06	49.80

MEAN - Mean amplitude
SD - Standard deviation
CV - Coefficient of variation (%)

Table 3.4. Frequency distribution of the wind direction for the period 1982 - 1993.

Class interval	Frequency (%)		
	1	2	3
0 - 30	2.80	11.05	6.61
30 - 60	0.58	8.48	4.19
60 - 90	0.48	4.70	2.93
90 - 120	1.94	17.97	9.56
120 - 150	0.58	5.95	2.55
150 - 180	0.19	1.18	0.63
180 - 210	0.40	4.34	2.11
210 - 240	1.54	8.19	4.23
240 - 270	2.04	10.84	6.31
270 - 300	21.60	53.38	35.53
300 - 330	12.12	24.66	17.20
330 - 360	2.89	17.71	8.15

1 - Lowest percentage based on the annual analysis for individual years

2 - Highest percentage based on the annual analysis for individual years

3 - Percentage based on the entire data set

Table 3.5. Seasonal and interannual variability of the oceanographic and surface meteorological parameters at Cochin for the 1976 - 1993 period.

PARAMETER	N	1	2	3	4	5
SST (°C)	156	0.98	1.16	0.62	1.58	71.34
Air Temperature (°C)	216	1.22	1.35	0.56	2.18	82.78
Atmospheric Pressure (mb)	216	1.30	1.50	0.75	1.73	75.36
Scalar wind (m/s)	144	0.25	0.40	0.31	0.81	40.56
Cross-shore wind (m/s)	144	0.25	0.42	0.35	0.71	33.65
Along-shore wind (m/s)	144	0.43	0.54	0.33	1.30	62.08
Rainfall (cm)	216	25.26	29.63	15.49	1.63	72.68
Relative density	216	7.35	8.04	3.26	2.25	83.54
Observed sea level (cm)	216	6.33	7.89	4.71	1.34	64.36
CSL-G (cm)	216	7.90	9.15	4.61	1.71	74.59
CSL-L (cm)	216	7.42	8.73	4.60	1.61	72.25

N - Number of months
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 3.6. Long-term mean and median for the entire data as well as for the premonsoon, summer monsoon and the postmonsoon seasons.

PARAMETER		1	2	3	4
SST (°C)	a)	28.95	30.03	28.11	28.72
	b)	28.80	29.99	28.11	28.71
Air temperature	a)	27.22	28.46	26.44	26.73
(°C)	b)	27.15	28.60	26.48	26.90
Atmospheric	a)	11.21	10.89	10.29	12.40
pressure (mb)	b)	11.20	10.89	10.39	12.50
Scalar wind speed	a)	2.02	2.22	2.12	1.73
(m/s)	b)	1.45	2.19	2.05	1.17
Rainfall	a)	0.78	0.68	1.07	0.65
(cm)	b)	0.59	0.55	0.72	0.54
Relative density	a)	11.95	17.19	4.00	13.49
	b)	14.69	19.51	1.62	16.00
Observed	a)	64.00	65.00	58.00	69.00
sea level (cm)	b)	64.00	65.00	57.00	70.00

a) Mean
b) Median

1 - Entire data
2 - Premonsoon data
3 - Summer monsoon data
4 - Postmonsoon data

Table 3.7. Regression coefficients of the non-seasonal data on various oceanographic and surface meteorological parameters against observed sea level at Cochin.

PARAMETER	1	2	3	4
SST	156	1.39 ± 1.31	0.17*	2.78
Atmospheric pressure	216	-1.52 ± 0.82	-0.24**	5.89
Scalar wind	144	-3.19 ± 2.19	-0.23**	5.48
Cross-shore wind	144	3.85 ± 1.91	0.32**	9.97
Along-shore wind	144	6.12 ± 1.83	0.49**	23.48
Rainfall	216	0.10 ± 0.04	0.34**	11.26
Relative density	216	-0.34 ± 0.19	-0.23**	5.43

1 - Number of months
2 - Regression coefficient with the error estimates
3 - Correlation coefficient
4 - Percentage variance explained by the relationship

* - Significant at 5% level
** - Significant at 1% level

Table 3.8. Interannual correlation between the observed sea level and corrected sea levels with the oceanographic and surface meteorological parameters at Cochin (1976-1993).

		1		2		3	
PARAMETER	N	R	V	R	V	R	V
SST	144	0.26	6.82	0.24	5.86	0.27	7.47
AIR TEMPERATURE	204	0.20	3.99	0.20	4.07	0.25	6.40
ATM. PRESSURE	204	-0.25	6.43	-0.22	5.00	-0.13^{ns}	1.65
SCALAR WIND	132	-0.43	18.36	-0.44	19.12	-0.47	22.06
CROSS-SHORE WIND	132	+0.65	41.57	+0.66	43.51	+0.70	49.48
ALONG-SHORE WIND	132	+0.64	41.04	+0.64	40.59	+0.62	37.89
RAINFALL	204	0.50	24.65	0.50	25.07	0.52	27.09
RELATIVE DENSITY	204	-0.24	5.55	-0.24	6.09	-0.24	5.75

P.S. All the values are significant at 1% level, excluding the only value marked as ns - not significant.

N - Number of months
R - Correlation coefficient
V - Percentage variance accounted by the relationship

1 - Observed sea level
2 - CSL-G
3 - CSL-L

Table 3.9. Annual mean and median for the 1981-1984 period for the various surface meteorological and oceanographic parameters.

PARAMETER		1981	1982	1983	1984
SST (°C)	a)	28.94	29.73	29.78	29.05
	b)	29.05	29.73	29.50	28.93
Air temperature (°C)	a)	27.37	28.34	28.17	27.47
	b)	27.56	28.40	27.89	27.24
Atmospheric pressure (mb)	a)	11.31	11.62	11.62	10.71
	b)	11.21	11.77	11.46	10.76
Scalar wind speed (m/s)	a)	----	1.72	1.98	1.94
	b)	----	1.15	1.34	1.36
Rainfall (cm)	a)	0.86	0.77	0.76	0.77
	b)	0.60	0.58	0.59	0.59
Relative density	a)	11.08	14.26	15.50	13.09
	b)	15.32	18.63	20.39	15.21
Sea level (cm)	a)	69.00	64.00	64.00	65.00
	b)	70.00	64.00	64.00	66.00

a) Mean
b) Median

Table 3.10. Interannual correlation between the Southern Oscillation Indices and the oceanographic and surface meteorological parameters at Cochin.

PARAMETER	N	R	V
SST	144	-0.30^{**}	9.21
AIR TEMPERATURE	192	-0.23^{**}	5.10
ATM. PRESSURE	192	-0.69^{**}	47.44
SCALAR WIND	120	0.02^{ns}	0.03
CROSS-SHORE WIND	120	-0.16^{ns}	2.55
ALONG-SHORE WIND	120	0.22^{*}	4.84
RAINFALL	192	0.08^{ns}	0.62
RELATIVE DENSITY	192	-0.40^{**}	15.79
OBSERVED SEA LEVEL	192	0.22^{**}	4.93
CSL-G	192	0.21^{**}	4.53
CSL-L	192	0.15^{*}	2.27

N - Number of months
R - Correlation coefficient.
V - Percentage variance accounted by the relationship.

ns - Not significant
* - Significant at 5% level
** - Significant at 1% level

CHAPTER 4

CHAPTER 4

STATISTICAL FORECASTING OF OCEANOGRAPHIC AND METEOROLOGICAL PARAMETERS AT COCHIN

4.1. INTRODUCTION

The seasonal sea level variability is known to result from surface meteorological, oceanographic and hydrological forcings. For the prediction of sea level, quantification of these forcings is important. At present there is no such network of observing systems which can monitor these parameters to predict the sea level variablility. An attempt is made in this chapter to examine the suitability of statistical models for their predictive potential for the surface meteorological and oceanographic parameters at Cochin.

Statistical techniques to forecast the evolution of meteorological and oceanographic variables find applications in several fields. This is facilitated by the strong autocorrelations of the meteorological and oceanographic time series and the seasonal patterns they follow. The forecast can be one of short term nature i.e., pertaining to the immediate future, or a long term one. The techniques are particularly successful with respect to some of the parameters. Where a forecast technique is successful, any abnormal deviation of the observed value from the forecast value for any of the parameters, may provide an indication of some pronounced changes in the environmental conditions, which warrant a detailed study.

El-Gindy (1991) used stepwise multiple regression analysis, using the least square method to find the best fit equations between sea level and atmospheric pressure for sea level prediction. Brundrit (1995) has shown that statistical models can be exploited to separate out the underlying interannual structure from seasonal and higher frequency fluctuations, in the case of long term sea level data along the coasts of Namibia and Africa. Nogueira et al. (1997) modelled the thermohaline properties of an estuarine ecosystem using wind regime, runoff in the drainage basin and incoming solar radiation as the main forcing variables.

Niu et al. (1998) studied the statistical structure of several key environmental variables (river discharge, local rainfall, transformation of wind speed and wind direction, salinity and water level fluctuations) in the Apalachicola Bay area based on daily averages (daily total in the case of rainfall) over a 45 - month sampling period. They concluded that compared with time-lagged multiple regression models, transfer function models explain a much larger proportion of salinity variability and give more accurate estimates of the environmental effects. Nogueira et al. (1998) studied the behaviour of nutrients and chlorophyll-a time series in response to external forcing (meteorological and thermohaline) using Box-Jenkins modelling approach in an estuarine upwelling ecosystem.

The forecasting is done by the application of statistical models, which take into consideration the earlier values of the time series, or depend on trigonometric functions to account for the seasonal pattern of the data (Chisholm and Whitaker, 1971).

The success of the model is measured by "RMS" (root mean square deviation, which gives mean deviation of the observed value from the forecast value) or by the number of observations which deviate from the forecast value by an acceptable percentage (say 5% or 10%) of the observed value. The model which gives the minimum of either of the above can be considered as a better model than the others. In this study, the following three models viz. the autoregressive model, the least square sinusoidal model and the exponentially weighted moving average model are utilised for each of the parameters. A well accounted procedure of the above three models is given by Mendenhall and Reinmuth (1978). Autoregressive and least square models are also discussed in Cooper and Weekes (1988). The procedures are briefly outlined below.

4.2. MATERIALS AND METHODS

4.2.1. AUTOREGRESSIVE MODEL

An autoregressive model is of the form

$$\hat{y}_t = a_0+a_1y_{t-1}+a_2y_{t-2}+ \dots\dots+a_py_{t-p}$$

where y_t is the observed value, $\hat{y}_t$ the estimated value and "t" refers to the point of time. The above expression represents the model of the order "p". The model suggests that to forecast a value at a point of time, the previous "p" values of the variable in the observed time series are utilised. The values of the constants viz. $a_0,a_1\dots\dots\dots a_p$ are to be estimated by the least squares method making use of the earlier data (Kundu and Jain, 1993; Emery and Thomson, 1998). The usual practice is to start with the minimum number of variables in the first instance and to study how the RMS error varies with the addition of each subsequent variable. The one which yields minimum RMS error can be preferred to others.

4.2.2. SINUSOIDAL MODEL

The sinusoidal model, on the other hand, is of the form

$$y_t = a_0+a_1t+a_2\cos(2\pi t/L)+a_3\sin(2\pi t/L)+a_4t\cos(2\pi t/L)+a_5t\sin(2\pi t/L)$$

where "t" refers to the position of the variable in the time series and "L" the period of the seasonal cycle of the variable. As already mentioned, some of the meteorological parameters respond well to certain models because of the seasonal pattern they follow (Annes and Mohankumar, 1997). If the predominant seasonal cycle is annual in nature and if we are forecasting monthly values, "L" will be 12 and if half yearly "L" will be 6, etc. The constants $a_0, a_1 \ldots$ etc. are estimated by the method of least squares. The model can also be utilized for long term forecasting.

4.2.3. EXPONENTIALLY WEIGHTED MOVING AVERAGE MODEL

The Exponentially Weighted Moving Average (EWMA) model is a time series forecasting model based on a smoothing technique developed by Brown (1963). The technique has been thoroughly examined by Mendenhall and Reinmuth (1978), who used it in econometric forecasting.

The EWMA model takes into consideration the trend and the seasonal factor in the observed values. The values at time-point "t", as given by the following equations, are estimated.

1. Smoothed average $S_t = (\alpha)y_t/F_{t-L} + (1-\alpha)(S_{t-1}+R_{t-1})$
2. Trend gain $R_t = \beta(S_t-S_{t-1}) + (1-\beta)R_{t-1}$
3. Seasonal factor $F_t = \gamma(y_t/S_t) + (1-\gamma)F_{t-L}$

In the above, "L" stands for the length of the seasonal cycle (12, 6 or 4 months) of the variable, while α, β and γ are arbitrary values chosen to represent the data. The latter values are chosen for the observed values by trial and error method (which gives close approximation to the observed values) and are utilized for subsequent forecasting. The values are revised and updated with the latest observations periodically. The forecast of the value of a parameter $\hat{y}_{t+1}$ for a particular month (t+1), is given by

$$\hat{y}_{t+1} = (S_t+R_t)F_{t-11}$$

The above formula indicates that the smoothed average and the trend gain for the previous time-point (i.e. month and the seasonal factor of the corresponding period of the previous year) are made use of in obtaining forecast for a particular month. The procedure requires a continuous record of the values of S_t,

R_t and F_t over a period, to obtain estimate at any particular subsequent month.

The above techniques were applied to the following parameters - mean sea level, rainfall, air temperature, relative density and atmospheric pressure measured at Cochin, to see their suitability. As already mentioned, for each parameter, a different technique might be suitable, in certain cases none of them might be satisfactory. The results obtained are presented in this chapter.

4.3. RESULTS AND DISCUSSION

4.3.1. AUTOREGRESSIVE MODEL

The observations of the first fifteen year period of 1976-90 were made use of to estimate the forecasting constants, and the suitability of the model was tried on the subsequent 3 year period (1991 - 1993). To obtain forecast estimate at point (t+12) of the monthly time series, the observed values utilized were those at the time points "t", "t+3","t+6" and "t+9". The data at three month intervals were taken for each of the above observations, to account for any variability during the period. Thus the model used is

$$\hat{X}_{t+12} = a_0 + a_1x_t + a_2x_{t+3} + a_3x_{t+6} + a_4x_{t+9}$$

The model was initially tried with only the first two terms (viz.) $a_0+a_1x_t$, and subsequently other terms were added, one by one, making note of how the RMS is affected at each stage.

The constants used for fitting the equations are given in Table 4.1. It is evident that the RMS error need not necessarily reduce, with the inclusion of additional terms in the fitting equations. The forecast values are presented in Figs. 4.1a to 4.5a.

4.3.2. SINUSOIDAL MODEL

As already mentioned, the model tried is

$$\hat{y}_t = a_0 + a_1 t + a_2 \cos(2\pi t/L) + a_3 \sin(2\pi t/L) + a_4 t\cos(2\pi t/L) + a_5 t\sin(2\pi t/L)$$

where "t" is the point of time for which estimate is made and "L" is the length of the cycle of the parameter. As the meteorological parameters have a cycle of one year, L is taken as 12 (months) and consequently $2\pi/L$ becomes 30°, except in the case of air temperature where L is taken as 6 (months) and hence $2\pi/L$ is 60° (for parameters which have strong annual cycle, L is taken as 12 months and for parameters which have strong semi-annual cycle, L is taken as 6 months).

The data for the entire period of 1976-1990 were utilized for calculating the constants of the forecast and the estimates of the parameters were worked out for the subsequent period and compared with the observed values. The constants used for fitting the curve are presented in Table 4.2. The forecast values are presented in Figs. 4.1b to 4.5b.

4.3.3. EXPONENTIALLY WEIGHTED MOVING AVERAGE METHOD

This model requires calculation of S_t, the smoothed average at time point "t" and, R_t and F_t - the trend gain and the seasonal factor. In what follows, the monthly values of the parameter for the preceding two year (1989 - 1990) period were utilised for preliminary calculations and the subsequent three year period of 1991-1993 were utilised to check the accuracy of the forecast values. The preliminary values for S_t, R_t and F_t were also obtained from the corresponding trend equations. An estimate for each month is obtained individually using this procedure and it was found to be more convenient to see to what extent it (the estimate) deviated from the observed value. The values chosen for α, β and γ and the RMS deviations are as given in Table 4.3. The forecast values are presented in Figs. 4.1c to 4.5c.

4.3.4. MODEL RESULTS

Both the troughs and ridges coincided with those of the observed values in the case of sea level, air temperature, relative density and atmospheric pressure. However, the values at peak points and trough points differed and the models were not suitable at certain specific points, while satisfactory at some other points. For the rainfall data, the deviations of the estimates were found to be quite high at particular points, in respect of all the three models.

The prediction errors in respect of individual values for the different parameters are presented in Table 4.4. It is evident that the errors are high in respect of rainfall and relative density, whereas they are less for air temperature, sea level and atmospheric pressure.

The correlation coefficients between the observed and the predicted values are highly significant (Table 4.5), showing that the observed and predicted data have a similar seasonal cycle, and also that their troughs and ridges coincide.

From Tables 4.1, 4.2 and 4.3, it is evident that the EWMA technique showed the least RMS, followed by autoregressive and sinusoidal techniques for all the parameters excluding sea level. Sea level showed the least RMS for EWMA technique followed by sinusoidal and autoregressive techniques.

4.4. CONCLUSIONS

The following conclusions are arrived at with regard to the performance of the three models, for the oceanographic and surface meteorological observations at Cochin.

1. Seasonal cycles in the data are well estimated by all the three methods of forecasting. The observed values and the predicted values are highly correlated for all the three models, showing good agreement in respect of the crests and troughs.

2. A few estimated points are widely off the observed values in some of the cases. This enhances the RMS errors. If

such points are excluded the RMS will be very much reduced, showing better agreement between estimated and observed values.

3. For the sinusoidal model, the estimated values are cyclical in nature without sharp kinks, and the crests and troughs are also relatively smooth. This is in contrast to the estimated values by autoregressive and EWMA techniques.

4. In the EWMA technique, forecast values showed a better agreement with the observed values during the third year.

5. Of the three techniques applied viz. autoregressive, sinusoidal, and EWMA, the EWMA technique showed the least RMS.

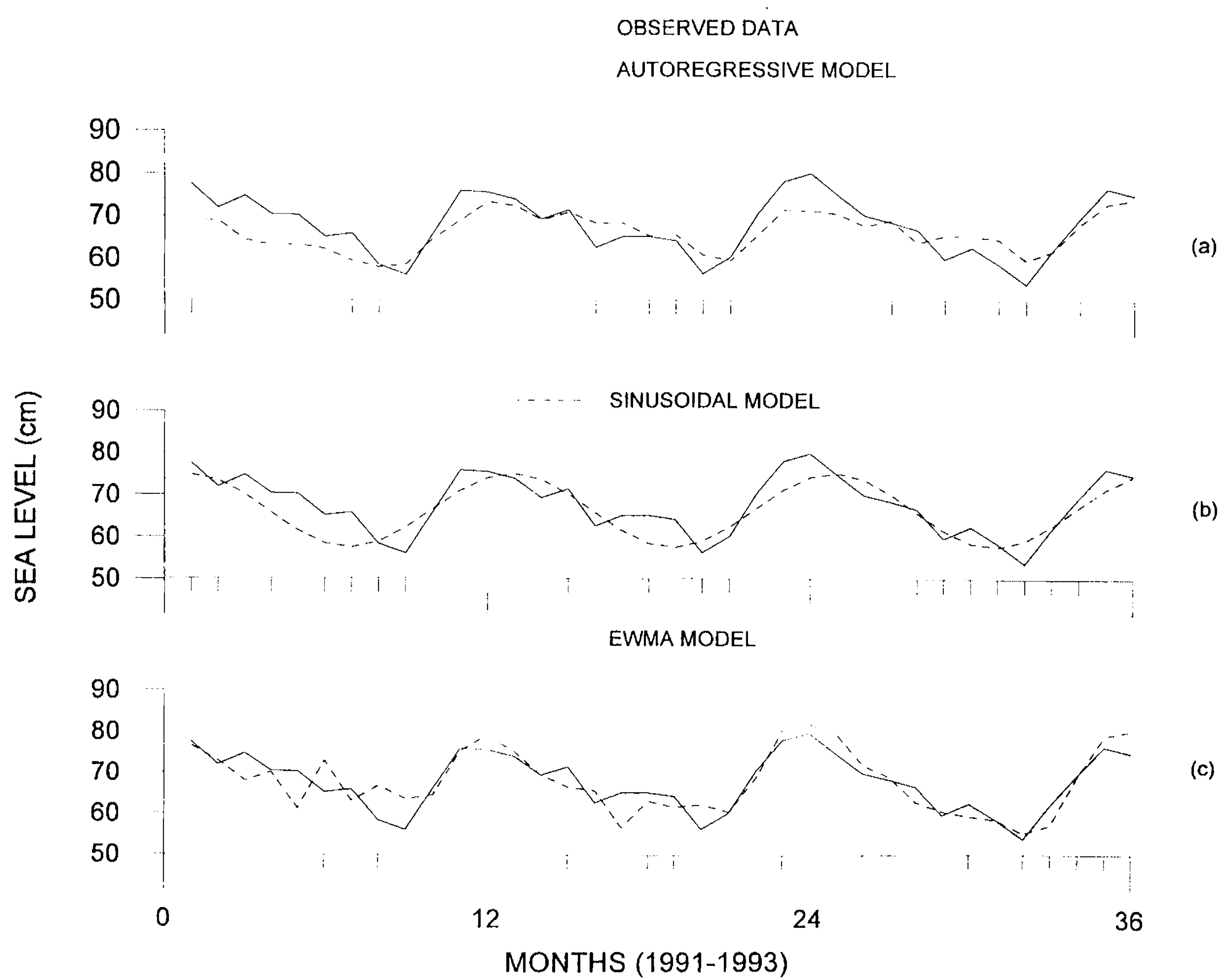


Fig. 4.1. Observed and predicted sea level at Cochin for the period 1991-1993.

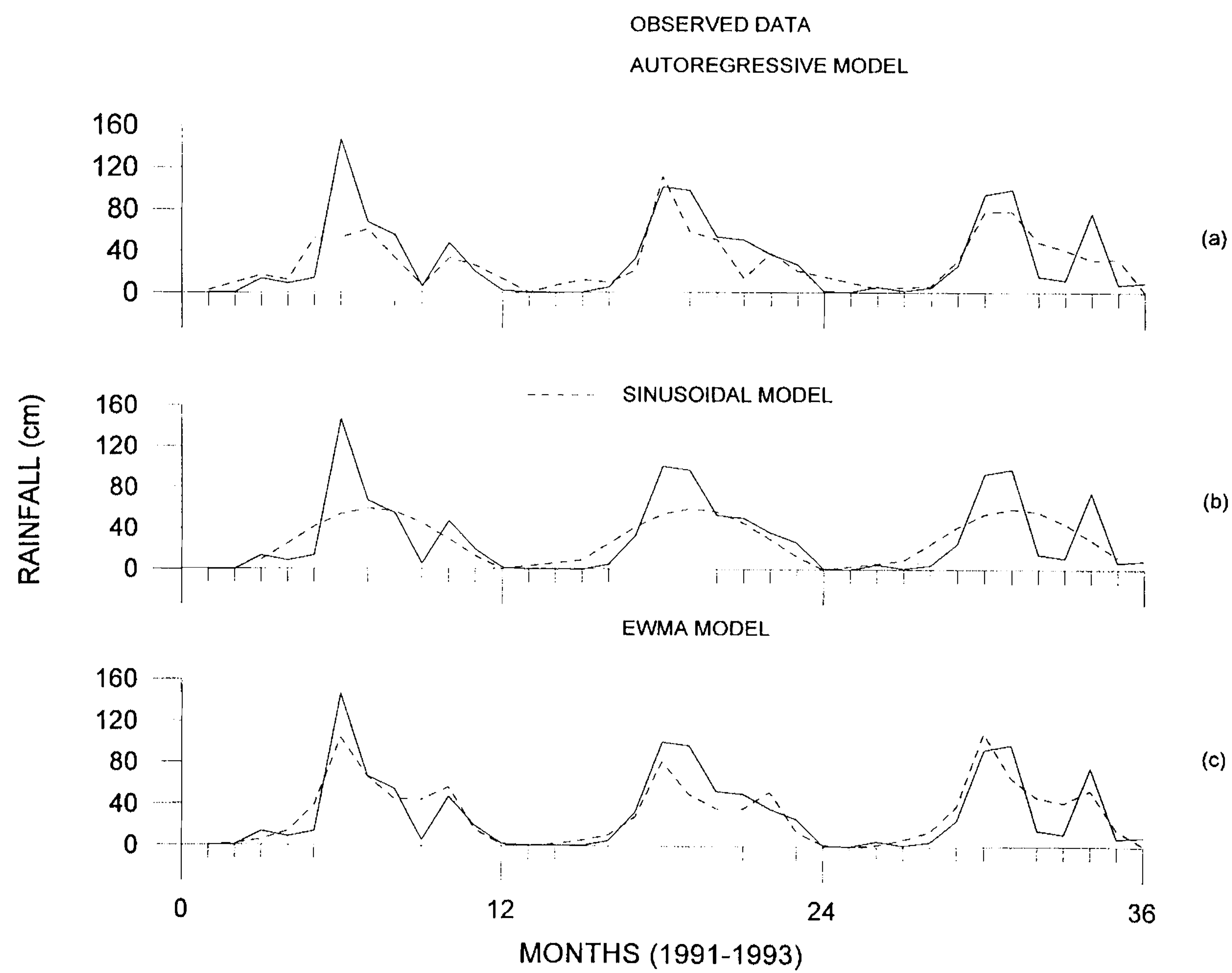


Fig. 4.2. Observed and predicted rainfall at Cochin for the period 1991-1993.

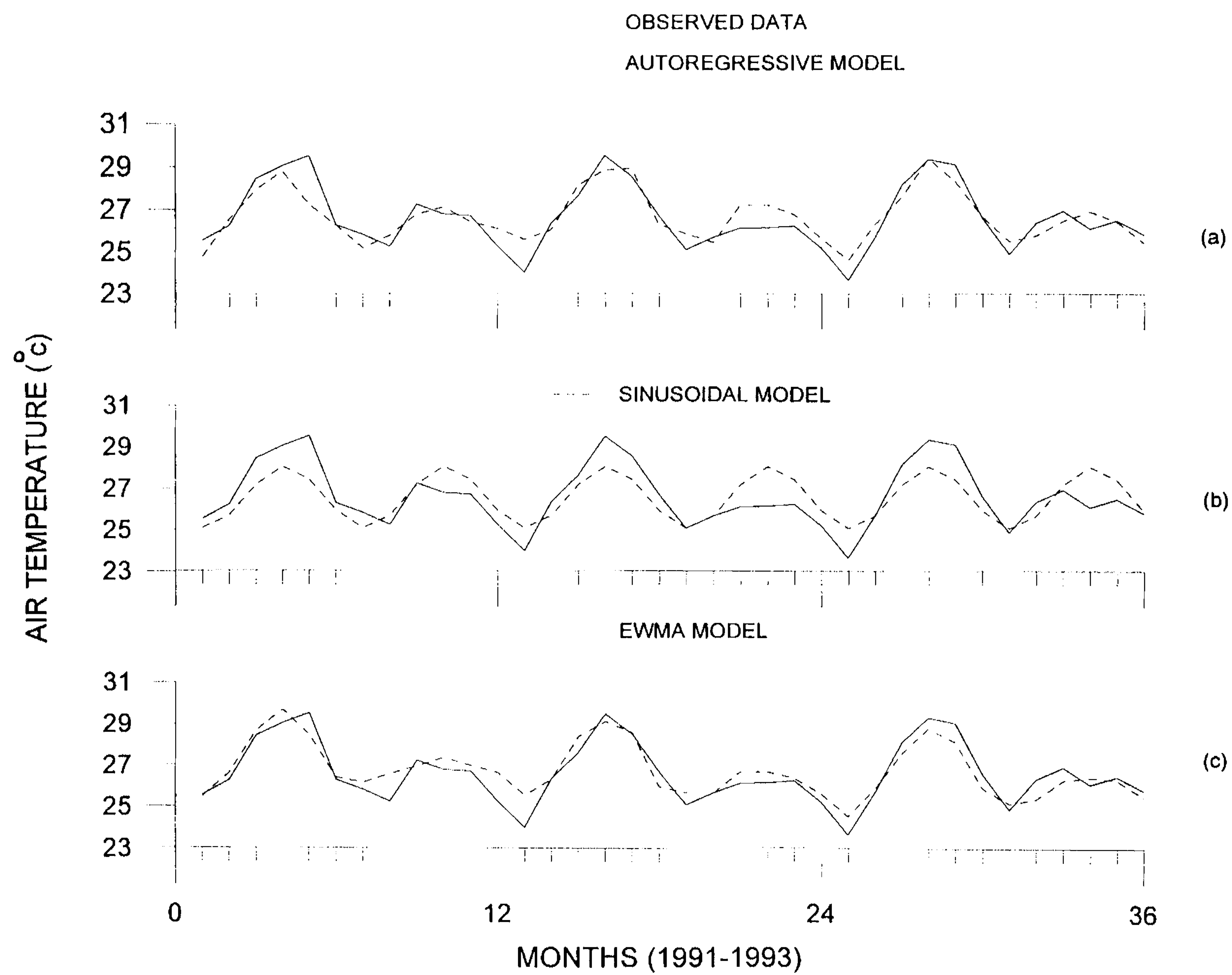


Fig. 4.3. Observed and predicted air temperature at Cochin for the period 1991-1993.

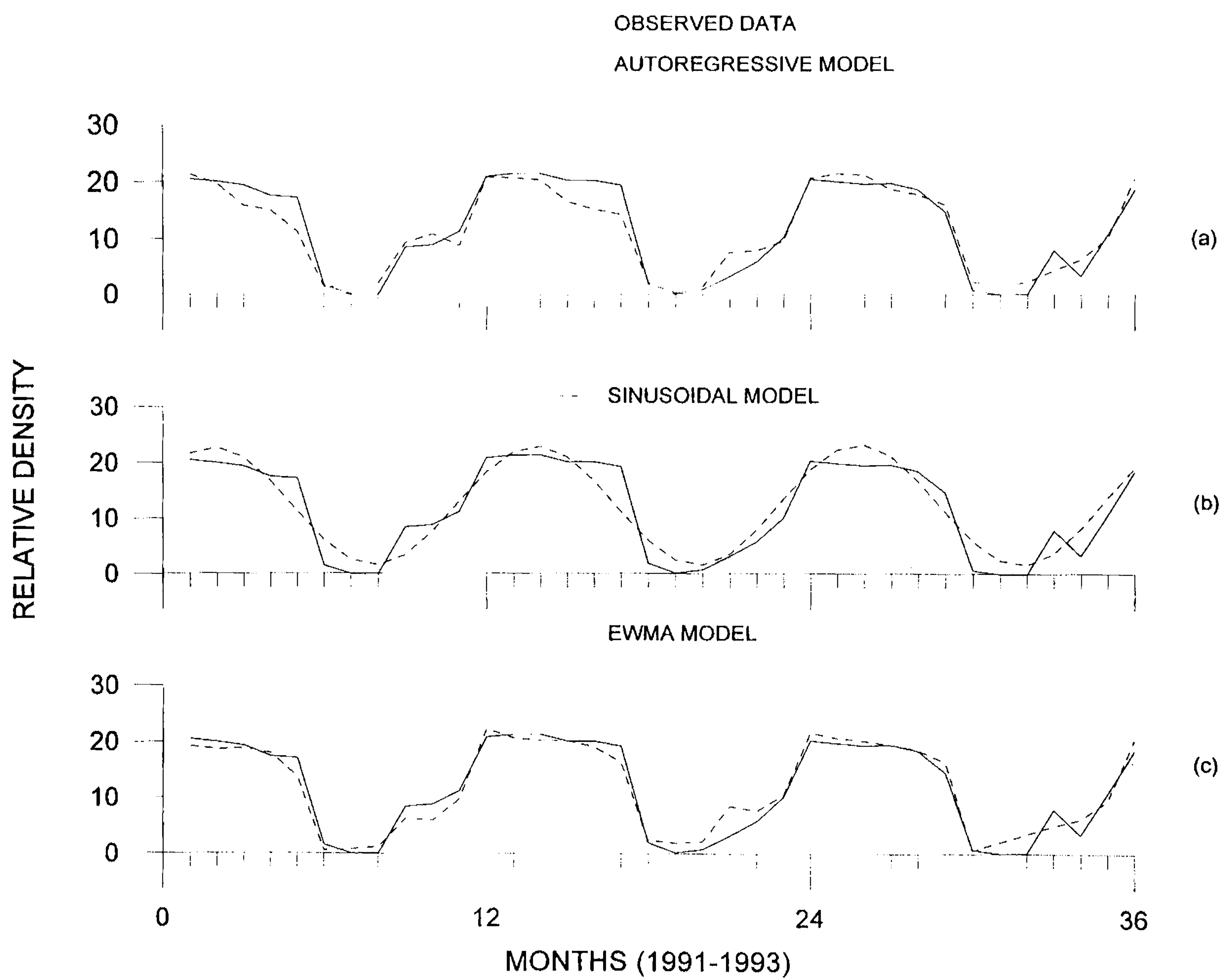


Fig. 4.4. Observed and predicted relative density at Cochin for the period 1991-1993.

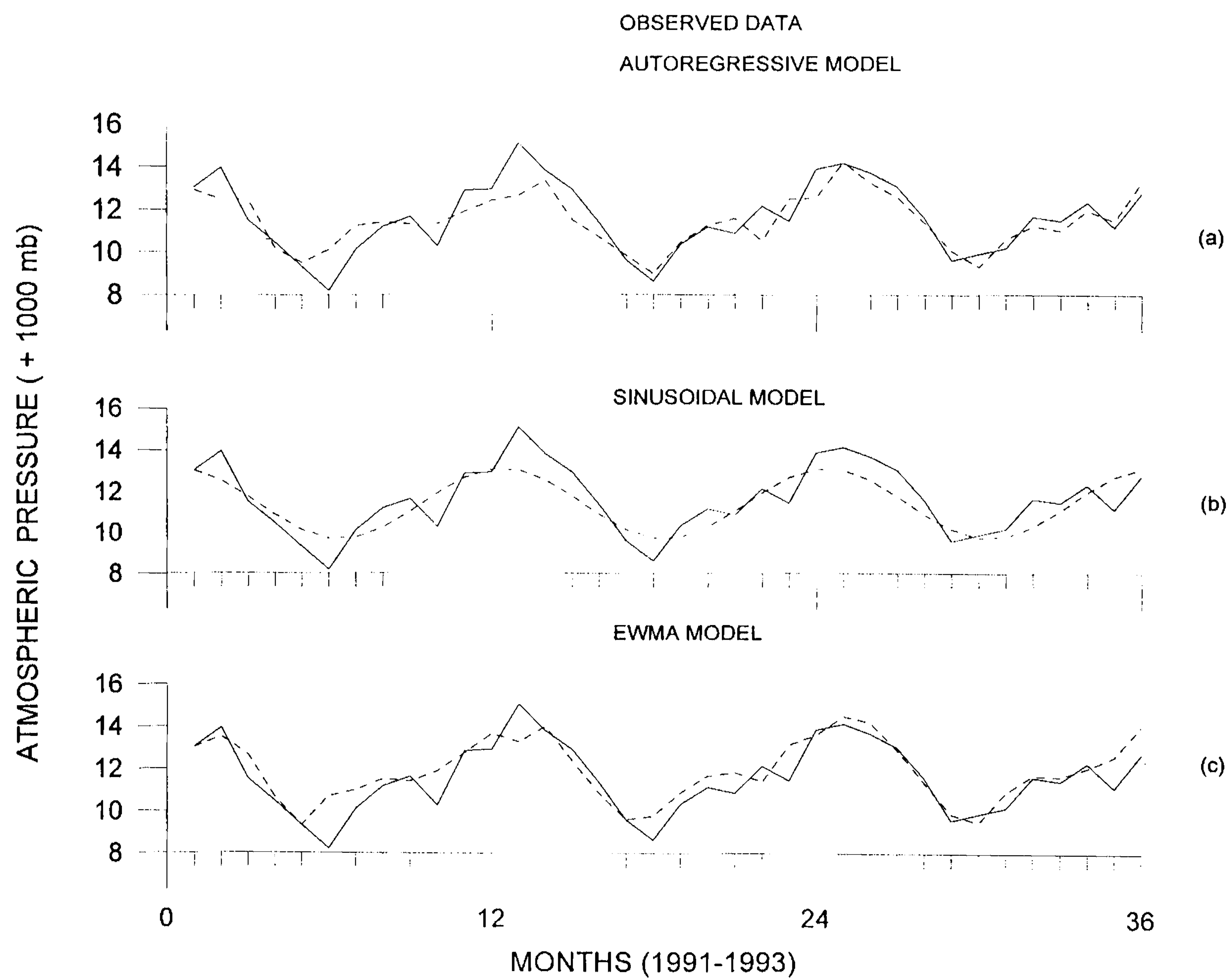


Fig. 4.5. Observed and predicted atmospheric pressure at Cochin for the period 1991-1993.

Table 4.1. Autoregressive coefficients for the various oceanographic and surface meteorological parameters at Cochin.

M	a_0	a_1	a_2	a_3	a_4	RMS ERROR
			SEA LEVEL			
M	a_0	a_1	a_2	a_3	a_4	RMS ERROR (cm)
1	26.0	60.1				4.64
2*	27.6	60.2	-2.6			4.62
3	48.5	49.1	-0.7	-23.3		4.80
4	44.7	48.7	1.5	-23.8	4.7	4.75
			RAINFALL			
M	a_0	a_1	a_2	a_3	a_4	RMS ERROR (cm)
1	6.753	0.755				24.935
2	7.163	0.754	-0.014			24.892
3	16.584	0.636	-0.044	-0.208		24.033
4*	25.638	0.590	-0.136	-0.258	-0.153	23.833
			AIR TEMPERATURE			
M	a_0	a_1	a_2	a_3	a_4	RMS ERROR (°C)
1	4.819	0.820				0.747
2	9.838	0.757	-0.126			0.741
3	9.767	0.757	-0.125	0.002		0.742
4*	18.779	0.683	-0.159	-0.073	-0.155	0.726
			RELATIVE DENSITY			
M	a_0	a_1	a_2	a_3	a_4	RMS ERROR
1	1.794	0.842				2.434
2	1.150	0.841	0.058			2.597
3*	6.779	0.621	0.062	-0.288		2.400
4	6.113	0.613	0.094	-0.294	0.042	2.425
			ATMOSPHERIC PRESSURE			
M	a_0	a_1	a_2	a_3	a_4	RMS ERROR (mb)
1	2.758	0.757				0.876
2*	2.827	0.757	-0.006			0.875
3	7.108	0.616	-0.018	-0.227		0.899
4	8.769	0.606	-0.066	-0.239	-0.077	0.891

M - Model number
* - Model with least R.M.S

Table 4.2. Terms of the sinusoidal equation and the RMS errors in respect of the oceanographic and surface meteorological parameters at Cochin.

	SEA LEVEL	RAINFALL	AIR TEMP.	REL. DEN.	ATM. PRESS.
a_0	63.50000	26.55800	26.716000	10.2000	11.247500
a_1	0.01420	0.00300	-0.000846	0.0106	0.000798
a_2	6.24000	-22.64700	-0.588700	2.6299	1.733000
a_3	5.52000	-17.41700	-1.288100	9.1554	0.401000
a_4	0.00809	-0.021900	-0.000190	0.0183	-0.000293
a_5	-0.08020	-0.003260	-0.000329	-0.0021	-0.000202
RMS ERROR	4.21000	26.423000	1.008000	3.1590	0.931000

$a_0, a_1, \ldots . a_5$ - are the terms of the sinusoidal equation

Table 4.3. Coefficients of the EWMA technique for the oceanographic and surface meteorological parameters and the RMS errors of the predictions.

PARAMETER	ALPHA	BETA	GAMMA	RMS ERROR
SEA LEVEL	0.60	0.10	0.60	4.170
RAINFALL	0.10	0.10	0.00	18.239
AIR TEMP.	0.10	0.10	0.40	0.652
REL. DENSITY	0.10	0.10	0.40	1.763
ATM. PRESSURE	0.01	0.01	0.50	0.872

Table 4.4. Prediction error of the forecast models for the three year period 1991-1993 (36 values).

MODEL		SEA LEVEL	RAINFALL	AIR TEMP.	REL. DENS.	ATM. PRESS.
AUTO	1.	30	3	36	14	29
	2.	21	2	34	6	22
SINU	1.	29	2	36	10	29
	2.	17	1	31	4	14
EWMA	1.	30	2	36	15	29
	2.	24	2	33	9	22

1 - Number of values in an interval of ±10% of the observed value

2 - Number of values in an interval of ±5% of the observed value

Table 4.5. Correlation coefficient between the observed and predicted data for the three year period (n = 36). All the correlation coefficients are highly significant (at 1% level of significance).

MODEL	SEA LEVEL	RAINFALL	AIR TEMP.	REL. DENS.	ATM. PRESS.
AUTO	0.79	0.78	0.88	0.96	0.86
SINU	0.82	0.72	0.74	0.93	0.84
EWMA	0.84	0.88	0.90	0.98	0.87

CHAPTER 5

CHAPTER 5

SEASONAL AND INTERANNUAL VARIABILITY OF SEA LEVEL ALONG THE INDIAN SUBCONTINENT

5.1. INTRODUCTION

Sea level has always been an important parameter in oceanographic studies as it has been linked to oceanic circulation, and its potential for ocean monitoring including marine life has been well demonstrated. Sea level has also been used for studies on climate change. Studies during the last two to three decades have shown that the monthly mean sea level can be used to monitor the large scale, low frequency circulation of the oceans (Wyrtki and Leslie, 1980). The relative ease with which it can be measured (as compared to the other oceanographic variables) and the availability of long time series of its measurement, makes it an ideal parameter for studies on seasonal and interannual time scales (Wunsch, 1972; Wyrtki 1974, 1979; Wyrtki and Leslie, 1980; Woodworth, 1984).

A survey of the literature on the relationships between the sea level and the meteorological and oceanographic elements was presented in Chapter 1. Several investigators have highlighted that the seasonal cycle of sea level is influenced by a number of oceanographic, meteorological and hydrological forcings. Some of the parameters are so interrelated that often it is difficult to separate their individual contributions. For example, variations in the density structure of the surface layers of the sea affect the sea level. The density structure in turn is affected by changes in temperature and salinity, which in their turn are affected by a number of processes such as heat and freshwater fluxes, river runoff, mixing by winds and currents.

In this chapter, the seasonal variability of some important meteorological and oceanographic forcings that drive the seasonal variability of sea level at some of the stations on the Indian coastline is examined. The relative importance of these forcings varies with geographic location and season. At some locations, hydrological forcing is of greater importance, particularly in the case of those where tide gauges are located nearer to river mouths and in the upstreams of rivers.

A number of workers have reported complex nature of the seasonal sea level cycle at stations which are separated even by a short distance. By using the techniques of harmonic analysis and principal component analysis, an attempt has been made to understand the alongshore variability of the parameters- alongshore coastal currents, rainfall, atmospheric pressure and sea level. A detailed account of the seasonal and interannual variability of sea level at selected stations on the coastline of the Indian subcontinent is presented in this chapter.

5.2. MATERIALS AND METHODS

The data used in this study have been provided by the Permanent Service for Mean Sea Level (PSMSL), UK, which compiles and archives monthly and annual mean sea level data received from different national organisations throughout the world (Woodworth, 1991). The Revised Local Reference (RLR) data of the PSMSL

(Spencer and Woodworth, 1993) - which are more accurate than the other data sets (e.g. metric data sets, also published by PSMSL) - were used in this analysis. For the Indian locations, the monthly data supplied to the PSMSL by the Surveyor General of India (located at Dehra Dun) have been used. The data pertaining to Karachi in Pakistan was made available to the PSMSL by the Chief Hydrographer to the Pakistan Navy. The monthly mean values for each month have been computed by averaging hourly values of a tidal record for that month. The normal monthly value (also referred to as climatological mean or mean monthly value) for a particular month, say, January, at a location is obtained by averaging the monthly mean values pertaining to January of the entire sea level record. The annual mean is determined from the 12 climatological monthly means. The climatological mean for each month with the annual mean subtracted, gives the monthly departures. The record of monthly mean sea level values has been reported to show considerable interannual variability, whose measure can be determined by the standard deviation of the entire monthly record (Shetye and Almeida, 1985). Though the interannual variability may be a source of noise for the climatological cycle considered here, this variability contains useful information on how oceanic conditions vary from year to year, and their association with the overlying atmosphere.

Tide gauge data on sea level collected at nine stations along the west coast viz. Cochin, Mangalore, Karwar, Mormugao, Bombay, Veraval, Bhavnagar, Kandla, and Karachi (Pakistan) and seven stations along the east coast viz. Tuticorin, Thangacchimadam, Nagapatnam, Madras, Visakhapatnam, Paradip and

Sagar Island were utilised in this study (Fig. 1.2 and Table 5.1). Island stations far off from the main coastline have been excluded in this study. Most of the previous studies utilised the observed sea level data collected at Karachi. It was, therefore, felt proper to include Karachi in the present study, as it is situated just outside the Tropic of Cancer and is also the northernmost limit of the eastern Arabian Sea. The latitudinal distance on the west coast between Cochin and Karachi is 1650 Km while on the east coast, it is 1430 Km between Tuticorin and Sagar Island. No attempt has been made to discuss the interannual variability at Veraval as the data were rather discontinuous. However, the seasonal cycle of this station was studied in this analysis (Table 5.1). The climatological monthly mean sea level (with the annual mean removed) over an annual cycle with one standard deviation bounds is presented for each station along both the coastlines (Figs. 5.1e - 5.16e).

The principal aim of the present chapter is to see how well alongshore current and sea level are related [equation (A2.9), Appendix II] at the locations along the west and east coasts of the Indian subcontinent. One of the factors, besides tides and the atmospheric pressure, which may introduce noise in the above relationship is the contribution to the sea level from cumulative runoff due to rainfall in the vicinity of a tide gauge. This may be of special concern during the southwest monsoon season for gauges located at or near the mouths of the rivers.

Shetye and Almeida (1985) have used the KNMI Atlas (1952) which gives the monthly mean ship-drift estimates in the Indian Ocean on a 2° by 2° grid for estimating the alongshore component of the coastal current. In the present study the climatological monthly mean currents extracted from Cutler and Swallow (1984) for the period 1854-1974 have been utilised. The use of ship-drift vectors as an indicator of surface currents is justified, as no direct measurements of surface currents along the coast of India are presently available. The data pertaining to shipping lanes are rich, and comparatively sparse outside the shipping lanes. The data for the Arabian Sea are rich whereas data for the Bay of Bengal are comparatively sparse. The alongshore component of current was determined by resolving the monthly mean drift along a straight line tangential to the coast. The angles used for resolving the alongshore components of current are presented in Table 5.2.

Following Shetye and Almeida (1985), along the west coast of India, a component of the current is taken as positive if the flow is northward, and along the east coast a component is taken as positive if the flow is southward. This choice was made to ensure that the sign of the sea level change and that of change in the alongshore current, v_l^s would be the same if geostrophic balance as given in equation (A2.9, Appendix II) holds.

The harmonic analysis of the mean seasonal cycle, for determining the annual, semi-annual and ter-annual cycle parameters (amplitude and phase) and that for each year (for studying the interannual variability of the seasonal cycle) has been done using the harmonic analysis methods described in Appendix II.

To understand the mechanisms causing the variability which has been observed, and to design sampling plans to observe future changes, it is important to identify the degree to which the variations are spatially coherent and the spatial pattern of coherence, which is achieved through Empirical Orthogonal Function analysis (Mountain and Taylor, 1998). The same technique (also known as Principal Component Analysis) has been used elsewhere for studies on sea level (Thompson, 1982; Chelton et al., 1990; Ridgway et al., 1993; Arnault and Cheney, 1994; Hannah and Crawford, 1996; Hendricks et al., 1996; Arnault and Le Provost, 1997; Wroblewski, 1998). The technique is also described in detail by Emery and Thomson (1998).

5.3. RESULTS AND DISCUSSION

The seasonal cycle of observed sea level and that corrected for the atmospheric pressure (over the global oceans) on one hand, and that for the local atmospheric pressure on the other, were studied (Figs. 5.1d to 5.16d). The former will be referred to as CSL-G and the latter as CSL-L, as mentioned earlier (Chapter 3 and Appendix II).

The seasonal cycle of the sea level shows that with the application of the pressure corrections, the range also changes. For both the coasts, Table 5.3 shows that the annual range either decreases or increases. Pattullo et al. (1955) reported that in most cases, the effect of "correcting" for atmospheric pressure is a small reduction in range. However, they have reported that in some regions the atmospheric pressure corrections reduce the range of sea level by 10 cm and in some others, they increase the same by 5 cm. Shetye and Almeida (1985) concluded that, in general, the effect of atmospheric pressure variations on the monthly mean sea level along the Indian coasts is significant. The amplitude of the effect, according to them, varied between 4 and 20 cm. It was dependent on the location and decreased towards south.

For the west coast, it was seen that the annual maxima of the corrected sea level (corrected for the effect of atmospheric pressure) occurred during January or December. Bhavnagar, however, showed a maximum during September. For the east coast, it was seen that the annual maxima of the corrected sea level occurred during the last quarter of the year.

In the present study, the harmonic analysis of the seasonal cycle based on long period monthly mean climatological data was carried out. As the seasonal cycle has been reported to show variability during different years (Woodworth, 1984; Spencer and Woodworth, 1993), the climatological monthly means have been used.

The detailed results of analysis of the three aspects of sea level for stations on the east and west coasts are described below:

5.3.1. WEST COAST

5.3.1.1. OBSERVED SEA LEVEL:

Most of the southern stations showed a drop in sea level during the late summer monsoon season, whereas the northernmost stations e.g. Karachi and Kandla showed low values even during winter months (Figs. 5.1d-5.9d). Mangalore showed a large hump during the summer monsoon season. Bhavnagar showed low values during the premonsoon season and high values during the summer monsoon season. All the stations showed a variance of less than 50 cm^2 with the exception of Bhavnagar, which showed a variance of nearly 490 cm^2 (Table 5.4).

The harmonic analysis revealed that both the annual and semi-annual frequencies together explained more than 65% of the variance at all stations, with the exception of Mangalore. When ter-annual harmonic was also included, the percentage variance increased to over 90% at all the stations. A northward progression of the annual phase (with the exception of Bhavnagar where local effects appear to dominate) could be seen. The phase of the semi-annual component remained more or less stationary during December-January (and June-July). The RMS deviation computed with the annual and semi-annual components was less than 4.0 cm for all the stations and this reduced to less than 2.0 cm when the ter-annual component was also included.

5.3.1.2. CSL-G:

All the stations except Mangalore and Bhavnagar, showed a concave pattern with broad minima during the summer monsoon season (Figs. 5.1d-5.9d). All the stations showed a variance of less than 80 cm^2, with the exception of Bhavnagar which showed a variance of 391 cm^2 (Table 5.5).

More than 65% of the total variance at all the stations was accounted by the annual and semi-annual components together, and this increased to more than 85% with the inclusion of the ter-annual component. With the exception of Bhavnagar, the phase of the annual harmonic was stationary during January-February at most of the stations. The phase of the semi-annual harmonic remained stationary during November-January (and May-July) again with the exception of Bhavnagar. The RMS deviation computed with the annual and semi-annual components was less than 4.0 cm and this reduced to less than 2.0 cm with the inclusion of the ter-annual component. The CSL-L series showed similar nature as that of CSL-G series (Figs. 5.1d-5.9d and Table 5.6).

5.3.2. EAST COAST

5.3.2.1. OBSERVED SEA LEVEL:

The southern stations showed a roughly concave pattern in the seasonal curve whereas northern stations (north of Madras) displayed a hump for the same period (Figs. 5.10d-5.16d). The northern stations showed minimum during winter and maximum during the summer monsoon, whereas the opposite was noticed at the southern stations.

For the east coast stations, both the annual and semi-annual frequencies together explained more than 95% of the variance at all the stations (Table 5.7). The variance accounted increased marginally with the inclusion of the ter-annual component. The phase of the annual cycle showed a clear southward progression, whereas the phase of the semi-annual cycle remained stationary during May/November. The RMS deviation computed with the annual and semi-annual components was less than 4.0 cm and this reduced to less than 2.0 cm when ter-annual component was also included.

5.3.2.2. CSL-G:

The southern stations showed a roughly concave pattern whereas the northern stations (north of Madras) showed a convex pattern for the summer monsoon season (Figs. 5.10d-5.16d). The maximum sea level was observed during the later part of the year.

The annual and semi-annual frequencies explain more than 95% of the total variance at all the stations (Table 5.8). The phase of the annual cycle showed a southward progression, whereas the phase of the semi-annual component remained stationary during May/November. The RMS deviation computed with the annual and semi-annual components was less than 4.0 cm and this reduced to less than 1.5 cm when the ter-annual component was also included. The CSL-L series showed similar nature as that of CSL-G series (Figs. 5.10d-5.16d and Table 5.9).

5.3.3. GENERAL - OBSERVED AND CORRECTED SEA LEVELS FOR BOTH THE COASTS

From the above account, it can be seen that for the west coast stations from Cochin to Bombay, the maxima of sea level occurred during winter (with the exception of Mangalore, where it occurred during July). Bombay showed equal magnitudes during winter and monsoon seasons. North of Bombay, the picture reversed i.e. minima occurred during winter at Bhavnagar, Kandla and Karachi, while maxima occurred during summer monsoon season. Both Kandla and Karachi showed greater resemblance in this respect while Bhavnagar was unique along the entire west coast. By and large, the observed sea level at all the stations on the west coast showed a great deal of similarity, the only exception being Bhavnagar, where the local effects such as river discharges appeared to have overwhelmed the oceanic effects. Most of the stations showed minima by the end of the summer monsoon and the maxima during either winter or June. The spatial variability of sea level along the west coast was minimum during April and October, and maximum during winter and June.

On the east coast, the concave shape of the seasonal cycle of the sea level observed in the southern locations changed to convex shape with latitude. The change from concave to convex shape was more prominent during the second half of the year. The maxima occurred in August at Sagar Island, in October at Paradip, in November at Visakhapatnam, Madras, Nagapatnam and Thangacchimadam, and in December at Tuticorin. This clearly showed the southward propagation of the sea level maxima along the east coast from August to December.

Both Tuticorin and Thangacchimadam showed some similarities in the seasonal march of the mean sea level. All the other stations showed similar march along the east coast. Most of the northern stations showed minima during March and maxima during August-November with a sharp rise from March to June. The spatial variability was less along the west coast compared to that along the east coast. This variability was particularly large during the summer monsoon season along the east coast.

In general, it was seen that the atmospheric pressure corrected sea level showed a higher degree of variance than the observed monthly mean sea level. The contention of Pattullo et al. (1955) was that changes in wind accompany changes in pressure and also that the wind effect is likely to be larger and opposite in sign to the pressure effect. This could be the reason for the higher variance in sea level corrected for the atmospheric pressure. It is to be noted that, in general, the effect of atmospheric pressure was small compared with observed variations in sea level for southern stations. The data clearly showed that with the application of pressure correction, the range of variation increased, but for northern stations, a decrease in range was noticed. Pattullo et al. (1955) have also reported that the effect of atmospheric pressure correction causes a change in the phase. Most of these stations have either small amplitudes or multiple maxima and minima, and the change of phase occurs when one of the maxima is accentuated by the correction. This class, however, lacks geographical coherence. Sometimes the timings of maxima or minima shift by three months or more.

The seasonal signal in the sea level is more in the Bay of Bengal as compared with that in the Arabian Sea (Fu et al., 1988; Zlotnicki et al., 1989; Jacobs et al., 1992; Perigaud and Delecluse, 1992; Tai, 1996; Chambers et al., 1997).

The semi-annual component of sea level can be of equal importance as of the annual component in the tropical areas where ocean currents, temperature, and winds are all semi-annual in character. However, a large semi-annual amplitude does not necessarily imply a realistic six-monthly oscillation, but could be the result of irregularities in the seasonal cycle caused, for example, by the sudden onset of the monsoon (Woodworth, 1984). At mid-latitudes and high-latitudes, the amplitude of the semi annual component is usually smaller than that of the annual component.

A significant portion of the total variance (or energy) contained in the seasonal sea level records is explained by a combination of annual and semi-annual harmonics in the Arabian Sea and Bay of Bengal regions (Bray et al., 1996; Fukumori et al., 1998). Amplitudes of the semi-annual period are much lower than the annual, peak amplitudes of semi-annual period occur in the northern Indian Ocean, and occur over the same areas as the annual (Jacobs et al., 1992).

The results obtained in this study agree well with those reported by Woodworth (1984), eventhough he adopted a different method of analysis where the least square fit was done on the entire time series of monthly mean sea level (Table 5.10).

5.3.4. CORRELATIONS BETWEEN THE OBSERVED AND CORRECTED SEA LEVELS

The relationship between the observed sea level and CSL-G indicated a significant correlation on seasonal time scales for most of the stations. The seasonal cycles of the observed and the CSL-G series are not correlated at Kandla and Karachi (Table 5.11). 79.2% of the variance along the west coast and 88.4% of the variance along the east coast is explained by the relationship between observed sea level and CSL-G. The CSL-G and

CSL-L series are highly correlated along the west and east coasts of the Indian subcontinent (Table 5.11).

5.3.5. PRINCIPAL COMPONENT ANALYSIS (PCA) OF SEA LEVEL

The variability of sea level (under three classifications) arising out of the stations over the months of January to December of the year, was studied by the application of PCA. The originally selected nine stations along the west coast and seven on the east coast for the parameter of sea level under three different classifications [viz. I) observed sea level, II) CSL-G and III) CSL-L] were considered in this study. Incorporating the twelve monthly values, twelve PC's (Principal Components) were obtained under six classifications (both the coasts for the three sea levels mentioned above). Fig. 5.17 a-f, gives the monthly eigen vectors for the first three PC's for the different classifications for both the coasts. The percentage variance accounted by each PC is also mentioned in the figure. Table 5.12 gives the PC scores of the stations, both under the six classifications. (PC score of a station is obtained as the sum of the product of CD over the twelve months, where "C" is the eigen vector for a month, and "D" is the deviation of the corresponding value of sea level from the annual mean, taking into consideration the positive or negative value of "C" and "D". The "CD" for a month is thus positive if C and D, both are either positive or negative, and negative if one of them is positive and the other negative. The overall sign of PC score of a station will be then positive or negative depending on the values obtained over the twelve months for the station). The variance of the PC scores of a station gives its PC variance. Of the three PC's, the first PC which can be seen to account for 70-75% of the total variance, is the most important one.

From the figure of eigen vectors, it can be seen that the periods of June to November for west coast, and May to October on east coast are negative for the first PC. The values for the end months of June and November are not high for west coast, thus indicating the period of July to October, in general, as different from other months. On east coast, the end months (of May and October), though have less values, are not as low as on west coast. Corresponding to the months of low values of PC-1, the PC-2 values are high. Thus in PC-2, the months of May, June on west coast and May on east coast, are high and positive, and for the month of November high and negative for both the coasts. The scores of PC-1, are positive for Bombay and stations south of Bombay on west coast, and negative for stations north of Bombay. Similarly on east coast, for Madras and south of Madras they are positive, and north of Madras they are negative. Bombay (west coast) and Madras (east coast) have very small PC scores for all the six classifications.

The negative values of eigen vectors for PC-1 are for June-November (west coast) and May-October (east coast) which can be taken broadly to correspond to the summer monsoon months. The high negative PC scores of Bhavnagar (west coast) and Sagar Island (east coast), in general, are arising out of negative D values when C is positive, and negative C values when D is positive (C and D as explained earlier). In other words, this means that the sea level is above annual mean during summer monsoon months, and below annual mean during other months for both these stations. The deviations observed in both the cases (Bhavnagar and Sagar Island) are quite high. Visakhapatnam and Paradip, with negative PC scores follow the same pattern (viz. with sea level above annual mean sea level during summer monsoon months and below for the remaining period, broadly). The high positive PC score for Thangacchimadam, on the other hand, is due to the opposite pattern (viz.) the monthly sea level below annual mean sea level during summer monsoon months and above for the remaining period (This is a very general conclusion and may not hold good for each month individually). Bombay (west coast) and Madras (east coast) have very low PC scores for all the three PC's, arising out of the monthly sea level varying about its annual mean in an irregular manner. In general, it is observed that the northern stations on both the coasts have higher sea level during summer monsoon period, and lower during other months, while reverse is the case for the southern stations. The high score under PC2 for Tuticorin, Kandla and Karachi are arising out of high sea levels for the months of November and December. Bhavnagar accounts for 60% of the total variance of west coast while Thangacchimadam and Sagar Island together account for approximately 55% on east coast. Madras and Bombay account for only 1-2% of the variance of the respective coasts. Tuticorin and Paradip account for about 20 and 10%, respectively, of east coast variance.

5.3.6. RAINFALL AND SEA LEVEL

Rainfall (and associated river discharge) is a very important factor as it is known to change the density characteristics of the upper layers of the sea, thereby affecting the sea level (Longhurst and Wooster, 1990). Hydrological contributions to the observed sea level will be important, particularly for those tide gauges located at the mouths of large rivers. This will attain increasing significance as one goes upstream of the estuaries and would be site specific. Ramanadham and Varadarajulu (1964) opined that to assess the impact of rainfall on sea level, one should consider a large area and time series of long duration. Prasada Rao and La Fond (1954) concluded in their study on sea level variations at Visakhapatnam, that monthly averages are more suitable for studying the association between sea level and rainfall because runoff is prolonged and lasts for many days after the rainfall, whereas the amount of water added by single day's rainfall soon gets mixed in the sea. They reported a positive relationship between the sea level and rainfall at Visakhapatnam during 1950. Rama Raju and Hariharan (1967) reported that the short period fluctuations in sea level are clearly associated with rainfall at Cochin during the southwest monsoon. Walters et al. (1985) have reported a direct relationship between sea level and river discharge in the San Francisco Bay during 1977-78. The net effect of rainfall is to raise the sea level, at that particular location. However, some authors have reported that rainfall by way of river discharge causes a localised upwelling near the river mouths along the west coast of India, causing the sea level to drop (Banse, 1968; Kesava Das, 1979).

The seasonal march of the monthly total rainfall at the sea level stations are given in Figs. 5.1b to 5.16b and the harmonic analysis of the seasonal cycle in Table 5.13, for west coast and Table 5.14, for the east coast.

5.3.6.1. WEST COAST

The annual cycle at most of the stations showed unimodal distribution with the maxima during the summer monsoon season. The maxima decreased from southern stations towards the northern stations. The seasonal amplitude of the rainfall decreased towards northern stations (with the exception of Cochin and Mangalore). Along the west coast, the meridional variability was maximum during the summer monsoon season. During the postmonsoon season there was a moderate meridional variability. There was very little variability during the premonsoon season.

The harmonic analysis indicated that both the annual and semi-annual harmonics together explained more than 65% of the total variance and the inclusion of ter-annual harmonic increased the total to 80% (Table 5.13). The maximum of the annual cycle occurred during July for all the stations. For the semi-annual cycle, the maxima occurred during January (and July) for majority of the stations. The RMS deviation computed with the annual and semi-annual harmonics was less than 14.0 cm and this reduced to less than 7.6 cm with the inclusion of the ter-annual harmonic.

Bhavnagar is located near the mouths of the rivers Narmada and Tapti. These rivers may have an effect on the signal recorded by the tide gauge. Its position deep inside the Gulf of Cambay also results in minimum oceanic influence. Kandla is also located deep inside the Gulf of Kutch where oceanic influence is minimum. The effect of freshwater runoff could be responsible for the observed positive relationship (Mehta and Philip, 1986).

At some of the stations on the west coast - Cochin, Karwar and Mormugao, the period of maximum rainfall is characterised by minimum sea level. Banse (1968) and Kesava Das (1979) attributed this drop in sea level to a locally induced upwelling near to the mouths of the estuaries due to river discharges. In the case of Bhavnagar and Kandla, the positive relationship between sea level and rainfall may be due to their peculiar locations deep inside the Gulf. Shetye and Almeida (1985), however, opined that the sea level drop observed during southwest monsoon at Veraval, Mormugao and Cochin is mainly due to the large scale coastal circulation.

5.3.6.2. EAST COAST

Sagar Island and Paradip showed peaks during the southwest monsoon season whereas the southern stations showed peaks during November-December. Along the east coast, the meridional variability was least during premonsoon season and October.

The harmonic analysis indicated that the annual and semi-annual harmonics together explained more than 80% of the total variance and this percentage increased to 90% with the inclusion of the ter-annual harmonic (Table 5.14). The annual harmonic showed a progressive increase from August at Sagar Island to November at Thangacchimadam. In the case of the semi-annual cycle, the maxima showed a progressive increase from February to November (and August to May) towards southern stations. The RMS deviations computed with the annual and semi-annual components was less than 5.3 cm and reduced to less than 3.1 cm with the inclusion of the ter-annual harmonic.

At most of the stations, the variation in sea level follows a pattern similar to that of the rainfall variation.

5.3.7. ATMOSPHERIC PRESSURE AND SEA LEVEL

A number of workers have reported an inverse relationship between the observed sea level and the atmospheric pressure pointing out that this effect is important at higher latitudes (Pattullo et al, 1955; Lisitzin, 1974; Pugh, 1987; Woodworth, 1993).

The seasonal march of the atmospheric pressure at the sea level stations are given in Figs. 5.1c to 5.16c and the harmonic analysis of the seasonal cycle for west coast in Table 5.15, and for the east coast in Table 5.16.

5.3.7.1. WEST COAST

Most of the stations showed a concave pattern with minima during the southwest monsoon season and maxima during the premonsoon and postmonsoon seasons. The meridional variability was maximum during southwest monsoon season. The seasonal variance of the atmospheric pressure increased northward along the west coast (Table 5.15).

The harmonic analysis indicated that both the annual and semi-annual frequencies explained more than 95% of the variance at all the stations. The contribution of the ter-annual harmonic was negligible. The phase of the annual cycle was stationary during January. The phase of the semi-annual cycle showed a progressive northward march from January to October (July to April). The RMS deviation computed with the annual and semi-annual components was less than 0.38 mb at all the stations and this reduced to less than 0.22 mb with the inclusion of the ter-annual harmonic.

A negative relationship between observed sea level and atmospheric pressure was seen at the northern stations only.

5.3.7.2. EAST COAST

All the stations showed a concave pattern, with minima during the summer monsoon season and maxima during the premonsoon and postmonsoon seasons. The meridional variability was maximum during the southwest monsoon season as in the case of the west coast. Seasonal variance increased northward.

The harmonic analysis indicated that the annual and semi-annual components together explained more than 95% of the variance at all the stations (Table 5.16). The contribution of the ter-annual harmonic was negligible. The annual harmonic remained stationary during January. For the semi-annual harmonic, the southern stations showed that the maxima was stationary during January/July, whereas the northern stations showed maxima during April/October. The RMS deviation computed with the annual and semi-annual components was less than 0.40 mb at all the stations and this reduced to less than 0.29 mb with the inclusion of the ter-annual harmonic.

A negative relationship between observed sea level and atmospheric pressure was seen only at the northern stations.

5.3.8. GENERAL (RAINFALL AND ATMOSPHERIC PRESSURE) - FOR BOTH THE COASTS

The amplitudes of the annual, semi-annual and ter-annual components of the seasonal cycle of rainfall along the west coast are much higher than those of the east coast stations at comparable latitudes.

In contrast to the west coast, (which showed a strong negative relationship between rainfall and CSL-G which explained 7.8% of the variance), stations on the east coast showed a highly significant positive relationship, which explained 42.3% of the variance (Table 5.11). The result obtained in this study is in agreement with the results of Shetye and Almeida (1985).

The variance of the atmospheric pressure increases towards north for both the coasts. There is also a remarkable dominance of the annual cycle over the semi-annual and ter-annual cycles along both the coasts. The amplitudes of the annual cycle also increase towards north along both the coasts.

The sea level data at the northern stations showed a negative relationship with atmospheric pressure on both the coasts, which was absent at the southern stations (Table 5.11). On the whole, there appears to be no statistically significant relationship between sea level and atmospheric pressure for both the coasts.

5.3.9. ALONGSHORE CURRENT AND SEA LEVEL

The seasonal march of the alongshore current in the coastal waters near to the sea level stations are given in Figs. 5.1a to 5.16a and the harmonic analysis of the seasonal cycle in Table 5.17 for west coast, and Table 5.18 for the east coast.

The relationship between observed sea level and alongshore current is due mainly to the Coriolis force, which is responsible for deflecting the mass (Lisitzin, 1974). Due to the action of the Coriolis force, a slope is created perpendicular to the direction of the currents and hence a change in sea level along the coast accompanies the currents parallel to the coast. The height of the sea level is thus greater on the right hand side and lower on the left hand side when looking in the direction of the flow in the northern hemisphere. The dynamics behind this relationship is discussed in Appendix II.

5.3.9.1. WEST COAST

The annual march of alongshore current showed a more or less concave shape with equatorward flow increasing in magnitude from January to July-August. After July, the magnitude decreased and by October, the current became poleward. All the stations showed that more than 80% of the total variance can be accounted by the annual and semi-annual harmonics, excepting for Bombay which showed 56% (Table 5.17). The phase of the annual harmonic was more or less stationary at December, and for the semi-annual harmonic around May and November.

The RMS deviation indicated that, but for Veraval (5.8 cm/s), it was less than 4.8 cm/s with the annual and semi-annual harmonics, and this reduced to less than 4.6 cm/s with the inclusion of the ter-annual harmonic.

The sea level corrected for local atmospheric pressure effects at Cochin, Mormugao and Veraval showed a good correlation with the alongshore component of coastal current. Reversals in the currents are clearly reflected in the sea level changes. The sea level at Cochin, Mormugao and Veraval decreased as the rainfall increased during the southwest monsoon season, suggesting that the contribution to the sea level change due to accumulation of rain runoff is small in comparison to that from large scale coastal circulation.

Shetye and Almeida (1985) also obtained a similar result in their study linking pressure corrected mean monthly sea level and alongshore current in respect of Cochin, Mormugao and Veraval. They suggested that the sea level records at these stations would be a good tool for long term monitoring of the surface geostrophic flow along the west coast of India. The sea level at many stations along the west coast decreased with an increase in rainfall during the southwest monsoon season suggesting that the contribution to the sea level change due to the accumulation of rain runoff is small in comparison to that from large scale coastal circulation.

5.3.9.2. EAST COAST

The annual march showed a concave shape, with northerly flow increasing from January to April-May and then decreasing thereafter (this was not obvious in the case of Tuticorin and Sagar Island). After around August-September, the flow turned southerly. The stations showed that the annual, semi-annual and ter-annual components together account for more than 90% of the total variance excepting for Tuticorin (75%) (Table 5.18). The phase of the annual harmonic was stationary around October. The phase of the semi-annual harmonic was stationary around May/November at all the stations. The RMS deviation indicated that it was less than 7.7 cm/s with the annual and semi-annual harmonics and reduced to less than 7.4 cm/s with the inclusion of the ter-annual harmonic.

All stations north of Nagapatnam showed a highly significant relationship between CSL-G and alongshore current (Table 5.11). Reversals in the currents are clearly reflected in the sea level changes.

Shetye and Almeida (1985) and Shetye et al. (1991b) reported that there is a good relationship between the pressure corrected sea level and the alongshore current in respect of Nagapatnam, Madras and Visakhapatnam. They suggested that the sea level records at these stations would be a good tool for long term monitoring of the surface geostrophic flow along the east coast of India.

In the present study, data pertaining to Sagar Island at the mouth of the river Hooghly have also been used. In this case also the annual march of the sea level and that of the alongshore current resemble each other. The sea level at Sagar Island is not significantly affected by the discharge of river Hooghly, eventhough this island is situated in the extreme northern Bay of Bengal, where the river debouches into the Bay of Bengal (Janardhan, 1967). At Nagapatnam, Madras and Visakhapatnam the annual cycles of rainfall and sea level show a similar march. This indicates that the observed monthly mean sea level changes during the southwest monsoon season are, atleast partially, a consequence of accumulation of river runoff. Three of the forcing functions for the current off the east coast are the local wind stress, curl of the wind stress over the Bay of Bengal and the alongshore density gradient. Gopalakrishna and Sastry (1985) have shown that during the southwest monsoon season, an alongshore density gradient occurs along the east coast of India. The main cause of this gradient is the dilution produced by runoff from the rivers which are fed by the rains over the catchment basins. The run off caused by rainfall along the east coast probably helps to establish an alongshore density gradient, which enhances a southward flow which in turn affects the sea level (Table 5.11).

The circulation in the Bay of Bengal is influenced by the combined effect of the freshwater influx, narrow shelf topography, winter cooling at the head of the Bay and the seasonally reversing winds (Suryanarayana et al, 1992). The near-surface flow is mainly southwesterly during northeast monsoon (the geostrophic current speeds vary from 20 cm/s to 90 cm/s) while during southwest monsoon, it is characterised by cyclonic and anticyclonic gyres (the geostrophic current speeds range from 10 cm/s to 60 cm/s). The influence of freshwater on the flow is dominant within 100 km from the coast north of 15°N. The flow is wind forced beyond 100 km from the coast.

5.3.10. GENERAL (ALONGSHORE CURRENT) - FOR BOTH THE COASTS

The seasonal variance of the coastal alongshore currents is more on the east coast than on the west coast, indicating that the alongshore current is more energetic along the east coast as compared to the west coast. The western boundary currents are characteristically fast, intense, deep and narrow while the eastern boundary currents are characteristically slow, wide, shallow and diffuse (Bearman, 1995).

It is clear that a northerly current would raise the sea level and southerly current would lower the sea level along the west coast, and the opposite situation occurs along the east coast.

The above result is in conformity with a previous study carried out by Shetye and Almeida (1985), wherein it was reported that the pressure corrected mean monthly sea level in respect of Cochin, Mormugao, Veraval, Nagapatnam, Madras and Visakhapatnam showed a good correlation with the alongshore component of the surface current ($r = 0.84$ for the 72 values considered). In the present study, the relationship between the CSL-G and alongshore current explained 42.3% variance along the west coast and 51.8% variance along the east coast. The relationship between the CSL-G and alongshore current was particularly strong along the east coast, and such a relationship was not evident along the west coast. Even Paradip and Sagar Island (stations not considered by Shetye and Almeida, 1985) showed a strong relationship between alongshore current and CSL-G.

Coastal currents driven by alongshore density gradients are believed to exist along the west coast of India (Shetye, 1984; Shetye et al., 1994). Coastal currents driven by alongshore density gradients are also reported along the west coast of Australia (McCreary et al., 1986). The coastal circulation off Bombay is weak and therefore no clear signal was seen in the sea level record.

The Indian rivers contribute about 4% of the global annual discharge, of which the major rivers contribute 126×10^{10} m^3y^{-1} to the Bay of Bengal which is approximately four times that to the Arabian Sea (29.7×10^{10} m^3y^{-1}) (Dileep Kumar et al., 1992). The major rivers are the Ganges, Brahmaputra and Indus which are among the major rivers of the world. There are about 46 rivers in addition to the above which debouch into the Arabian Sea and the Bay of Bengal from the subcontinent and the more important amongst these are Godavari, Krishna, Mahanadi, Narmada, Tapti and Cauvery. Maximum runoff occurs during the summer monsoon season. The seasonal and annual rainfall over the Bay of Bengal was reported to be about 2-3 times the Arabian Sea values (Ramesh Kumar and Prasad, 1997). In the Bay of Bengal, the distribution of fresh water is largely controlled by density driven flows and prevailing winds over the Bay and hence we do not find a uniform rise caused by direct precipitation and surface discharge into the Bay (Murty et al., 1992; Varkey et al., 1996). Currents driven by the alongshore density difference could be stronger along the east coast as compared to the west coast.

5.3.11. KELVIN WAVES

The continental shelf width off the western coast of India (average 150 km) is three times that of off the east coast. The shelf is widest near the Gulf of Cambay (about 400 km across), and narrowest off the delta mouths (near Sundarbans or Krishna mouth - width less than 30-35 km). The most common slope of the eastern continental shelf as a whole is about 21' whereas on the west coast, the slope changes from about 10' near Cape Comorin to about 1' in the Cambay region.

Early work of Madden and Julian (1972) detected a global scale for 40 to 50 day atmospheric events moving eastwards from the Indian Ocean to East Pacific in the tropics. There is a growing body of evidence for energetic fluctuations in the equatorial atmosphere in the intraseasonal band of weeks to months (Spillane et al., 1987). Wang and Rui's (1990) study of the tropical intraseasonal convection anomaly identified 77 strong to moderate events (out of 122 in 10 years) that propagated along the equator from the western Indian Ocean to the Mid-Pacific. Such atmospheric forcing could directly excite equatorial Kelvin waves.

Coastal Kelvin waves could originate from the impact of equatorial Kelvin waves on the eastern boundary of the Indian Ocean (Gill, 1982; Jacobs et al., 1992; Prasanna Kumar and Unnikrishnan, 1995; Arief and Murray, 1996; As-Salek, 1998 and Bruce et al. 1998). Similar waves have been reported for the Pacific Ocean (Enfield, 1987; Merrifield and Winant, 1989; Johnson, 1990; Bearman, 1995; Gu et al., 1997 and Shaffer et al., 1997).

Shetye et al. (1991b) and Wiseman and Garvine (1995), however, suggested that variation of river discharge at the coast may generate continental shelf waves. Occurrence of these waves can have important implications for upwelling events along the coast. In their presence, the upwelling intensity at any location depends on the history of shelf wave generation events to the north of the location (for east coast in the Northern Hemisphere).

The Kelvin wave off the east coast of India is complex, and is the result of Kelvin waves of different frequencies and phases, forced by several mechanisms (Shankar and Shetye, 1997; Shetye, 1998). McCreary et al. (1996) identified three such mechanisms : local alongshore winds adjacent to the east coasts of India and Sri Lanka, remote alongshore winds adjacent to the eastern and northern boundaries of the bay (McCreary et al., 1993), and remote forcing from the equatorial wave guide (Potemra et al., 1991; Yu et al., 1991). The first two mechanisms are of predominantly annual frequency and the third one has a strong semi-annual frequency.

The phase of the semi-annual and annual cycle for the CSL-G series in the case of the west coast, is more or less constant (excluding Mangalore, Bhavnagar, and Kandla - river discharge dominates at these locations), suggesting that there is no propagation of Kelvin waves at these frequencies. In the case of the east coast, for the CSL-G series, the phase of the semi-annual cycle is constant, while it is not so with the annual cycle. The phase of the annual cycle shows a clear southward propagation at a velocity of about 18 cm/s. This result seems to indicate that the Kelvin waves moving southward along the east coast of India, on arriving off the southwest coast of India, propagate in the offshore direction as Rossby waves (Shankar and Shetye, 1997; Bruce et al., 1998; Prasanna Kumar et al., 1998). Rashmi Sharma et al. (1998) found these Rossby waves to be pronounced at 10°N, propagating westward at a speed of 24 cm/s. It is, thus, suggested that the alongshore wind (local and remote) mechanisms which are of a predominantly annual nature, generate these Kelvin waves.

5.3.12. SEASONAL VERSUS INTERANNUAL VARIABILITY OF SEA LEVEL

To understand the relative importance of seasonal versus interannual variability, the ratio of seasonal standard deviation (SD) (computed with 12 monthly mean climatological values) and interannual SD (computed with individual anomaly values for each month for the entire time series) were obtained (Table 5.1).

There is a considerable degree of variability in the seasonal signal along the west coast. Bhavnagar displayed a high degree of variability for both the seasonal and interannual signals. This station appeared to be very much dominated by riverine influence. Significant contributions from the funnelling effect and the station's location along the Bay, appeared to be important. As already mentioned, the effect of river discharge is also important.

It is also clear that the interannual variability was comparable to the seasonal variability along the west coast (excepting for Bhavnagar, as already mentioned). For Bombay, Kandla and Karachi, the interannual signal even exceeded the seasonal signal. It is clear that the seasonal signal is stronger for the east coast than that for the west coast, at comparable latitudes. Bhavnagar is an exception in that the seasonal and interannual signals at this station were larger than those of Sagar Island, the corresponding station on the east coast. Sagar Island showed maximum seasonal and interannual variability along the east coast. For the east coast, the standard deviations for the monthly data indicate that, in general, there was a tendency for the seasonal variability to increase towards the northern latitudes.

For the west coast stations, the seasonal variance (in percentage, methodology as described in Chapter 3), contained in the observed time series varied from 29.41 at Kandla to 77.96 at Bhavnagar. In the case of the east coast stations, the seasonal variance (in percentage) contained in the observed time series varied from 39.03 at Tuticorin to 82.49 at Nagapatnam. Interestingly, the stations close to each other are showing maximum and minimum seasonality for both the coasts, which must be due to purely local phenomena. Further, for the west coast, the seasonal and interannual signal are maximum at northerly latitudes and for the east coast, the seasonal and interannual signal are maximum at southerly latitudes. However, we can generalise that the seasonality is generally more along the east coast (6 out of 7 stations show a seasonality greater than 55%) whereas for the west coast it is much less (4 out of 8 show a seasonality greater than 55%).

5.3.13. SEASONAL AND INTERANNUAL VARIABILITY FOR EACH MONTH

A comparison was further made between the seasonal signal and the interannual signal for each of the calendar months (Figs. 5.1f to 5.16f). This comparison is facilitated by computing the ratio of seasonal SD (of the climatological mean seasonal cycle) to the long-term SD of each of the 12 individual calendar months.

If the value is less than unity, the month is dominated by interannual signal and if greater than unity, the seasonal signal dominates.

For the west coast stations, the interannual signal was found to be marginally stronger than the seasonal signal for Bombay and Kandla for all the 12 months. For most of the stations, the dominance of the seasonal signal over the interannual signal for individual months was seen. One of the summer monsoon months indicated the maximum interannual variability.

The seasonal signal was stronger than the interannual signal for each of the calendar months for the following east coast stations - Nagapatnam, Visakhapatnam, Paradip and Sagar Island. It is also clear from the figures that November was the month that displayed considerable interannual variability along the east coast.

5.3.14. YEAR-TO-YEAR VARIABILITY OF THE SEASONAL CYCLE AMPLITUDES

The analysis, largely indicated that the mean of the annual cycle amplitudes was the largest, followed by that of the semi-annual amplitudes (Table 5.19). In the case of Mangalore, Bombay and Karachi on the west coast and Nagapatnam and Madras on the east coast, the amplitudes of the annual cycle were comparable to those of the semi-annual cycle.

The coefficients of variation were generally less for the annual and semi-annual cycles on the east coast as compared to those of the west coast. The coefficients of variation were however quite high for the ter-annual cycles for both the east and west coasts.

It is clear that there exists year-to-year variability in the seasonal cycle amplitudes of the sea level. The amplitudes based on the climatological mean cycle (Table 5.4 and 5.7) were all less than the long-term mean amplitudes derived from individual years (Table 5.19).

5.3.15. SOUTHERN OSCILLATION INDICES (SOI) AND THE INTERANNUAL VARIABILITY OF SEA LEVEL

Studies on the influence of Southern Oscillation on the sea level along the Indian subcontinent are lacking. The sea level data sets (Table 5.1) were made use of to examine this issue. Continuous monthly time series data on SOI were available only from 1933 onwards, and the data prior to this year were discontinuous, with large gaps. For the 1933-1988 period, the highest positive value of 2.9 (La Nina) occurred during November, 1973 and the highest negative value of 4.6 (El Nino) during February, 1983. The sea level data were first detrended and then the anomalies of the monthly mean sea level were determined and then smoothened with a 13-month moving average for the estimation of the correlation with detrended and 13-month moving averages of SOI (Table 5.20)

It is evident that most of the stations along the west and east coast show a significant relationship between the anomalies of sea level and the SOI. All the stations along the east coast of India showed that the percentage variability accounted by the phenomenon is quite high, whereas along the west coast most of the stations showed a high percentage variability accounted by the phenomenon.

The percentage variance in residual adjusted sea level explained by SOI was less than 10% for the west and east coast of India based on tide gauge data constrained by space and time scales (Bray et al., 1996).

It is suggested that the anomalously low sea levels observed during El Nino periods along the east coast of India may be due to a number of factors - reduced rainfall over the Indian subcontinent and resultant river discharge, higher than normal atmospheric pressure and anomalous northward propagating western boundary current signals (e.g. Ridgway et al., 1993). The model study of Behera et al. (1998) showed anomalous northward upper layer meridional transport for the 1982-83 period, along the east coast of India. At low frequency, spatial coherence of sea level is very great (Sturges, 1990; Douglas, 1992). Steric effects will be far larger in magnitude than meteorological ones at very low frequencies.

5.4. CONCLUSIONS

1. A very high percentage of the total variance of the seasonal cycle (observed, CSL-G and CSL-L) could be accounted by the sum of the annual, semi-annual and ter-annual components. The importance of these three components varied with the stations.

2. The atmospheric pressure corrected sea levels (CSL-G and CSL-L) showed higher variance than the observed sea level for the southern stations along both the coasts.

3. The correlation between CSL-G and CSL-L was found to be very high for both the coasts.

4. PCA shows that the first three PC's account for 95-99% of the total variance of the sea level (observed, CSL-G and CSL-L), of which the first PC alone accounts for 70-75% of the total variance, for west coast and east coast taken separately. The eigen vectors for the monsoon months are negative in sign. While Bhavnagar (west coast) and Sagar Island and Thangacchimadam (east coast) account for a considerable part of the total variance (of the respective coasts), Madras and Bombay account for a very low variance (again of the respective coasts). High PC scores are traced to high deviations of the monthly sea level from its annual mean. Thus the high contribution to the total variance of Bhavnagar and Sagar Island could be attributed to higher sea levels during summer monsoon months and lower sea levels during other months, while Thangacchimadam to that of lower sea level during summer monsoon months and higher during other months (all deviations taken from the annual mean sea level of the respective stations).

5. In contrast to the west coast, (which showed a strong negative relationship between rainfall and CSL-G which explained 7.8% of the variance), stations on the east coast showed a highly significant positive relationship, which explained 42.3% of the variance.

6. The sea level at the northern stations showed a negative relationship with atmospheric pressure on both the coasts, which was absent at the southern stations. On the whole, there appears to be no statistically significant relationship between sea level and atmospheric pressure for both the coasts.

7. The seasonal variance of the coastal alongshore currents is more on the east coast than on the west coast, indicating that the alongshore current is more energetic along the east coast as compared to the west coast.

8. A northerly current would raise the sea level and southerly current would lower the sea level along the west coast, and the opposite situation occurs along the east coast. Alongshore current and CSL-G are highly correlated along the east coast as compared to the west coast. CSL-G can be used to monitor the surface geostrophic current.

9. Currents driven by the alongshore density difference could be stronger along the east coast as compared to the west coast.

10. Annual Kelvin waves moving southward, at a speed of 18 cm/s, along the east coast of India, on arriving off the southwest coast of India, propagate in the offshore direction as Rossby waves. These Rossby waves move offshore along the southwest coast of India at around 10°N (latitude of Cochin).

11. The seasonal signal of sea level, in general, appears to be stronger than the interannual signal, for both the coasts. We can generalise that the seasonality is more along the east coast

than on the west coast. Stations close to each other are showing maximum and minimum seasonality for both the coasts, which must be due to local phenomena.

12. The interannual variability in the sea level was larger at the stations on the west coast during the summer monsoon season, and larger during November at the stations on the east coast.

13. Year-to-year variability exists in the seasonal cycle amplitudes of the sea level. The amplitudes based on the climatological mean cycle were all less than the long-term mean amplitudes derived from individual years. The coefficients of variation were generally less for the annual and semi-annual cycles on the east coast as compared to those of the west coast.

14. Most of the stations along both the coasts showed a significant relationship between the anomalies of sea level and the SOI. All stations along the east coast and most of the stations on the west coast showed a high percentage variability accounted by the phenomenon. The sea level is lower than normal during El Nino periods.

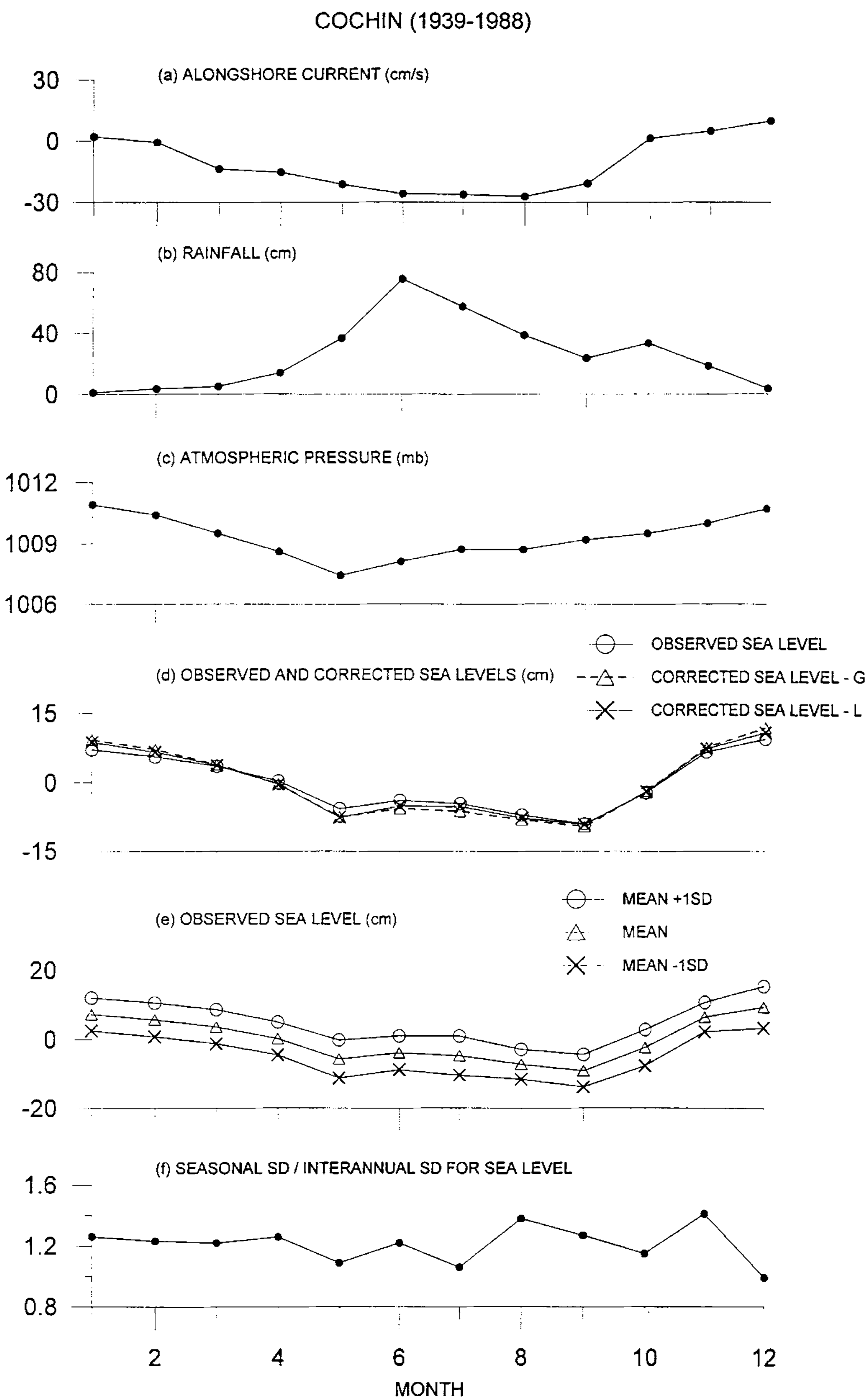


Fig. 5.1. Seasonal march of (a) alongshore current (b) rainfall (c) atmospheric pressure (d) observed sea level and corrected sea levels (e) sea level with 1 SD (standard deviation) bounds and (f) ratio of seasonal SD to interannual SD for sea level at Cochin.

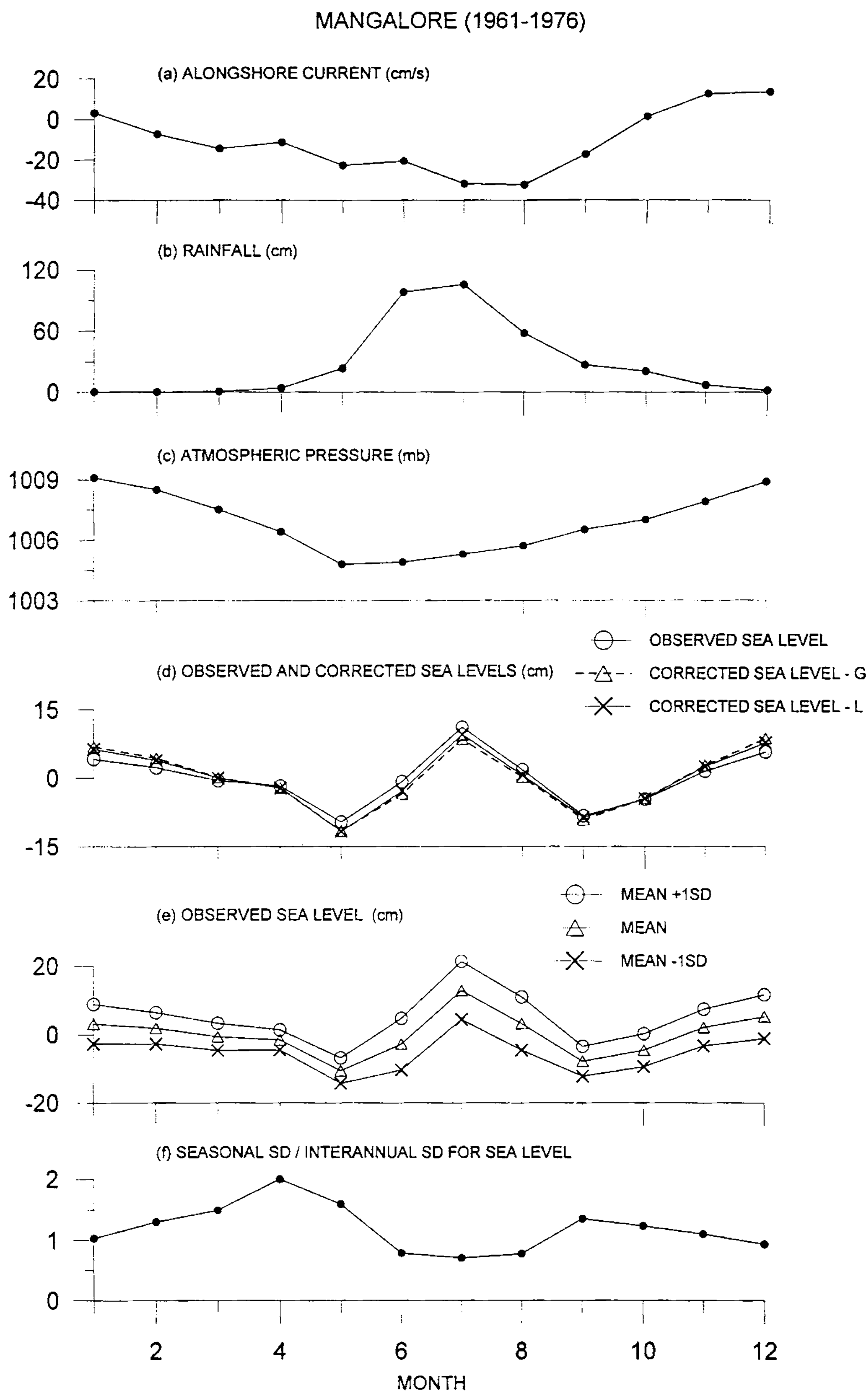


Fig. 5.2. Seasonal march of (a) alongshore current (b) rainfall (c) atmospheric pressure (d) observed sea level and corrected sea levels (e) sea level with 1 SD (standard deviation) bounds and (f) ratio of seasonal SD to

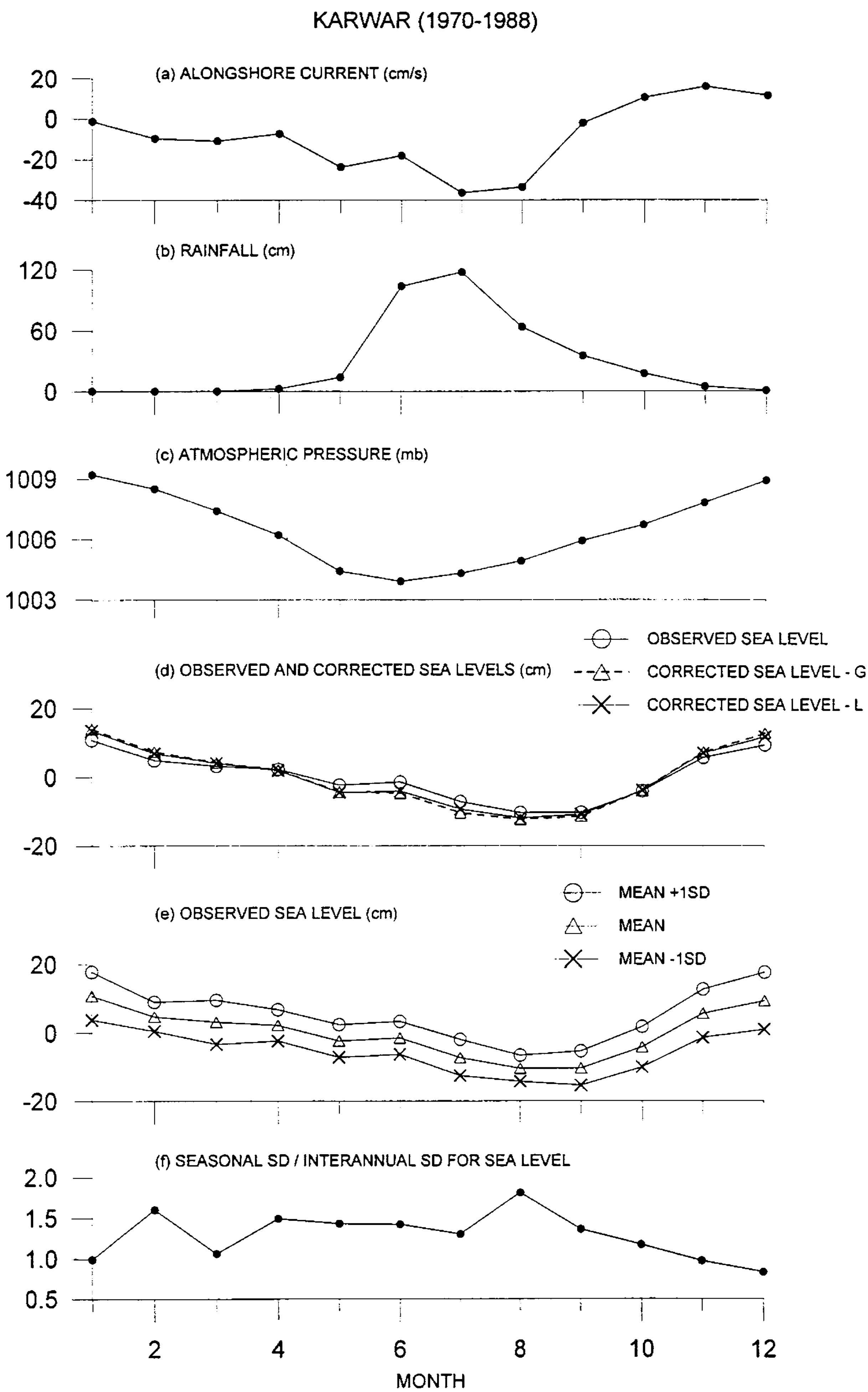


Fig. 5.3. Seasonal march of (a) alongshore current (b) rainfall (c) atmospheric pressure (d) observed sea level and corrected sea levels (e) sea level with 1 SD (standard deviation) bounds and (f) ratio of seasonal SD to interannual SD for sea level at Karwar.

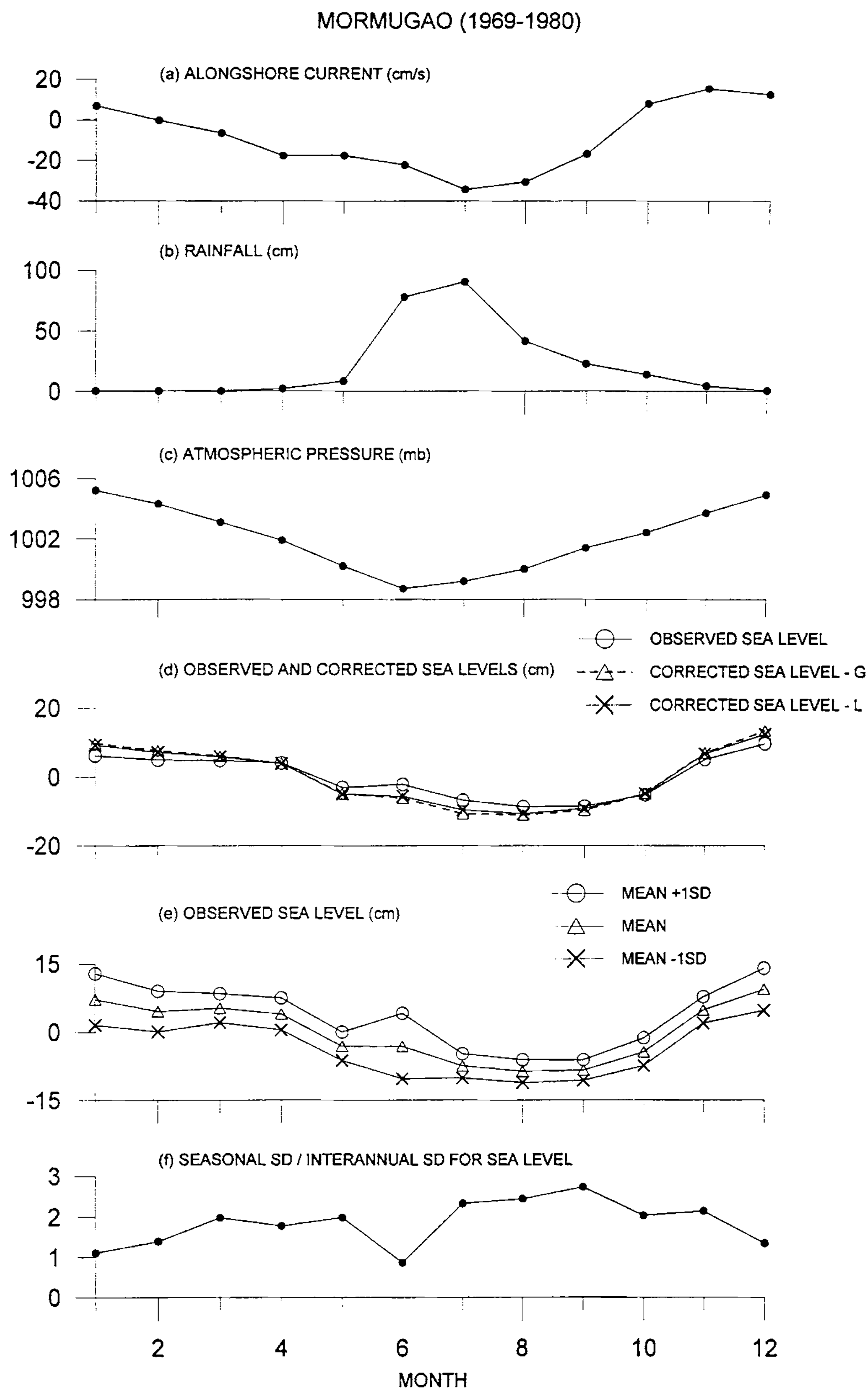


Fig. 5.4. Seasonal march of (a) alongshore current (b) rainfall (c) atmospheric pressure (d) observed sea level and corrected sea levels (e) sea level with 1 SD (standard deviation) bounds and (f) ratio of seasonal SD to

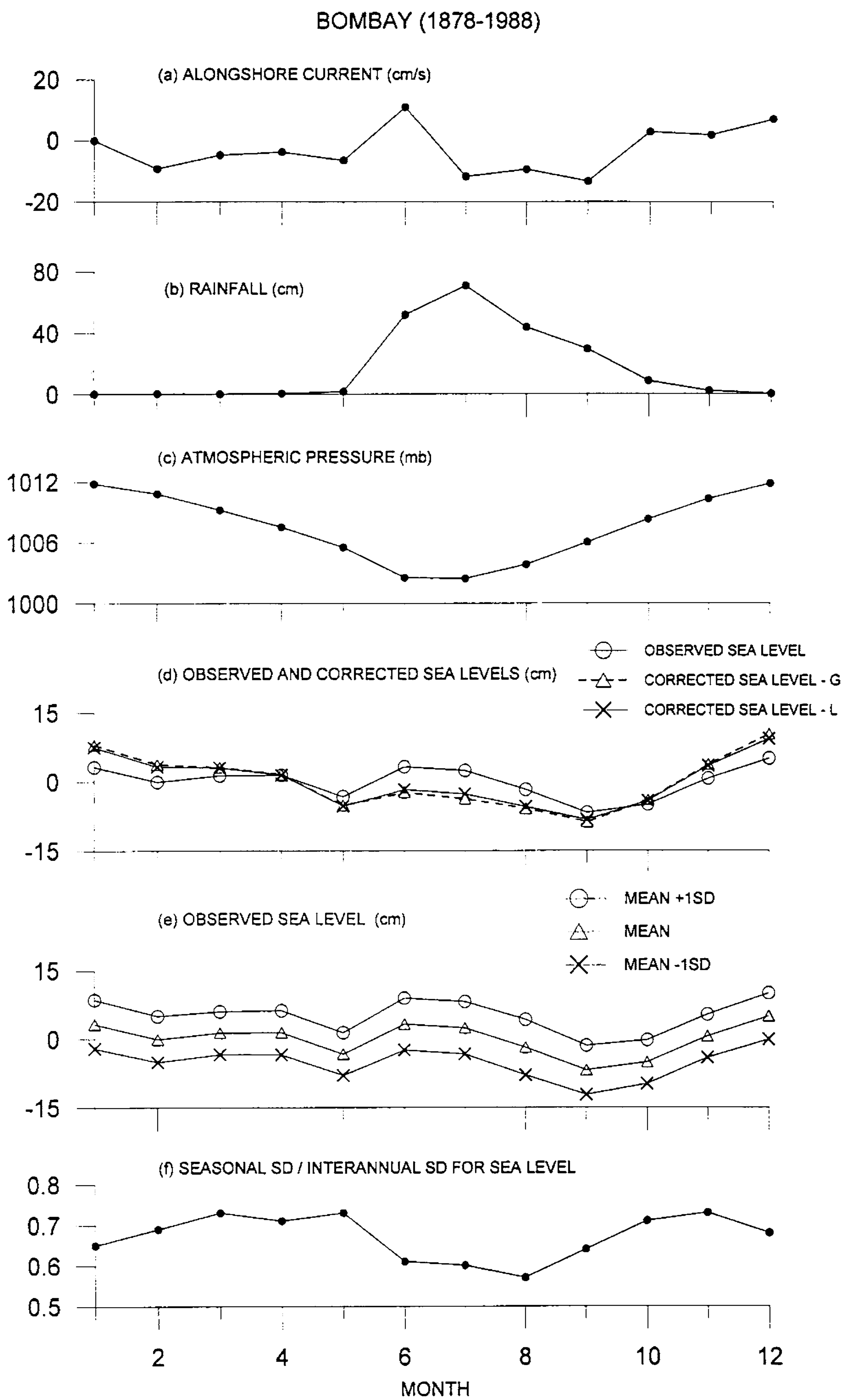


Fig. 5.5. Seasonal march of (a) alongshore current (b) rainfall (c) atmospheric pressure (d) observed sea level and corrected sea levels (e) sea level with 1 SD (standard deviation) bounds and (f) ratio of seasonal SD to interannual SD for sea level at Bombay.

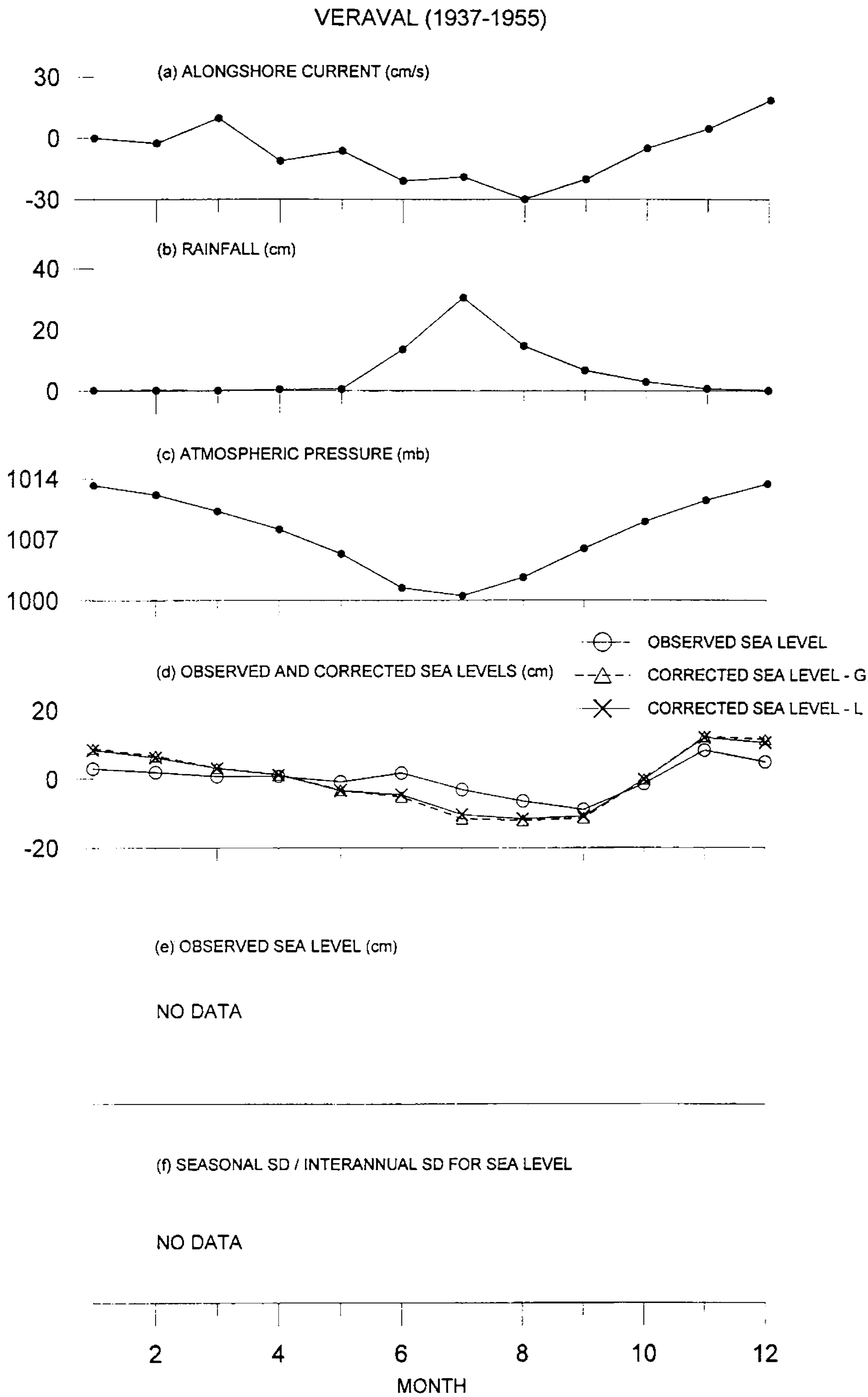


Fig. 5.6. Seasonal march of (a) alongshore current (b) rainfall (c) atmospheric pressure (d) observed sea level and corrected sea levels (e) sea level with 1 SD (standard deviation) bounds and (f) ratio of seasonal SD to

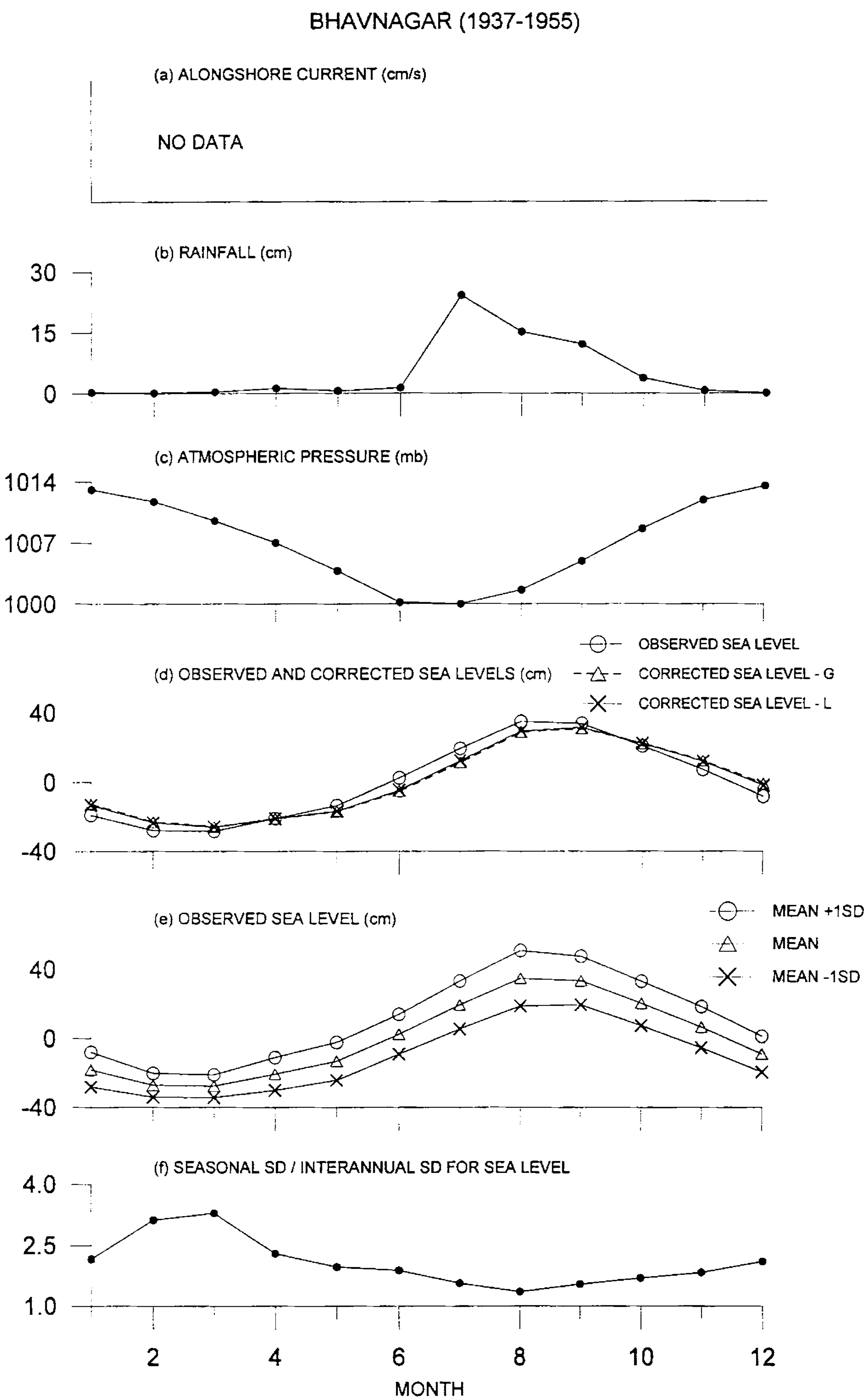


Fig. 5.7. Seasonal march of (a) alongshore current (b) rainfall (c) atmospheric pressure (d) observed sea level and corrected sea levels (e) sea level with 1 SD (standard deviation) bounds and (f) ratio of seasonal SD to interannual SD for sea level at Bhavnagar.

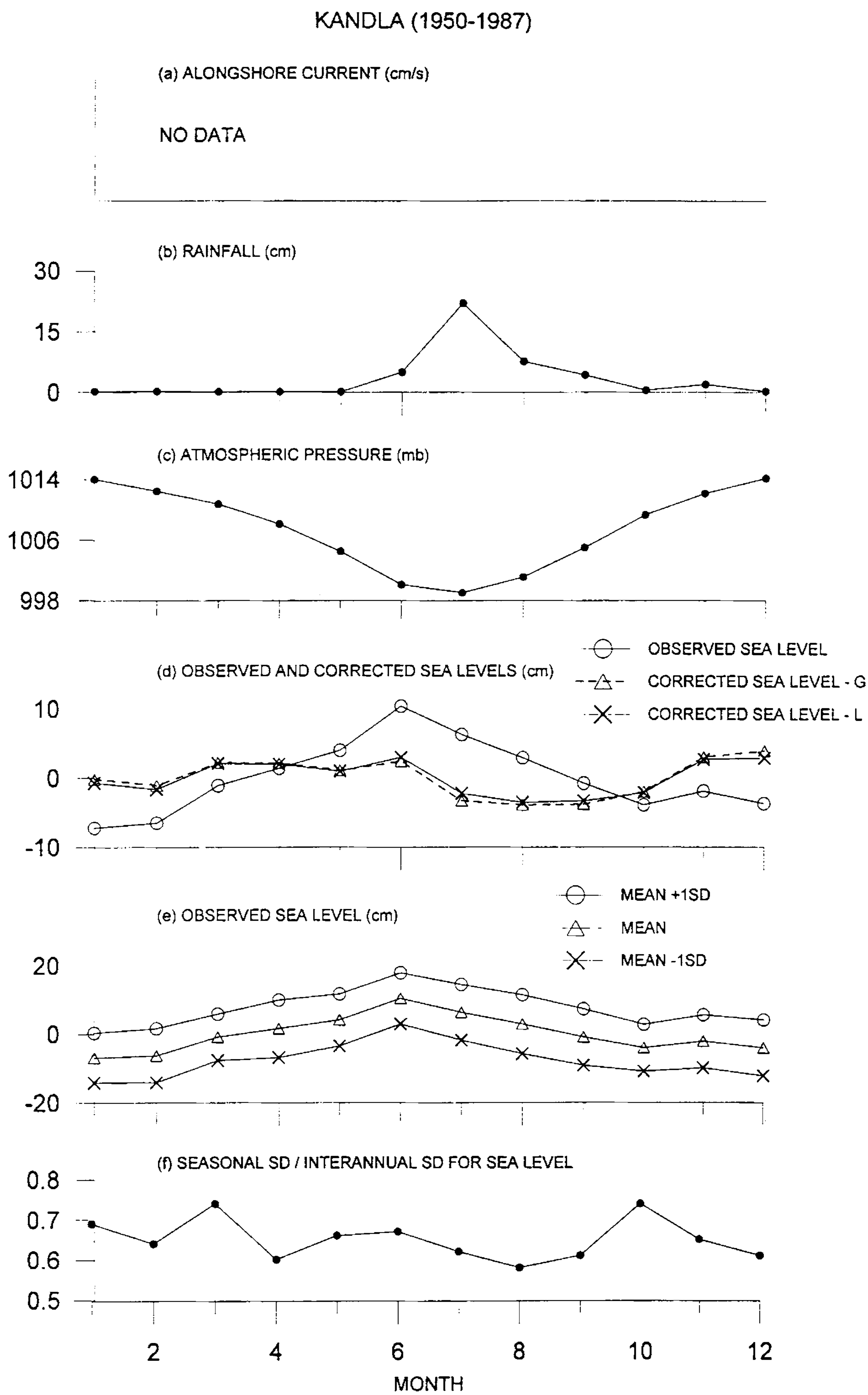


Fig. 5.8. Seasonal march of (a) alongshore current (b) rainfall (c) atmospheric pressure (d) observed sea level and corrected sea levels (e) sea level with 1 SD (standard deviation) bounds and (f) ratio of seasonal SD to

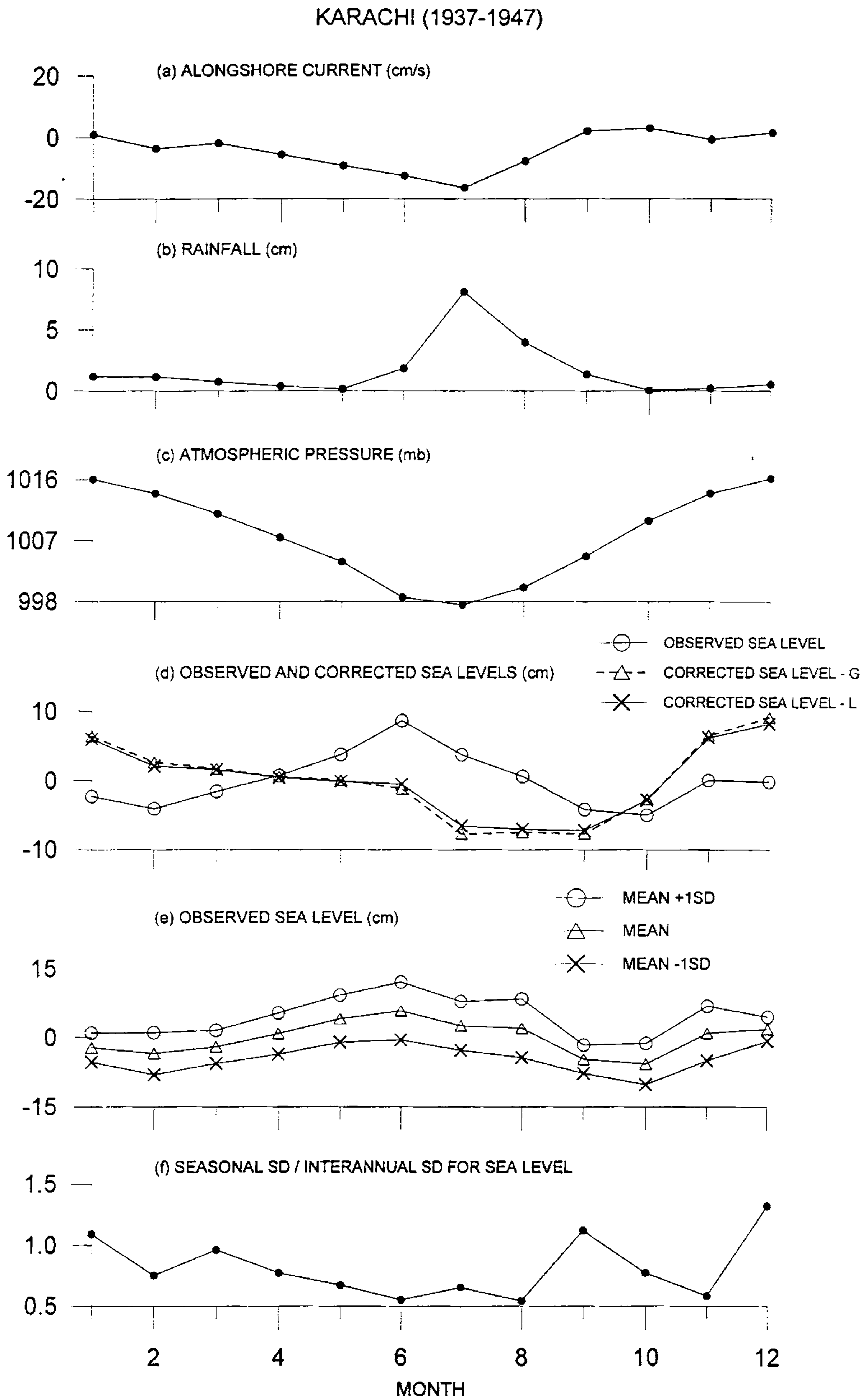


Fig. 5.9. Seasonal march of (a) alongshore current (b) rainfall (c) atmospheric pressure (d) observed sea level and corrected sea levels (e) sea level with 1 SD (standard deviation) bounds and (f) ratio of seasonal SD to interannual SD for sea level at Karachi.

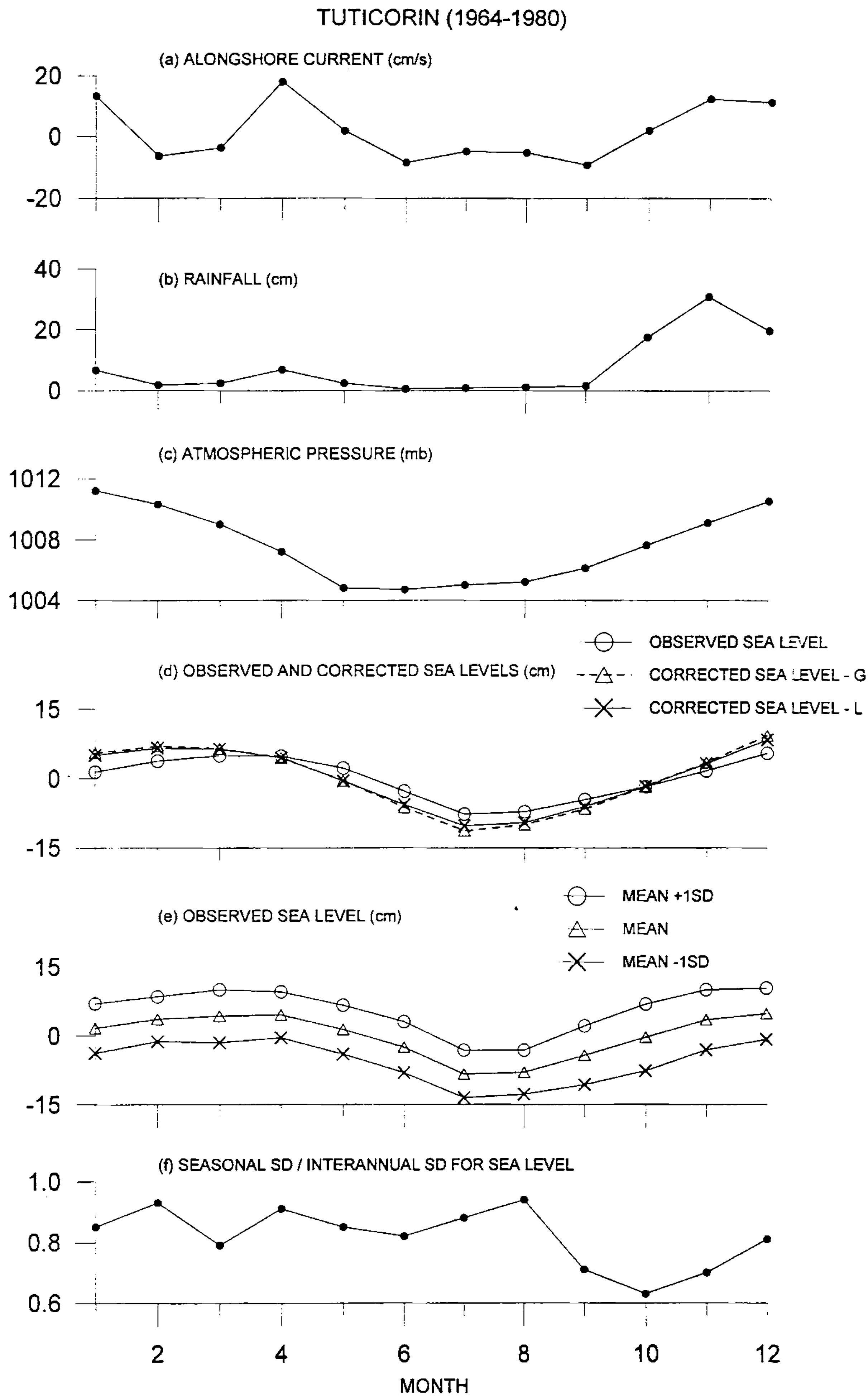


Fig. 5.10. Seasonal march of (a) alongshore current (b) rainfall (c) atmospheric pressure (d) observed sea level and corrected sea levels (e) sea level with 1 SD (standard deviation) bounds and (f) ratio of seasonal SD to interannual SD for sea level at Tuticorin

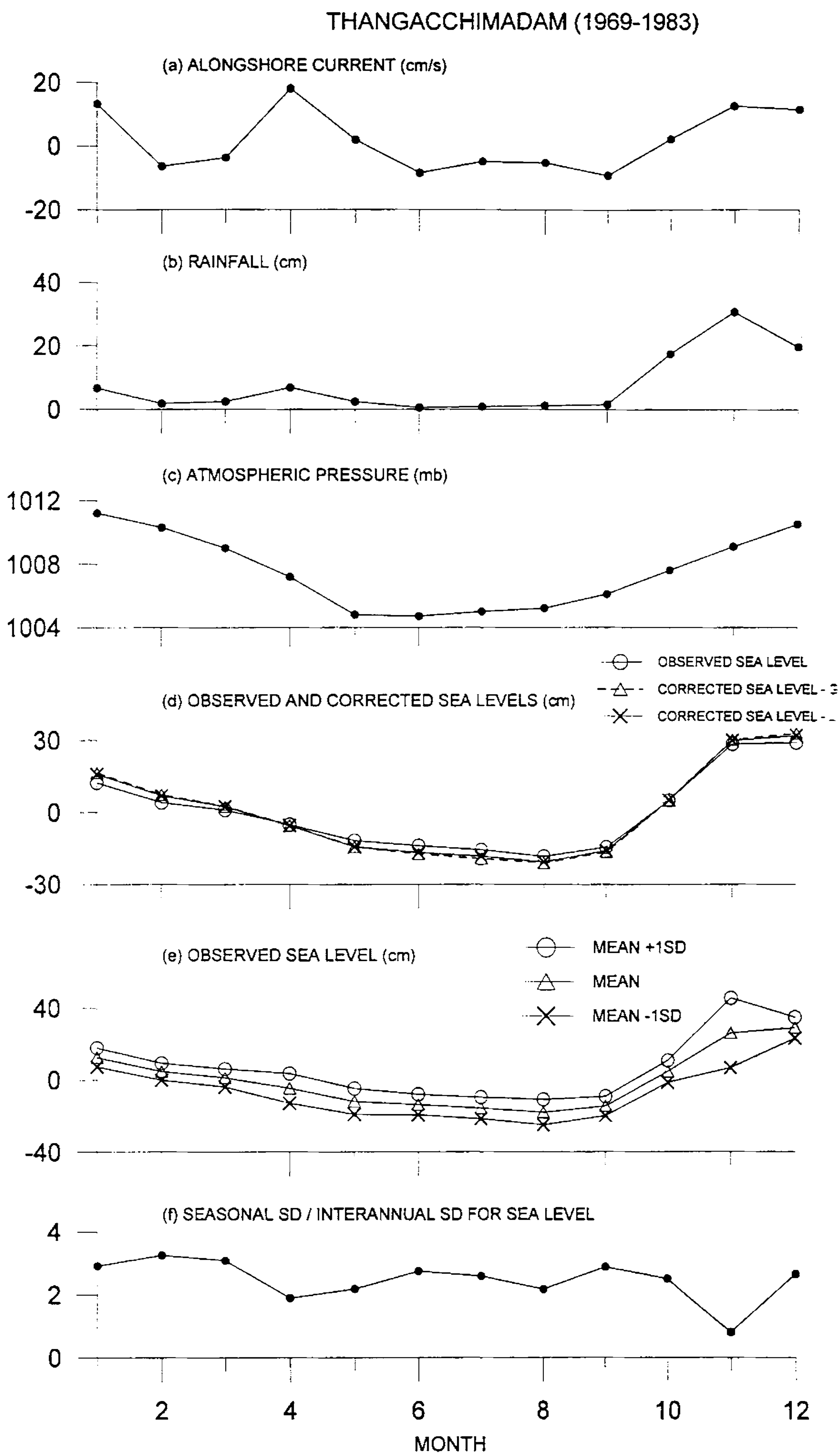


Fig. 5.11. Seasonal march of (a) alongshore current (b) rainfall (c) atmospheric pressure (d) observed sea level and corrected sea levels (e) sea level with 1 SD (standard deviation) bounds and (f) ratio of seasonal SD to

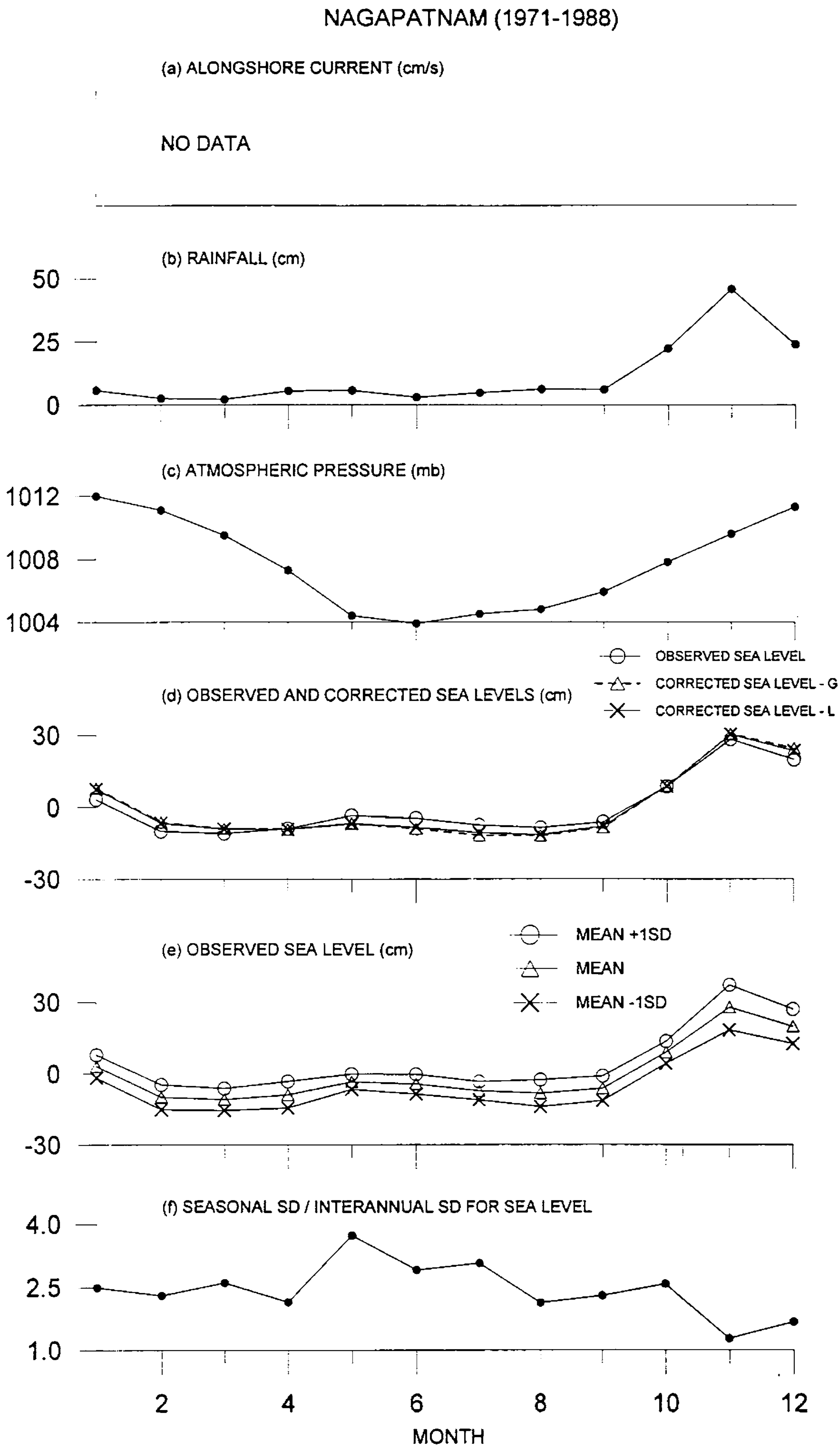


Fig. 5.12. Seasonal march of (a) alongshore current (b) rainfall (c) atmospheric pressure (d) observed sea level and corrected sea levels (e) sea level with 1 SD (standard deviation) bounds and (f) ratio of seasonal SD to interannual SD for sea level at Nagapatnam.

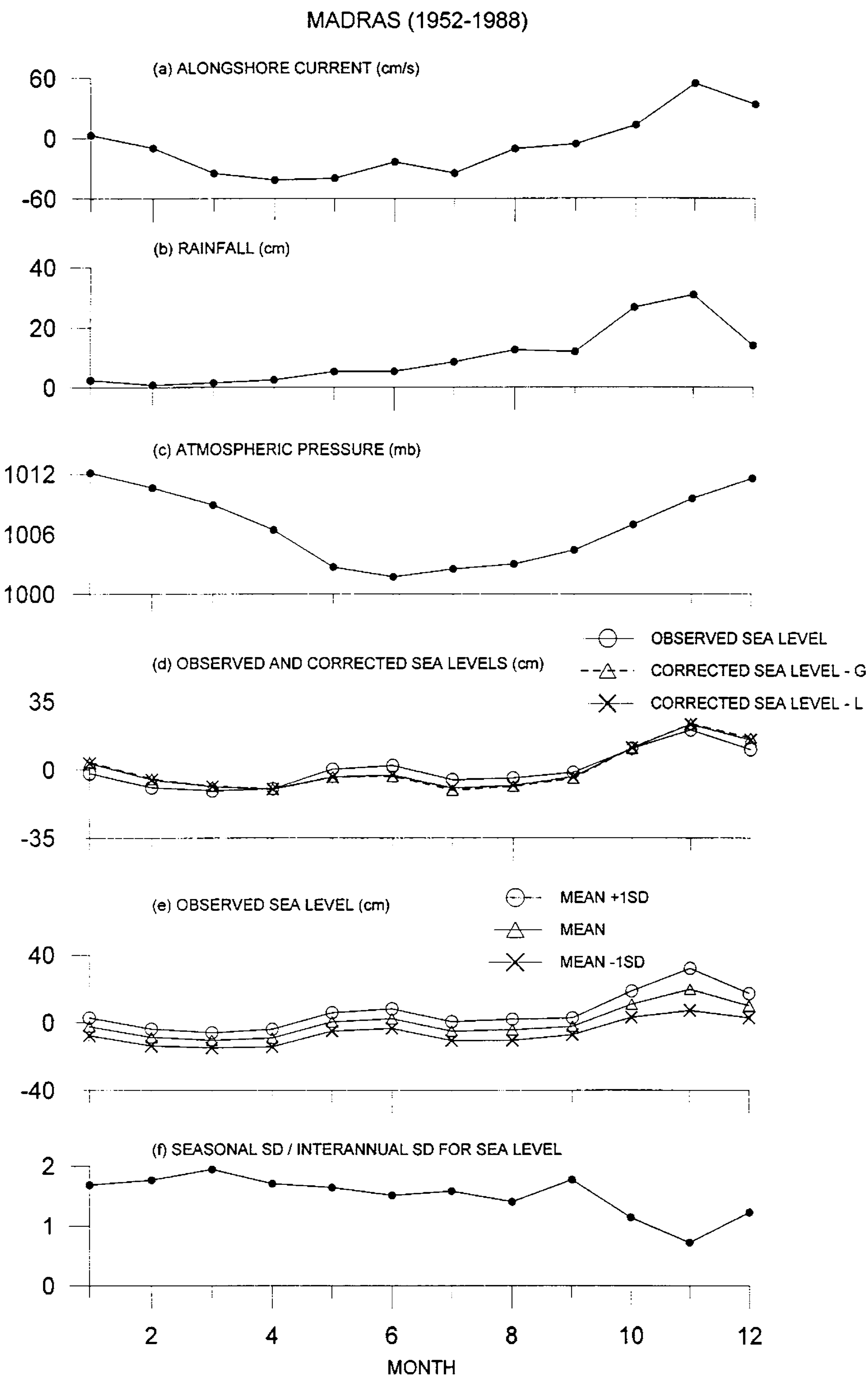


Fig. 5.13. Seasonal march of (a) alongshore current (b) rainfall (c) atmospheric pressure (d) observed sea level and corrected sea levels (e) sea level with 1 SD (standard deviation) bounds and (f) ratio of seasonal SD to

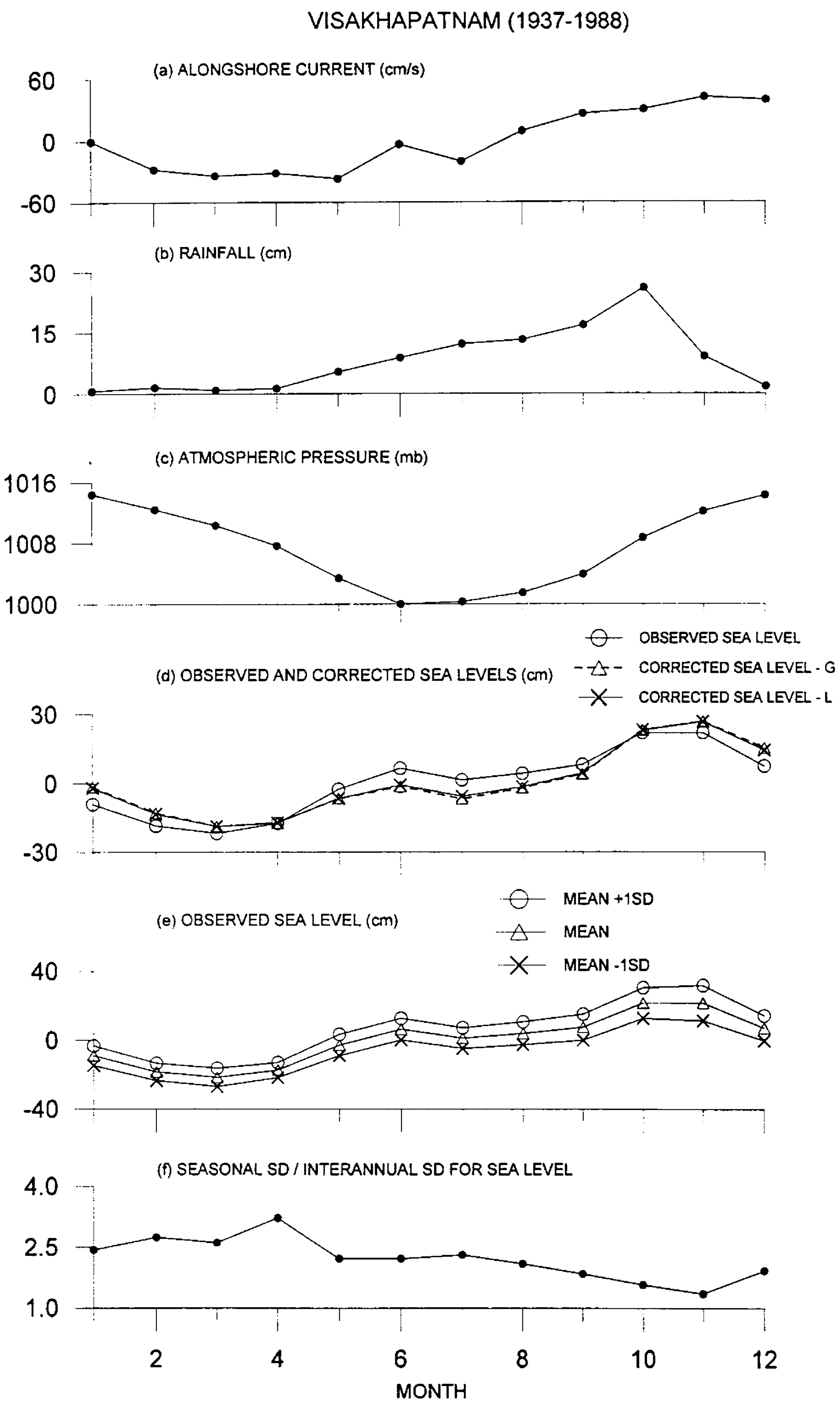


Fig. 5.14. Seasonal march of (a) alongshore current (b) rainfall (c) atmospheric pressure (d) observed sea level and corrected sea levels (e) sea level with 1 SD (standard deviation) bounds and (f) ratio of seasonal SD to

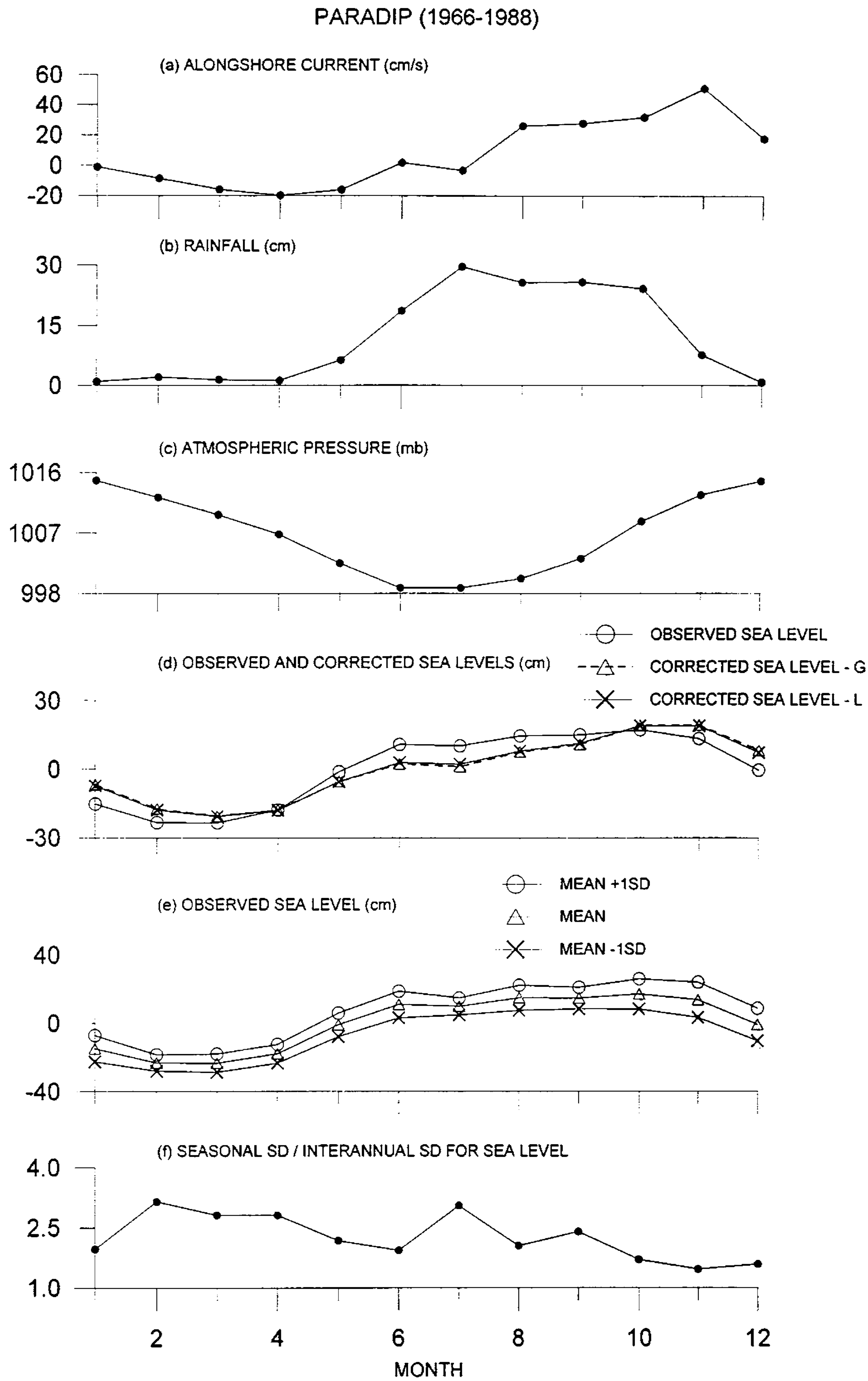


Fig. 5.15. Seasonal march of (a) alongshore current (b) rainfall (c) atmospheric pressure (d) observed sea level and corrected sea levels (e) sea level with 1 SD (standard deviation) bounds and (f) ratio of seasonal to interannual SD for sea level at Paradip

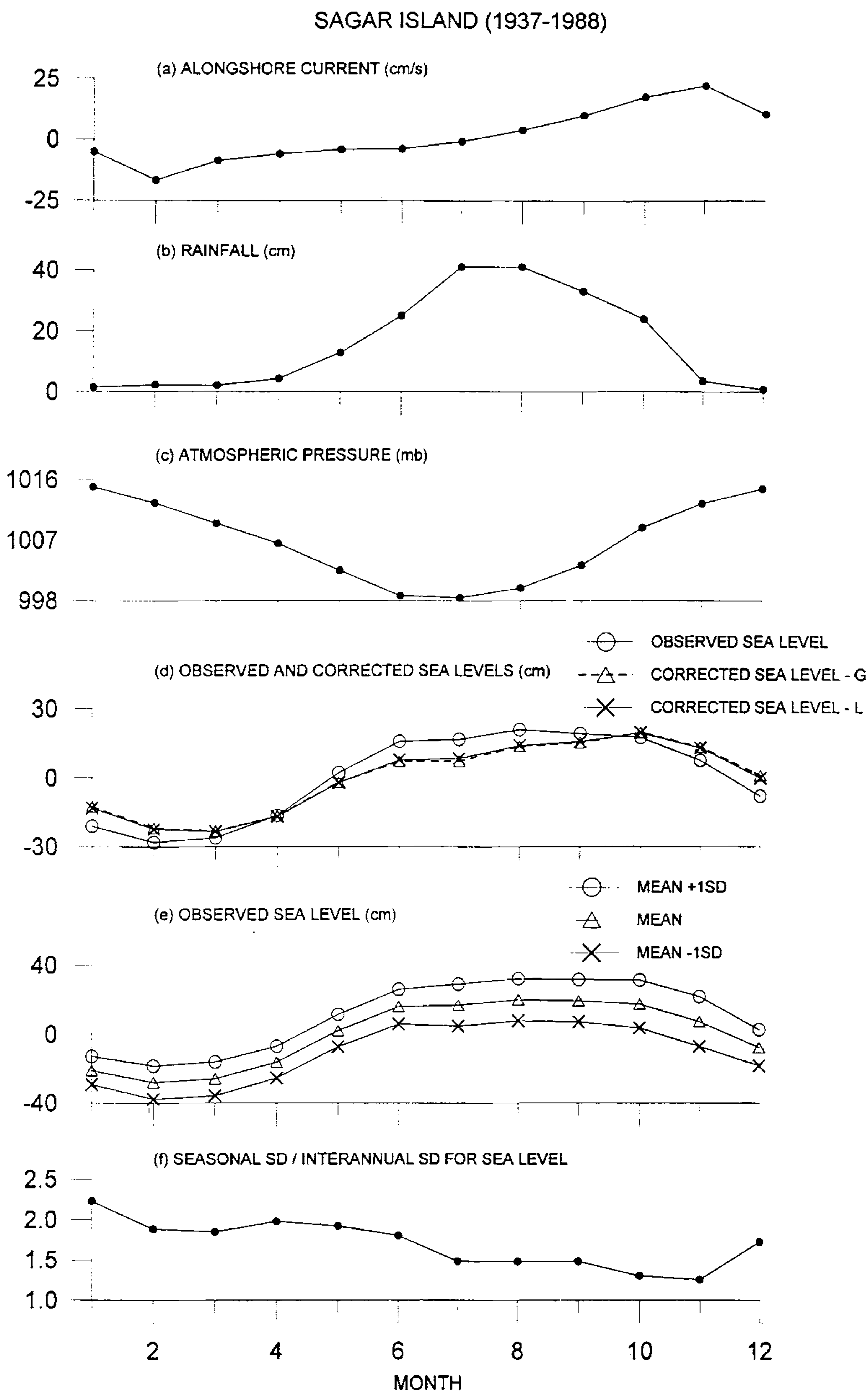


Fig. 5.16. Seasonal march of (a) alongshore current (b) rainfall (c) atmospheric pressure (d) observed sea level and corrected sea levels (e) sea level with 1 SD (standard deviation) bounds and (f) ratio of seasonal SD to

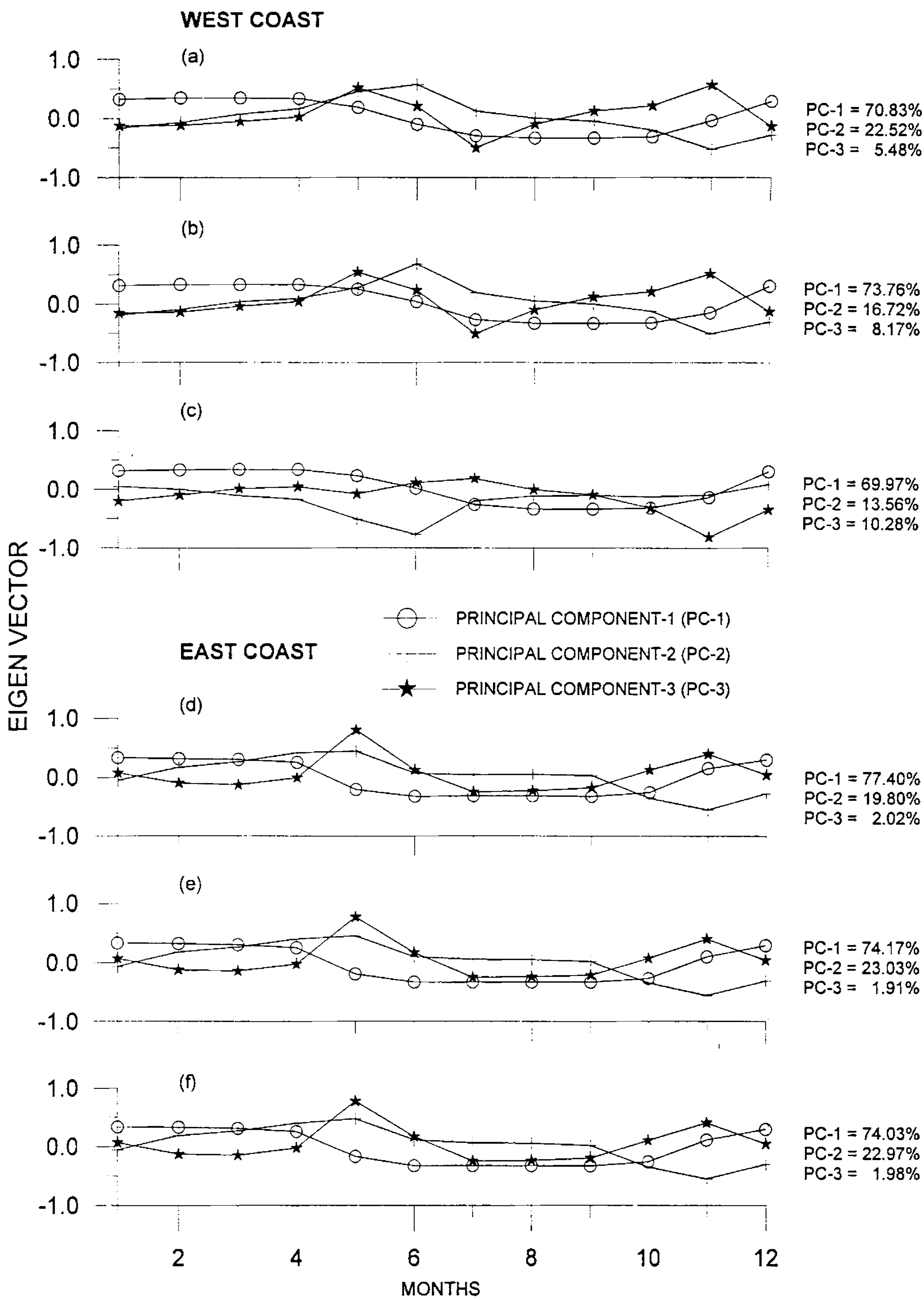


Fig. 5.17. The eigen vectors of the first three Principal Components in the case of west coast for (a) observed sea level (b) corrected sea level - G and (c) corrected sea level - L, and that for the east coast for (d) observed sea level (e) corrected sea level - G and (f) corrected sea level - L.

Table 5.1. Details of the sea level data analysed in this study.

WEST COAST

STATION	1	2	3	4	5	6	7	8
COCHIN	1939	1988	50	6.01	5.04	1.19	7.84	58.79
MANGALORE	1961	1976	16	5.95	5.74	1.04	8.26	51.81
KARWAR	1970	1988	19	6.88	5.77	1.19	8.98	58.74
MORMUGAO	1969	1980	12	6.24	4.03	1.55	7.43	70.56
BOMBAY	1878	1988	111	3.43	5.17	0.66	6.21	30.57
VERAVAL	1955	1965	11	4.53	-	-	-	-
BHAVNAGAR	1937	1955	19	21.75	11.57	1.88	24.64	77.96
KANDLA	1950	1987	38	5.02	7.78	0.65	9.25	29.41
KARACHI	1937	1947	11	3.44	4.74	0.73	5.86	34.50

EAST COAST

STATION	1	2	3	4	5	6	7	8
TUTICORIN	1964	1980	17	4.55	5.69	0.80	7.29	39.03
THANGACCHIMADAM	1969	1983	15	15.44	8.13	1.90	17.45	78.30
NAGAPATNAM	1971	1988	18	12.03	5.54	2.17	13.25	82.49
MADRAS	1952	1988	37	8.89	6.64	1.34	11.09	64.16
VISAKHAPATNAM	1937	1988	52	13.93	6.83	2.04	15.51	80.61
PARADIP	1966	1988	23	15.22	7.37	2.07	16.91	81.00
SAGAR ISLAND	1937	1988	52	18.14	11.17	1.62	21.30	72.51

1 - Starting year of data
2 - Ending year of data
3 - Total number of years
4 - Standard deviation of the climatological seasonal cycle of sea level (cm)
5 - Standard deviation of anomalies from long term seasonal cycle (cm)
6 - Ratio of 4 to 5
7 - Standard deviation of observed series (cm)
8 - Seasonal variance (%) contained in the observed series

Table 5.2. The angle which the coastline at the station makes with respect to true north.

WEST COAST			EAST COAST		
No.	STATION	ANGLE	No.	STATION	ANGLE
1.	COCHIN	339°	1.	TUTICORIN	21°
2.	MANGALORE	340°	2.	NAGAPATNAM	0°
3.	KARWAR	335°	3.	MADRAS	0°
4.	MORMUGAO	331°	4.	VISAKHAPATNAM	47°
5.	BOMBAY	351°	5.	PARADIP	80°
6.	VERAVAL	317°	6.	SAGAR ISLAND	80°
7.	KARACHI	320°			

Table 5.3. Seasonal sea level ranges along the west and east coast of the Indian subcontinent for the observed and corrected sea levels.

WEST COAST

STATION	1	2	3
COCHIN	18.4	21.4	19.9
MANGALORE	20.7	20.2	21.2
KARWAR	21.3	26.5	25.6
MORMUGAO	18.2	24.5	23.1
BOMBAY	11.8	19.1	17.6
VERAVAL	17.3	24.4	23.7
BHAVNAGAR	63.2	56.9	57.5
KANDLA	17.6	7.8	6.5
KARACHI	13.6	16.8	15.4

EAST COAST

STATION	1	2	3
TUTICORIN	13.1	20.7	18.6
THANGACCHIMADAM	47.3	54.0	52.6
NAGAPATNAM	39.1	42.2	41.5
MADRAS	31.3	34.0	33.2
VISAKHAPATNAM	43.5	45.5	45.3
PARADIP	40.8	40.0	39.8
SAGAR ISLAND	49.4	43.0	43.0

1 - OBSERVED SEA LEVEL (cm)
2 - CSL-G (cm)
3 - CSL-L (cm)

Table 5.4. Results of harmonic analysis of the observed sea level (climatological means) for the stations along the west coast of the Indian subcontinent.

TATION	1	2	3	4	5	6	7	8	9	10	11	12	13
)CHIN	36.11	84.36	8.05	6.97	99.38	7.81	2.41	2.24	0.60	11.62	10.65	1.6552	0.4720
NGALORE	30.73	3.58	54.20	33.20	90.98	1.48	5.77	4.52	11.83	0.46	10.71	3.6021	1.6652
RWAR	47.46	82.95	14.62	0.46	98.03	8.87	3.73	0.66	0.99	11.39	10.82	1.0733	0.9652
)RMUGAO	37.50	84.22	8.16	4.82	97.20	7.95	2.47	1.90	1.09	11.22	10.96	1.6905	1.0243
)MBAY	11.72	23.28	46.86	19.87	90.01	2.34	3.31	2.16	2.02	11.93	10.83	1.8707	1.0819
RAVAL	20.50	46.47	37.08	11.54	95.09	4.36	3.90	2.17	0.87	11.09	10.35	1.8361	1.0030
IAVNAGAR	489.40	98.24	1.32	0.33	99.89	31.01	3.60	1.80	8.12	1.94	11.67	1.4619	0.7253
NDLA	25.22	83.79	8.96	2.95	95.70	6.50	2.13	1.22	5.88	11.23	10.55	1.3524	1.0410
RACHI	14.13	49.86	42.09	2.61	94.56	3.75	3.45	0.86	5.30	11.44	10.70	1.0667	0.8768

l - Variance of the 12 monthly values (cm^2)
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 (cm)
7 - Amplitude of the semi-annual cycle (cm)
8 - Amplitude of the ter-annual cycle (cm)
9 - Phase of the annual cycle: in months centered to mid-month
0 - Phase of the semi-annual cycle: in months centered to mid-month
1 - Phase of the ter-annual cycle: in months centered to mid-month
2 - RMS deviation of the observed minus that calculated using annual and semi-annual cycle parameters
3 - RMS deviation of the observed minus that calculated using annual, semi-annual and ter-annual cycle parameters

Table 5.5. Results of harmonic analysis of CSL-G (climatological means) for the stations along the west coast of the Indian subcontinent.

STATION	1	2	3	4	5	6	7	8	9	10	11	12	13
COCHIN	53.37	88.49	6.12	4.77	99.38	9.72	2.56	2.26	0.47	11.73	10.68	1.6955	0.5719
MANGALORE	39.42	22.04	44.93	25.86	92.83	4.17	5.95	4.52	0.03	0.48	10.75	3.6087	1.6816
KARWAR	78.44	89.93	8.60	0.35	98.88	11.88	3.67	0.74	0.79	11.41	11.08	1.0727	0.9378
MORMUGAO	70.53	91.74	4.16	2.78	98.68	11.38	2.42	1.98	0.82	11.18	11.10	1.7014	0.9666
BOMBAY	32.14	76.39	14.22	6.77	97.38	7.01	3.02	2.09	0.80	11.78	10.99	1.7375	0.9180
VERAVAL	72.42	84.66	12.16	1.81	98.63	11.07	4.20	1.62	0.54	10.87	10.45	1.5160	0.9923
BHAVNAGAR	390.56	97.93	1.34	0.63	99.90	27.66	3.24	2.22	8.55	2.16	11.69	1.6919	0.6326
KANDLA	7.18	35.76	45.32	5.97	87.05	2.27	2.55	0.93	1.75	10.73	10.84	1.1659	0.9646
KARACHI	29.96	74.59	22.47	0.69	97.75	6.69	3.67	0.64	0.77	11.09	11.19	0.9374	0.8205

1 - Variance of the 12 monthly values (cm^2)
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 (cm)
7 - Amplitude of the semi-annual cycle (cm)
8 - Amplitude of the ter-annual cycle (cm)
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
12 - RMS deviation of the observed minus that calculated using annual and semi-annual cycle parameters
13 - RMS deviation of the observed minus that calculated using annual, semi-annual and ter-annual cycle parameters

Table 5.6. Results of harmonic analysis of CSL-L (climatological means) for the stations along the west coast of the Indian subcontinent.

TATION	1	2	3	4	5	6	7	8	9	10	11	12	13
OCHIN	46.98	86.68	6.71	5.91	99.30	9.02	2.51	2.36	0.47	11.80	10.64	1.7623	0.5720
ANGALORE	37.97	16.13	48.07	27.84	92.04	3.50	6.04	4.60	11.94	0.50	10.72	3.6869	1.7386
ARWAR	70.33	89.06	9.07	0.40	98.53	11.19	3.57	0.75	0.80	11.45	10.93	1.1491	1.0205
ORMUGAO	62.68	91.20	4.17	3.10	98.47	10.69	2.29	1.97	0.85	11.22	11.04	1.7045	0.9799
OMBAY	27.57	72.48	16.17	8.06	96.71	6.32	2.99	2.11	0.84	11.84	10.94	1.7686	0.9514
ERAVAL	64.47	83.56	12.59	2.42	98.57	10.38	4.03	1.77	0.54	10.88	10.42	1.5763	0.9624
HAVNAGAR	400.12	97.93	1.43	0.54	99.90	27.99	3.38	2.07	8.51	2.13	11.67	1.6057	0.6603
ANDLA	5.80	26.99	48.63	8.57	84.19	1.77	2.37	1.00	2.22	10.75	10.73	1.1884	0.9568
ARACHI	25.00	71.60	25.12	0.81	97.53	5.98	3.54	0.64	0.80	11.14	11.02	0.9052	0.7852

1 - Variance of the 12 monthly values (cm^2)
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 (cm)
7 - Amplitude of the semi-annual cycle (cm)
8 - Amplitude of the ter-annual cycle (cm)
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
12 - RMS deviation of the observed minus that calculated using annual and semi-annual cycle parameters
13 - RMS deviation of the observed minus that calculated using annual, semi-annual and ter-annual cycle parameters

Table 5.7. Results of harmonic analysis of the observed sea level (climatological means) for the stations along the east coast of the Indian subcontinent.

STATION	1	2	3	4	5	6	7	8	9	10	11	12	13
TUTICORIN	20.28	81.57	14.09	0.99	96.65	5.75	2.39	0.63	1.47	10.08	11.53	0.9382	0.8241
THANGACCHIMADAM	248.91	80.02	15.02	4.77	99.81	19.96	8.65	4.87	11.82	10.92	10.73	3.5139	0.6898
NAGAPATNAM	147.11	54.42	41.11	3.19	98.72	12.65	11.00	3.06	10.68	10.86	10.81	2.5641	1.3716
MADRAS	83.10	48.76	46.59	1.91	97.26	9.00	8.80	1.78	9.91	10.76	10.00	1.9662	1.5108
VISAKHAPATNAM	194.18	75.59	21.58	1.96	99.13	17.13	9.16	2.76	8.90	10.74	9.70	2.3424	1.2931
PARADIP	232.84	91.70	7.19	0.45	99.34	20.66	5.79	1.45	8.16	10.85	9.60	1.6079	1.2372
SAGAR ISLAND	332.21	96.07	3.30	0.33	99.70	25.26	4.68	1.48	7.72	10.77	1.33	1.4548	1.0077

1 - Variance of the 12 monthly values (cm^2)
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 (cm)
7 - Amplitude of the semi-annual cycle (cm)
8 - Amplitude of the ter-annual cycle (cm)
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
12 - RMS deviation of the observed minus that calculated using annual and semi-annual cycle parameters
13 - RMS deviation of the observed minus that calculated using annual, semi-annual and ter-annual cycle parameters

Table 5.8. Results of harmonic analysis of CSL-G (climatological means) for the stations along the east coast of the Indian subcontinent.

STATION	1	2	3	4	5	6	7	8	9	10	11	12	13
TUTICORIN	46.24	92.80	4.90	0.69	98.39	9.26	2.13	0.80	1.01	10.14	11.50	1.0302	0.8610
THANGACCHIMADAM	331.57	85.08	11.07	3.72	99.87	23.75	8.57	4.96	11.90	10.95	10.75	3.5694	0.6472
NAGAPATNAM	194.55	66.42	30.07	2.70	99.19	16.08	10.82	3.24	11.10	10.88	10.84	2.6109	1.2503
MADRAS	114.56	64.12	32.95	1.19	98.26	12.12	8.69	1.65	10.81	10.79	10.16	1.8321	1.4114
VISAKHAPATNAM	200.32	74.41	23.31	1.32	99.04	17.27	9.66	2.30	9.79	10.71	9.75	2.1340	1.3793
PARADIP	176.69	86.90	11.98	0.29	99.17	17.52	6.51	1.02	9.00	10.78	9.63	1.4075	1.2087
SAGAR ISLAND	213.90	92.24	6.85	0.39	99.48	19.86	5.41	1.29	8.34	10.69	1.20	1.3954	1.0563

1 - Variance of the 12 monthly values (cm^2)
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 (cm)
7 - Amplitude of the semi-annual cycle (cm)
8 - Amplitude of the ter-annual cycle (cm)
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
12 - RMS deviation of the observed minus that calculated using annual and semi-annual cycle parameters
13 - RMS deviation of the observed minus that calculated using annual, semi-annual and ter-annual cycle parameters

Table 5.9. Results of harmonic analysis of CSL-L (climatological means) for the stations along the east coast of the Indian subcontinent.

STATION	1	2	3	4	5	6	7	8	9	10	11	12	13
TUTICORIN	39.69	93.10	4.84	0.61	98.55	8.60	1.96	0.70	1.06	10.10	11.38	0.9058	0.7603
THANGACCHIMADAM	315.04	84.64	11.22	4.04	99.90	23.09	8.41	5.05	11.89	10.96	10.73	3.6130	0.5663
NAGAPATNAM	184.84	65.54	30.67	2.95	99.16	15.57	10.65	3.30	11.05	10.89	10.80	2.6436	1.2395
MADRAS	108.07	63.28	33.54	1.54	98.36	11.69	8.51	1.83	10.72	10.79	10.14	1.8558	1.3325
VISAKHAPATNAM	197.07	74.83	22.83	1.54	99.20	17.17	9.49	2.46	9.71	10.71	9.77	2.1460	1.2545
PARADIP	178.89	87.74	11.20	0.38	99.32	17.72	6.33	1.17	8.92	10.79	9.68	1.3759	1.1018
SAGAR ISLAND	220.90	92.99	6.20	0.41	99.60	20.27	5.23	1.34	8.29	10.70	1.28	1.3400	0.9445

1 - Variance of the 12 monthly values (cm^2)
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 (cm)
7 - Amplitude of the semi-annual cycle (cm)
8 - Amplitude of the ter-annual cycle (cm)
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
12 - RMS deviation of the observed minus that calculated using annual and semi-annual cycle parameters
13 - RMS deviation of the observed minus that calculated using annual, semi-annual and ter-annual cycle parameters

Table 5.10. Comparison of the present results with those published by Woodworth (1984).

PRESENT ANALYSIS

WEST COAST

STATION	A_1	Φ_1	A_2	Φ_2
COCHIN	7.81	0.60	2.41	5.62
BOMBAY	2.34	2.02	3.31	5.93
BHAVNAGAR	31.01	8.12	3.60	1.94
KARACHI	3.75	5.30	3.45	5.44

EAST COAST

STATION	A_1	Φ_1	A_2	Φ_2
MADRAS	9.00	9.91	8.80	4.76
VISAKHAPATNAM	17.13	8.90	9.16	4.74
SAGAR ISLAND	25.26	7.72	4.68	4.77

RESULTS OF WOODWORTH (1984)

WEST COAST

STATION	A_1	Φ_1	A_2	Φ_2
COCHIN	7.71	0.60	2.51	5.72
BOMBAY	2.26	2.09	3.43	5.99
BHAVNAGAR	23.35	7.96	2.05	1.55
KARACHI	4.33	5.20	3.35	5.33

EAST COAST

STATION	A_1	Φ_1	A_2	Φ_2
MADRAS	9.92	9.90	9.15	4.71
VISAKHAPATNAM	17.17	8.97	8.99	4.65
SAGAR ISLAND	25.91	7.73	4.45	4.74

A_1 and Φ_1 - Amplitude (cm) and phase (in months) of the annual cycle.

A_2 and Φ_2 - Amplitude (cm) and phase (in months) of the semi-annual cycle.

Table 5.11. Correlations between the meteorological and oceanographic parameters along the west and east coast of the Indian subcontinent on a seasonal time scale.

WEST COAST

STATION	3 x 4	4 x 5	5 x 6	1 x 5	2 x 5	1 x 2
COCHIN	0.79	1.00	1.00	0.88	-0.73	-0.70^{*}
MANGALORE	0.32^{ns}	0.95	1.00	0.34^{ns}	-0.01^{ns}	-0.69^{*}
KARWAR	0.81	0.99	1.00	0.63^{*}	-0.70^{*}	-0.67^{*}
MORMUGAO	0.82	0.98	1.00	0.79	-0.72	-0.71
BOMBAY	0.22^{ns}	0.76	1.00	0.48^{ns}	-0.58^{*}	-0.20^{ns}
VERAVAL	0.62^{*}	0.89	1.00	0.88	-0.73	-0.66^{*}
BHAVNAGAR	-0.53^{ns}	0.97	1.00	-	0.63^{*}	-
KANDLA	-0.89	-0.02^{ns}	0.98	-	-0.52^{ns}	-
KARACHI	-0.64^{*}	-0.11^{ns}	1.00	0.45^{ns}	-0.60^{*}	-0.69^{*}
NUMBER	108	108	108	84	108	84
R	-0.15^{ns}	0.89	1.00	0.65	-0.28	-0.61
VARIANCE	2.30	79.20	100.00	42.30	7.80	37.20

EAST COAST

STATION	3 x 4	4 x 5	5 x 6	1 x 5	2 x 5	1 x 2
TUTICORIN	0.67^{*}	0.96	1.00	0.60^{*}	0.42^{ns}	0.63^{*}
THANGACCHIMADAM	0.82	1.00	1.00	0.65^{*}	0.81	0.63^{*}
NAGAPATNAM	0.43^{ns}	0.98	1.00	-	0.90	-
MADRAS	0.18^{ns}	0.93	1.00	0.93	0.77	0.77
VISAKHAPATNAM	-0.17^{ns}	0.92	1.00	0.92	0.55^{ns}	0.49^{ns}
PARADIP	-0.49^{ns}	0.91	1.00	0.91	0.58^{*}	0.42^{ns}
SAGAR ISLAND	-0.68^{*}	0.95	1.00	0.81	0.69^{*}	0.21^{ns}
NUMBER	84	84	84	72	84	72
R	-0.18^{ns}	0.94	1.00	0.72	0.65	0.42
VARIANCE	3.20	88.40	100.00	51.80	42.30	17.60

1 - Alongshore current
2 - Rainfall
3 - Atmospheric pressure
4 - Observed sea level
5 - CSL-G
6 - CSL-L

NUMBER - Number of data points
R - Correlation coefficient
VARIANCE - Variance explained by the relationship

Correlations above 99% significance are not indicated, whereas those at 95% significance (marked as *) and those not significant (marked as ns) are indicated.

Table 5.12. The Principal Component scores for the west and east coasts of the Indian subcontinent, for the observed sea level and corrected sea levels.

PC SCORES FOR ALL THE STATIONS

WEST COAST

STATION	1	2	3
COCHIN	1.66	0.96	1.27
MANGALORE	0.22	-0.22	-0.20
KARWAR	2.18	1.87	1.81
MORMUGAO	2.09	1.82	1.26
BOMBAY	0.77	0.98	1.00
VERAVAL	1.03	1.20	1.34
BHAVNAGAR	-7.35	-7.73	-7.54
KANDLA	-0.63	0.18	0.11
KARACHI	0.02	0.93	0.96

EAST COAST

STATION	1	2	3
TUTICORIN	2.06	1.83	1.80
THANGACCHIMADAM	4.41	4.43	4.43
NAGAPATNAM	1.71	1.58	1.58
MADRAS	0.49	0.49	0.53
VISAKHAPATNAM	-1.50	-1.28	-1.28
PARADIP	-2.91	-2.76	-2.76
SAGAR ISLAND	-4.26	-4.29	-4.29

1 - OBSERVED SEA LEVEL
2 - CSL-G
3 - CSL-L

Table 5.13. Results of harmonic analysis of the rainfall (climatological means) for the stations along the west coast of the Indian subcontinent.

STATION	1	2	3	4	5	6	7	8	9	10	11	12
COCHIN	503.09	77.20	10.85	9.75	27.87	10.45	9.91	6.51	11.48	9.71	7.7553	3.3286
MANGALORE	1325.14	70.68	19.76	7.43	43.28	22.89	14.03	6.54	0.23	10.04	11.2528	5.3082
KARWAR	1638.63	68.62	20.83	7.10	47.42	26.13	15.25	6.62	0.37	10.10	13.1479	7.5179
MORMUGAO	921.15	64.28	21.47	9.61	34.41	19.89	13.31	6.59	0.31	10.09	11.4572	6.5384
BOMBAY	580.43	69.91	21.50	4.78	28.49	15.80	7.45	6.84	0.66	10.26	7.0604	4.6995
VERAVAL	80.65	58.86	24.60	9.90	9.74	6.30	4.00	6.79	0.64	10.46	3.6522	2.3131
BHAVNAGAR	57.27	56.86	21.98	6.74	8.07	5.02	2.78	7.30	1.27	10.97	3.4813	2.8736
KANDLA	36.75	43.86	24.35	14.65	5.68	4.23	3.28	6.90	0.66	10.57	3.4178	2.5099
KARACHI	4.89	33.60	41.01	12.73	1.81	2.00	1.12	6.67	0.81	10.68	1.1139	0.7867

1 - Variance of the 12 monthly values (cm^2)
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 - Amplitude of the annual cycle (cm)
6 - Amplitude of the semi-annual cycle (cm)
7 - Amplitude of the ter-annual cycle (cm)
8 - Phase of the annual cycle: in months centered to mid-month
9 - Phase of the semi-annual cycle: in months centered to mid-month
10 - Phase of the ter-annual cycle: in months centered to mid-month
11 - RMS deviation of the observed minus that calculated using annual and semi-annual cycle parameters
12 - RMS deviation of the observed minus that calculated using annual, semi-annual and ter-annual cycle parameters

Table 5.14. Results of harmonic analysis of the rainfall (climatological means) for the stations along the east coast of the Indian subcontinent.

STATION	1	2	3	4	5	6	7	8	9	10	11	12
THANGACCHIMADAM	86.93	53.10	34.86	9.75	9.61	7.78	4.12	10.85	10.49	10.70	3.2359	1.4119
NAGAPATNAM	158.08	50.30	32.31	11.45	12.61	10.11	6.02	10.39	10.51	10.64	5.2438	3.0664
MADRAS	88.41	67.62	21.20	7.41	10.93	6.12	3.62	9.47	10.21	10.39	3.1449	1.8272
VISAKHAPATNAM	56.81	75.16	8.63	9.75	9.24	3.13	3.33	8.25	9.17	1.48	3.0339	1.9143
PARADIP	125.89	89.65	4.57	3.62	15.02	3.39	3.02	7.58	1.61	9.70	2.6969	1.6486
SAGAR ISLAND	234.53	89.70	8.88	0.16	20.51	6.45	0.87	7.23	1.39	1.42	1.8266	1.7208

Table 5.15. Results of harmonic analysis of the atmospheric presssure (climatological means) for the stations along the west coast of the Indian subcontinent.

STATION	1	2	3	4	5	6	7	8	9	10	11	12
COCHIN	1.05	86.91	10.18	0.65	1.35	0.46	0.12	11.69	1.00	10.50	0.1745	0.1538
MANGALORE	2.13	95.71	3.19	0.29	2.02	0.37	0.11	0.02	1.20	11.20	0.1532	0.1312
KARWAR	3.22	98.02	1.33	0.35	2.51	0.29	0.15	0.14	1.45	11.50	0.1450	0.0988
MORMUGAO	4.54	98.58	0.39	0.80	2.99	0.19	0.27	0.18	2.13	11.83	0.2156	0.1017
BOMBAY	10.85	98.35	0.91	0.54	4.62	0.44	0.34	0.27	9.59	11.98	0.2832	0.1475
VERAVAL	19.26	97.47	1.91	0.53	6.13	0.86	0.45	0.30	9.63	0.10	0.3443	0.1254
BHAVNAGAR	22.76	98.61	1.13	0.17	6.70	0.72	0.27	0.20	9.83	11.66	0.2422	0.1445
KANDLA	27.34	97.30	2.38	0.26	7.29	1.14	0.38	0.32	9.69	0.04	0.2943	0.1234
KARACHI	41.63	98.19	1.47	0.22	9.04	1.11	0.43	0.23	9.87	0.19	0.3776	0.2215

1 - Variance of the 12 monthly values (mb^2)
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 - Amplitude of the annual cycle (mb)
6 - Amplitude of the semi-annual cycle (mb)
7 - Amplitude of the ter-annual cycle (mb)
8 - Phase of the annual cycle: in months centered to mid-month
9 - Phase of the semi-annual cycle: in months centered to mid-month
10 - Phase of the ter-annual cycle: in months centered to mid-month
11 - RMS deviation of the observed minus that calculated using annual and semi-annual cycle parameters
12 - RMS deviation of the observed minus that calculated using annual, semi-annual and ter-annual cycle parameters

Table 5.16. Results of harmonic analysis of the atmospheric pressure (climatological means) for the stations along the east coast of the Indian subcontinent.

STATION	1	2	3	4	5	6	7	8	9	10	11	12
THANGACCHIMADAM	5.34	97.36	1.76	0.28	3.22	0.43	0.17	0.31	1.00	10.69	0.2176	0.1795
NAGAPATNAM	8.10	97.81	1.43	0.35	3.98	0.48	0.24	0.30	1.15	10.78	0.2472	0.1806
MADRAS	13.15	98.43	0.58	0.61	5.09	0.39	0.40	0.27	1.06	11.00	0.3613	0.2241
VISAKHAPATNAM	26.70	99.03	0.37	0.33	7.27	0.45	0.42	0.30	10.02	11.24	0.3994	0.2686
PARADIP	33.76	98.93	0.66	0.16	8.17	0.67	0.33	0.23	10.23	11.31	0.3714	0.2878
SAGAR ISLAND	34.68	99.11	0.63	0.05	8.29	0.66	0.18	0.22	10.18	11.74	0.2987	0.2704

1 - Variance of the 12 monthly values (mb^2)
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 - Amplitude of the annual cycle (mb)
6 - Amplitude of the semi-annual cycle (mb)
7 - Amplitude of the ter-annual cycle (mb)
8 - Phase of the annual cycle: in months centered to mid-month
9 - Phase of the semi-annual cycle: in months centered to mid-month
10 - Phase of the ter-annual cycle: in months centered to mid-month
11 - RMS deviation of the observed minus that calculated using annual and semi-annual cycle parameters
12 - RMS deviation of the observed minus that calculated using annual, semi-annual and ter-annual cycle parameters

Table 5.17. Results of harmonic analysis of the along-shore current (climatological means) for the stations along the west coast of the Indian subcontinent.

STATION	1	2	3	4	5	6	7	8	9	10	11	12
COCHIN	170.29	90.86	5.63	0.60	17.59	4.38	1.43	11.81	10.77	9.87	2.4452	2.2247
MANGALORE	225.65	81.35	16.42	0.14	19.16	8.61	0.80	11.72	10.60	9.99	2.2454	2.1735
KARWAR	268.53	69.82	22.78	0.83	19.36	11.06	2.11	11.40	10.06	1.30	4.4573	4.1991
MORMUGAO	264.14	86.61	10.37	2.35	21.39	7.40	3.52	11.77	10.43	9.57	2.8286	1.3434
BOMBAY	53.10	7.96	48.65	3.80	2.91	7.19	2.01	0.01	11.01	9.78	4.8003	4.5852
VERAVAL	185.66	71.73	10.38	3.89	16.32	6.21	3.80	0.58	10.63	10.68	5.7625	5.0982
KARACHI	35.31	72.55	16.86	6.29	7.16	3.45	2.11	11.35	9.10	0.42	1.9336	1.2325

1 - Variance of the 12 monthly values (cm^2/s^2)
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 - Amplitude of the annual cycle (cm/s)
6 - Amplitude of the semi-annual cycle (cm/s)
7 - Amplitude of the ter-annual cycle (cm/s)
8 - Phase of the annual cycle: in months centered to mid-month
9 - Phase of the semi-annual cycle: in months centered to mid-month
10 - Phase of the ter-annual cycle: in months centered to mid-month
11 - RMS deviation of the observed minus that calculated using annual and semi-annual cycle parameters
12 - RMS deviation of the observed minus that calculated using annual, semi-annual and ter-annual cycle parameters

Table 5.18. Results of harmonic analysis of the along-shore current (climatological means) for the stations along the east coast of the Indian subcontinent.

STATION	1	2	3	4	5	6	7	8	0	10	11	12
TUTICORIN	86.05	29.38	26.32	22.41	7.11	6.73	6.21	0.55	10.59	11.53	6.1736	4.3394
MADRAS	850.47	83.85	9.30	1.29	37.77	12.58	4.68	10.59	11.06	10.55	7.6301	6.8756
VISAKHAPATNAM	830.86	86.72	6.14	0.60	37.96	10.10	3.15	9.80	10.84	11.51	7.6985	7.3688
PARADIP	475.15	87.60	2.87	1.35	28.85	5.22	3.58	9.48	10.25	10.47	6.7325	6.2377
SAGAR ISLAND	120.26	73.76	22.14	3.30	13.32	7.30	2.82	9.37	10.28	11.00	2.2188	0.9763

1 - Variance of the 12 monthly values (cm^2/s^2)
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 - Amplitude of the annual cycle (cm/s)
6 - Amplitude of the semi-annual cycle (cm/s)
7 - Amplitude of the ter-annual cycle (cm/s)
8 - Phase of the annual cycle: in months centered to mid-month
9 - Phase of the semi-annual cycle: in months centered to mid-month
10 - Phase of the ter-annual cycle: in months centered to mid-month
11 - RMS deviation of the observed minus that calculated using annual and semi-annual cycle parameters
12 - RMS deviation of the observed minus that calculated using annual, semi-annual and ter-annual cycle parameters

Table 5.19. Year to year variability of the seasonal cycle amplitudes of sea level at the stations along the Indian subcontinent.

WEST COAST

STATION	YEARS	ANNUAL MEAN	ANNUAL SD	ANNUAL CV	SEMI-ANNUAL MEAN	SEMI-ANNUAL SD	SEMI-ANNUAL CV	TER-ANNUAL MEAN	TER-ANNUAL SD	TER-ANNUAL CV
COCHIN	50	8.10	1.90	23.41	2.94	1.45	49.26	2.89	1.18	40.76
MANGALORE	16	4.26	2.21	51.99	6.20	1.45	23.33	5.78	2.20	38.07
KARWAR	19	9.29	2.09	22.50	4.22	2.67	63.13	2.96	1.58	53.31
MORMUGAO	12	8.49	1.69	19.86	2.88	1.69	58.75	2.24	1.00	44.80
BOMBAY	111	3.59	1.59	44.21	3.98	1.55	38.78	2.79	1.46	52.37
BHAVNAGAR	19	31.12	7.63	24.53	6.10	3.48	57.13	3.89	2.27	58.35
KANDLA	38	7.27	2.38	32.74	3.04	1.51	49.58	2.36	1.28	54.54
KARACHI	11	4.16	2.44	58.67	3.76	1.64	43.59	2.64	1.47	55.44

EAST COAST

STATION	YEARS	ANNUAL MEAN	ANNUAL SD	ANNUAL CV	SEMI-ANNUAL MEAN	SEMI-ANNUAL SD	SEMI-ANNUAL CV	TER-ANNUAL MEAN	TER-ANNUAL SD	TER-ANNUAL CV
TUTICORIN	17	6.56	1.87	28.54	3.42	1.96	57.44	1.47	0.91	62.11
THANGACCHIMADAM	15	20.14	3.15	15.65	9.20	2.85	30.93	5.75	2.22	38.62
NAGAPATNAM	18	12.67	3.32	26.21	11.12	2.83	25.48	4.02	1.90	47.39
MADRAS	37	9.33	3.14	33.72	9.30	2.94	31.59	3.23	1.93	59.57
VISAKHAPATNAM	52	17.41	3.66	21.04	9.52	3.23	33.98	3.98	2.00	50.32
PARADIP	23	20.97	2.47	11.79	6.61	2.77	41.93	3.66	2.15	58.69
SAGAR ISLAND	52	25.52	3.37	13.20	6.01	2.71	45.17	3.13	1.76	56.27

MEAN - Mean amplitude (cm) SD - Standard deviation (cm) CV - Coefficient of variation (%)

Table 5.20. Correlation between SOI and the sea level anomalies at the stations along the Indian subcontinent.

WEST COAST

STATION	1	2	3
COCHIN	588	0.372^{**}	13.82
MANGALORE	180	0.570^{**}	32.51
KARWAR	216	0.461^{**}	21.26
MORMUGAO	132	-0.124^{ns}	1.54
BOMBAY	660	0.188^{**}	3.52
BHAVNAGAR	216	0.110^{ns}	1.21
KANDLA	444	0.179^{**}	3.19
KARACHI	120	-0.265^{**}	7.00

EAST COAST

STATION	1	2	3
TUTICORIN	192	0.190^{**}	3.61
THANGACCHIMADAM	168	0.154^{*}	2.37
NAGAPATNAM	204	0.372^{**}	13.82
MADRAS	432	0.487^{**}	23.72
VISAKHAPATNAM	612	0.539^{**}	29.03
PARADIP	264	0.597^{**}	35.69
SAGAR ISLAND	612	0.256^{**}	6.57

1 - Number of months of data used
2 - Correlation coefficient
3 - Percentage variance explained by the correlation coefficient

ns - Not significant
* - Significant at 5% level
** - Significant at 1% level

CHAPTER 6

CHAPTER 6

CONTINENTAL SHELF WAVES OFF KERALA COAST

6.1. INTRODUCTION

The variability in estuarine sea level and net flow on time scales longer than the predominant tidal cycle, are two aspects which have not received much attention in the context of estuary-coastal ocean exchanges in the Indian context. Elliott (1976) focussed on the transient nature of estuarine circulation and its relation to local and far-field forcings with periodicity from 2 to 20 days. This forcing was well correlated with the local atmospheric variability, primarily through wind forced events. He also emphasised that an ideal estuary for such studies of non-local forcing should have minimal or near-absence of fresh water discharge. From a study of one year time series records of sea level, atmospheric pressure, and wind speed and direction, Kjerfve et al. (1978) concluded that a 6 day (3.2 cm high) wave in the sea level was attributable to atmospheric pressure, and a 9.2 day (6.4 cm high) fluctuation varied with the alongshore wind stress. Further, they hypothesised that the forcing is transferred to the estuary from the coastal ocean through continental shelf waves. Elliott (1976) studied the forcing mechanisms that control the circulation - river discharge, wind stress, atmospheric pressure, water elevation, rate of change of water elevation, and water surface slope along the estuary. He also pointed out that the main problem in analysing the importance of the individual effects lies in the inter-dependency between the forcing mechanisms. Elliott (1976) concluded that the response of the Potomac estuary could be explained by two modes. The first mode accounted for 55% of the total variance and was best correlated with local effects such as wind stress and net surface slope. The second mode accounted for 25% of the total variance and was primarily correlated with far-field effects such as the time rate of change of the mean water surface. Smith (1977) found that the lagoonal estuary of Corpus Christi Bay experienced sustained energetic sea level fluctuations that were coherent with cross-shore winds parallel to the Bay inlet for short periods (2-4 days) consistent with local forcing. Weisberg (1976) showed that 48% of the current variance in a 51 day record from Narragansett Bay resided at sub-tidal frequencies. On a time scale of 4-5 days in particular, these fluctuations were impeccably coherent with local winds. All low frequency current and sea level variations are not due to local effects. Wang and Elliott (1978) found that current and sea-level fluctuations in the Chesapeake Bay were due to non-local forcing with variance peaks at periods of 5 and 20 days. These far-field-driven fluctuations are probably due to the response of the estuary to continental shelf waves. The continental shelf waves with periods from 3 to 10 days have been found to propagate southward because of atmospheric forcing along the continental shelf off North Carolina (Mysak and Hamon, 1969). The continental shelf waves in the Florida Current have been measured to have periods from 7 to 14 days (Brooks and Mooers, 1977). Wong and Garvine (1984) found that the remote effect of the wind was dominant within the Delaware estuary for all sub-tidal frequencies in respect of currents. Locally forced waves have been observed travelling with the wind stress perturbation in the north and south American shelves (Csanady, 1978; Mitchum and Clarke, 1986; Schroeder and Wiseman, 1986; Lee et al., 1989; Smith, 1993; Castro and Lee, 1995)

The theoretical framework of the relative dominance of local versus remote wind effects was put forward by Garvine (1985). His contention was that because of relative shortness of most estuaries in comparison to the low subtidal wavelength, the remote effect will tend to dominate subtidal sea level and barotropic current fluctuations, particularly for the longer periods. The orientation of the estuary with respect to the coast then determines whether the local and remote effects will act in unison or in opposition. The topography - depth, length and orientation, will exert a substantial influence on estuarine response to local meteorological forcing.

Mooers and Smith (1968) searched tide gauge records from stations along the Oregon coast for statistical evidence of continental shelf waves.

Pariwono et al. (1986) obtained remarkable coherence of simultaneous non-tidal residuals in the South Australian waters spanning a distance of 700 kilometers. This was attributed to progressive coastal long waves (height of nearly 1m and period in the range 5-20 days) influenced by the presence of the shelf and its ability to act as a wave guide. They reported that these synoptic perturbations in the sea level have a significant influence that is approximately half of the tide (semi-diurnal tide has an amplitude of 0.7m)

Goodrich (1988) as a part of a study on the meteorologically induced flushing along three U.S. east coast estuaries, observed that the filtered sea level records at Chesapeake Bay and Naragansett Bay were strongly coherent, having similar amplitudes, despite a separation of 600 km.

The low-frequency propagation along the west coast of the Americas has most often been studied using coastal sea level records corrected for surface atmospheric pressure (Chelton and Davis, 1982; Enfield and Allen, 1983; Denbo and Allen, 1987; Halliwell and Allen, 1987; Spillane et al., 1987).

The propagating events in the coastal wave guide, such as Kelvin waves, topographic or shelf waves, and hybrid waves (where both stratification and topography are important) are all expected to travel poleward (Gill, 1982; Ramp et al., 1997; Shaffer et al., 1997).

Yuce and Alpar (1997) studied the subtidal sea-level variations in the Sea of Marmara. They found that the dominant sea level fluctuations occurred at time scales greater than 10 days, as also shorter period fluctuations occurring between 3-8 days.

Robinson (1964) suggested that travelling waves on the continental shelf might explain the observed departures from isostasy. For this explanation to hold good, it must be assumed that the travelling waves are forced by pressure variations, or by wind stress correlated with pressure. Sea level at any station would then be regarded as containing the sum of the direct (isostatic) response to pressure and the elevation due to the shelf wave. The direct response and the shelf wave elevation might be of opposite sign at some stations, leading to an apparent reduction of the barometer factor. At other stations, where the two components have the same sign, the barometer factor would be increased. Early research on continental shelf waves assumed wind forcing to be the primary driving mechanism (Mysak, 1980; Foreman et al., 1994).

The following is a brief summary of the main properties of the continental shelf waves.

i) The waves can travel along the shelf in one direction only. The direction is such that the coast is on the right when we look in the direction of wave motion in the northern hemisphere and left in the southern hemisphere.

ii) Sea level has a node at the edge of the shelf and an anti-node at the coast. For the second and higher modes, there are other nodes and anti-nodes at intermediate distances.

iii) The component of current parallel to the coast, is approximately geostrophic.

iv) The wave velocity for each mode depends only on the shelf width and Coriolis parameter. Since the wave velocity does not depend on the frequency, the waves are non-dispersive.

v) Shelf waves of appreciable amplitude can occur only as a result of resonance. The conditions for resonance are found only on a sloping shelf.

vi) These very low frequency waves (with amplitudes of centimeters and wavelengths of megameters) progress parallel to the coast.

6.1.1. BAROMETRIC FACTOR

From hydrostatic considerations, the sea level is expected to be depressed by 1 cm for every 1 mb rise in atmospheric pressure (Kjerfve et al., 1978; Pugh, 1987). The observed inverse barometric (or "isostatic") factor (ratio of sea level change to atmospheric pressure change) is usually close to the theoretical value of -1.01 cm/mb. It is computed by linear regression from uncorrected sea level and atmospheric pressure. During earlier investigations along the Australian coast, Hamon (1962,1966) showed that the sea level did not respond isostatically to atmospheric pressure. He concluded that the barometric factor can show deviations with location. Hamon (1966) concluded that at some of the tropical stations of Australia, atmospheric pressure changes were small and the direct effect of pressure on sea level could normally be neglected. The sea level variance, however, was still appreciable. Another conclusion was that at stations where both the summer and winter series were examined, there was no obvious dependence of barometer factor on season. Kjerfve et al. (1978) observed that the pressure variation would be small compared to the sea level change and also that the mean pressure and sea level would fluctuate in the same manner, opposite to what could be expected, in the North Inlet, South Carolina. Hamon (1966), however, observed that a simple one to minus one correspondence between sea level pressure and sea level might not always be observed, because of factors such as coastal trapped waves which might contribute to the deviations from the hydrostatic approximation. Hamon (1966) found that changes in sea level follow changes in sea level pressure with upto 2 days lag. Recently, Woodworth et al. (1995) suggested that the forcing of sea level variability by means of atmospheric pressure changes, would not be applicable to a narrow band of the spectrum of approximately 5 days period in the Central South Atlantic.

Some variable that is well correlated with atmospheric pressure could lead to an apparently anomalous barometric factor. It would, therefore, be of interest to consider the combined effects of the necessary adjustments of the sea level and then study the residual for free waves.

6.1.2. AUTO AND CROSS-CORRELATION

Hamon (1966) concluded from his study that travelling continental shelf waves exist at all times on the east as well as west Australian coast. He also concluded that these travelling waves are probably energized by atmospheric pressure variations. Mooers and Smith (1968) reported that along the Oregon coast, Brookings lagged the northern stations (Coos Bay and Newport) by a fraction of a day, and also that the predominant period was apparently 6-8 days. A time lag of one day between sea levels at Sydney and Coff's harbour was noticed (Hamon, 1962). Osmer and Huyer (1978) observed that the sea level at Crescent City leads the sea level at Tofino (British Columbia, a distance of 820 km) by about a day. Huyer et al. (1975) reported that fluctuations in sea level are highly coherent over alongshore separations of a few hundred kilometers.

In view of the importance of propagation of these waves along the continental shelf, a study pertaining to this aspect was carried out to understand the pattern of wave movement along the Kerala coast. Being the location of the study, Cochin was considered as one centre while Beypore (on the Malabar coast, to the north of Cochin) was considered as the other. The results of the study are presented in this chapter.

6.2. MATERIALS AND METHODS

This investigation presents an analysis of simultaneous sea level records (with and without pressure corrections) collected from two locations on a straight coast, running north-northwest and south-southeast. The standard techniques of time series analysis have been used to find evidence of energy peaks at periods of several days (Jenkins and Watts, 1968; Chatfield, 1975; Emery and Thomson, 1998).

Hourly observations of water level at Cochin (9° 58'N; 76° 16'E) and Beypore (11° 10'N; 75° 48'E) from 0000 hours of 1 January, 1977 to 2300 hours of 31 December, 1977 were utilised in this study (Figs. 6.1 and 6.2). The important lunar phases are also indicated in each figure to appreciate their forcings on the tides.

Daily values were first obtained using a two-step filtering procedure. First, the dominant diurnal and semi-diurnal tidal components were removed from the quality controlled hourly values. Second, a 119 - point convolution filter (Bloomfield, 1976) centered on noon is applied to remove the remaining high frequency energy and to prevent aliasing when the data are computed to daily values (Fig. 6.3a). These daily data were matched with local atmospheric pressure (mean of 0830 and 1730 hrs) close to these sites (Fig. 6.3b). The overall mean for each time series has been subtracted in the figures. The corrected sea level (corrected for local atmospheric pressure) was obtained by adding the atmospheric pressure to the filtered daily sea level. This procedure partially corrects for the inverse barometer effect so that the remaining pressure fluctuations are primarily due to oceanic phenomena (Brown et al., 1985; Ramp et al., 1997). The need for this correction is highlighted in the section on barometric factor.

The data must, at the very least, be detrended by subtracting the straight line best-fit from the data segment leaving a modified time series (Osmer and Huyer, 1978, Stull, 1988). This is to avoid spurious frequencies (called red noise) that appear at the low frequency end of the spectrum. The water level and atmospheric pressure records were detrended and sine tapered (Stull, 1988). The mathematical procedure in respect of filtering, spectral and cross-spectral computations is given in Appendix III.

The study has envisaged the use of lag correlation (auto-correlation and cross-correlation) for the different parameters between Cochin and Beypore.

The results of the correlation analysis, as well as spectral and cross spectral analysis of the sea level, atmospheric pressure and corrected sea level time series are presented. To highlight the waves of our interest and see the differences between the contrasting seasons, the data were partitioned into two seasons namely summer monsoon and premonsoon (each of 90 days duration), for all aspects of the study.

The presence of a travelling wave might be expected to be readily revealed by cross correlation between the corrected sea level at both the stations, specifically by the maximum correlation occurring at some lagged time. Moreover, the time lags should be more readily observed between corrected sea levels, which do not contain the assumed isostatic response to local pressure (Hamon,1962). Usually maximum correlations are slightly higher, and lags more definite, for the corrected sea levels. Time lags between sea levels at adjacent ports imply the existence of time lags between sea level and atmospheric pressure, at least at some stations, because the pressures are nearly in phase.

6.3. RESULTS AND DISCUSSION

6.3.1. THE DATA

From the time series of hourly tidal heights presented in Figs 6.1 and 6.2, it is clear that the tidal range is larger at Beypore than at Cochin. Harmonic analysis of the hourly tidal heights was performed and the results are presented in Table 6.1.

The harmonic analysis also confirms that most of the constituents are slightly larger for Beypore compared to those of Cochin. The long period constituents (Sa, Ssa, Mf, Msf - Appendix-I) are usually small, and depend largely upon regional meteorological conditions during the time when the observations were made (Cheng and Gartner, 1985; Bell and Goring, 1998). From the amplitudes of Mm, Msf and Mf for Cochin and Beypore, we find that non-linear contribution of semi-diurnal tides is comparatively more at Beypore than at Cochin. The reasons for the same are discussed below.

At Cochin, the mean spring range was 55.1 cm and the mean neap range was 25.0 cm. At Beypore, the mean spring range was 76.3 cm and the mean neap range 35.9 cm. The Form Numbers indicated that the tide was mixed and predominantly semi-diurnal for both the stations having values of 0.92 for Cochin and 0.80 for Beypore. The meteorological residuals for Cochin and Beypore (Figs. 6.4 and 6.5) indicated that the residuals are more noisy at Beypore due to nonlinear influence from the shallow depth, interaction with Chaliyar river, irregular coastal geometry and bottom topography (the region off Beypore faces heavy siltation) on the tides. The periodic fluctuations (seen riding on the residuals) are caused by the ineffectiveness of the tidal predictions to resolve all the nonlinear harmonics in the tides. These fluctuations are particularly prominent during heavy discharge periods. The residuals for Cochin, however, did not reveal any such feature. In this regard, it is worth mentioning that the discharge into the Cochin backwater region is largely controlled by the hydel projects situated upstream of the rivers causing minimum riverine influence. In the case of Beypore, probably because of the absence of hydel projects upstream of the river Chaliyar, considerable riverine influence on the tidal heights near the mouth could be observed, particularly during summer monsoon months. The non-tidal circulation is heavily influenced by the highly variable river discharge at Beypore. Similar results have been reported elsewhere (Walters and Gartner, 1985; Stanton, 1995; Wang et al., 1997).

6.3.2. STATISTICS OF THE OBSERVED TIDE AND METEOROLOGICAL RESIDUALS

The frequency distributions of the hourly observed sea level and the hourly meteorological residuals at Cochin and Beypore are presented in Fig. 6.6. The skewness and kurtosis parameters were found to be negative for both Cochin and Beypore for the observed hourly data (Fig. 6.6a). The standard deviations of the hourly observed sea level were 21.7 cm and 28.9 cm for Cochin and Beypore, respectively. For the hourly meteorological residuals, the skewness was negative for Cochin and positive for Beypore whereas the kurtosis was positive but low at Cochin while at Beypore it was positive and high (Fig. 6.6b). The standard deviations of the meteorological residuals were 5.5 cm and 9.5 cm for Cochin and Beypore, respectively. Filtering the observed hourly heights for tides removed about 93.7% and 89.2% of the original variance (of Cochin and Beypore, respectively) showing that sea level variance is dominated mainly by tidal signals.

6.3.3. AUTO-CORRELATION

The autocorrelograms for Cochin and Beypore for the premonsoon and summer monsoon seasons in respect of daily sea level, atmospheric pressure and pressure corrected sea level are presented in Fig. 6.7. The autocorrelograms for Cochin and Beypore are : premonsoon observed sea level (Fig. 6.7a), summer monsoon observed sea level (Fig. 6.7b), premonsoon atmospheric pressure (Fig. 6.7c), summer monsoon atmospheric pressure (Fig. 6.7d), premonsoon corrected sea level (Fig. 6.7e) and summer monsoon corrected sea level (Fig. 6.7f).

There is clear evidence of the presence of a wave of about 9 to 10 day period in the observed sea level at Cochin and Beypore during premonsoon season (Fig. 6.7a). For the summer monsoon season, there is an indication of waves of 7 day period in the series for Cochin, and 4 day period in that of Beypore (Fig. 6.7b). The peaks are, however, not very prominent.

Waves of approximately 8 day period can be seen in the series of the atmospheric pressure at Cochin and Beypore during premonsoon season (Fig. 6.7c). The summer monsoon period, on the other hand, displayed periods of approximately 5 to 6 days (Fig. 6.7d). The peaks for both the seasons and at both the places are not marked. Cochin and Beypore showed strikingly similar autocorrelograms, for both the premonsoon and summer monsoon series.

With the application of the pressure corrections, the premonsoon series showed a marked peak at 9 day lag (Fig. 6.7e), which was sharper and more distinct than that in Fig. 6.7a. The summer monsoon series of corrected sea level also displayed a period of approximately 7 to 8 days at Cochin, and 5 days at Beypore (Fig. 6.7f). The peaks displayed for the corrected sea levels were more marked than those displayed for the observed sea levels (Fig. 6.7b).

6.3.4. CROSS-CORRELATION

The cross-correlograms between Cochin and Beypore for daily data are presented in Fig.6.8a for premonsoon sea level (observed and corrected), Fig.6.8b for summer monsoon sea level (observed and corrected) and Fig.6.8c for atmospheric pressure (premonsoon and summer monsoon).

From Fig. 6.8a, it is seen that the maximum cross-correlation occurs, slightly to the right of zero lag, which shows that Cochin leads Beypore, marginally. This is true for both observed and corrected sea levels. It is also seen that waves with a period of about 9 to 10 days are present in the premonsoon series. The correlogram is more or less symmetric with respect to lag 0.

From Fig. 6.8b, it is evident that Cochin marginally leads Beypore by about a day during the summer monsoon season for both the observed and corrected sea levels. It is also seen that the cross-correlogram is not symmetrical with respect to zero lag and also that Beypore may be leading Cochin at higher lags. The cross-correlograms for both the corrected and observed sea levels did not vary greatly as reported for the Australian coast by Hamon (1962).

Along the west coast of North America, the sea level fluctuations with periods of several days were reported to propagate northward in summer (Clarke, 1977; Wang and Mooers,1977) but southward in winter (Mooers and Smith, 1968).

The cross-correlograms of the atmospheric pressure time series for the premonsoon and summer monsoon seasons between Cochin and Beypore, show that the correlation is maximum at zero lag (Fig. 6.8c). The cross-correlograms are also symmetrical with respect to zero lag. The premonsoon period shows a weak 8 day period and the summer monsoon period shows a 5 day period. Elsewhere, Mooers and Smith (1968) also reported strong alongshore correlation of atmospheric pressures over 500 km station separation. Ramp et al. (1997) also reported the large coherence scales of the atmospheric pressure fields.

6.3.5. SPECTRAL AND CROSS-SPECTRAL ANALYSIS

The variances of the premonsoon and summer monsoon data sets in respect of observed sea level, pressure and pressure corrected sea levels are presented in Table 6.2. In addition, the percentage contribution of waves between 2 and 10 days to total variance, percentage contribution of waves less than 20 days cycle to total variance and the percentage contribution of the first eight important cycles to the total variance are also provided for the same data sets.

6.3.5.1. OBSERVED SEA LEVEL

The variance of the premonsoon data set for observed sea level is less than that of the summer monsoon data set, both at Cochin and Beypore (Table 6.2). Eventhough the variance during the summer monsoon period is slightly higher at Cochin, it is nearly six times more at Beypore.

The spectra of observed sea level for the premonsoon season are presented in Figs. 6.9a and 6.9b for Cochin and Beypore (Table 6.3). The cross-amplitude and phase spectra of observed sea level for the premonsoon season between Cochin and Beypore are presented in Figs. 6.9c and 6.9d (Table 6.4).

The spectra of observed sea level for the summer monsoon season are presented in Figs. 6.10a and 6.10b for Cochin and Beypore (Table 6.3). The cross-amplitude and phase spectra of observed sea level for the summer monsoon season between Cochin and Beypore are presented in Figs. 6.10c and 6.10d (Table 6.4).

The energy spectra of the subtidal sea level are almost red. The phases are, in general, slightly positive, indicating that Cochin leads Beypore for the premonsoon season. For the summer monsoon season such a clear picture is not seen.

6.3.5.2. ATMOSPHERIC PRESSURE

The premonsoon time series of the atmospheric pressure shows variance which is marginally less than that of the summer monsoon time series, both at Cochin and Beypore (Table 6.2).

The spectra of atmospheric pressure for the premonsoon season at Cochin and Beypore are presented in Fig. 6.11a and that for the summer monsoon season in Fig. 6.11b (Table 6.3). During the summer monsoon season, the spectrum is dominated by 45 day waves, whereas during premonsoon season, 22.5 day waves are prominent. The cross-amplitude spectra of atmospheric pressure between Cochin and Beypore for the premonsoon and summer monsoon seasons are presented in Fig. 6.11c and that for the phase spectra in Fig. 6.11d (Table 6.4). The phase values, in general, indicate a marginal lead at Cochin during the premonsoon season, and a marginal lead by Beypore for the summer monsoon season.

6.3.5.3. CORRECTED SEA LEVEL

The variance of corrected sea level time series during the premonsoon period, is marginally less than that for the summer monsoon at Cochin, whereas the summer monsoon time series shows a variance roughly six times that of the premonsoon period at Beypore (Table 6.2).

The premonsoon series of the observed sea level at Cochin and Beypore show a marginally smaller variance than of the corrected sea level series. On the other hand, during the summer monsoon season, the observed sea level series shows a marginally higher variance than that of the corrected sea level series. Castro and Lee (1995) also reported that the atmospheric pressure adjustment process did not significantly change the variance of the original sea level time series.

The spectra of corrected sea level for the premonsoon season are presented in Figs. 6.9a and 6.9b for Cochin and Beypore (Table 6.3). The cross-amplitude and phase spectra of corrected sea level for the premonsoon season between Cochin and Beypore are presented in Fig. 6.9c and 6.9d (Table 6.4).

The spectra of corrected sea level for the summer monsoon season are presented in Figs. 6.10a and 6.10b for Cochin and Beypore. The cross-amplitude and phase spectra of corrected sea level for the summer monsoon season between Cochin and Beypore are presented in Figs. 6.10c and 6.10d, respectively.

The spectra of the observed sea level and that of the corrected sea level do not vary much. If atmospheric pressure is the main excitation and this excitation is to be transmitted hydrostatically, the observed and pressure corrected sea level spectra would have differed to a greater extent. This suggests that the atmospheric pressure is not an important controlling factor on sea level at the two sites.

The energy spectra of the pressure corrected subtidal sea level are almost red. The phase values are, in general, positive indicating that Cochin leads Beypore during the premonsoon season, whereas during the summer monsoon season, such a clear picture is not seen.

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

The coherence (from cross-spectra) is strong at periods greater than 10 days. Changes in sea level at these periods may be due to the presence of coastally trapped shelf waves, the wavelength of which is of the order of hundreds of kilometers. At shorter periods, the sea level records are found to be much less coherent with the independent oscillations driven by local meteorological and hydrological forcing (Goodrich, 1988).

The lead-lag relationship in the sea level time series between Cochin and Beypore, would be consistent with Ekman transport normal to the coast from wind fields (spatially coherent along the coast), combined with a shorter response time in the much shallower waters off Beypore than off Cochin. Longer time series would clearly bring to light such responses. Similar results have been reported elsewhere (Arief and Murray, 1996; Greenberg et al., 1997).

Meteorological forcing in shelf and estuarine waters provide a relatively important supplement to tidal processes. Estuary-shelf exchanges can be tidal or non-tidal in nature, and this distinction is important. Semi-diurnal and diurnal tidal exchanges are continuous and predictable as they are periodic. Hence, they constitute a reliable baseline for flushing. In regions with low tidal ranges and strong winds, energy density spectra (computed from time series of water level or current data) may exhibit dominant concentrations of energy at subtidal frequencies. Variability over time scales of the order of several days is generally attributed to meteorological forcing (Smith, 1977; Smith, 1979; Lee et al., 1990; Geyer, 1997).

6.4. CONCLUSIONS

1. The harmonic analysis of hourly data on tidal heights indicates that the tidal amplitudes are larger at Beypore than at Cochin. The Form Numbers indicate that the tide is mixed, predominantly semi-diurnal both at Cochin and Beypore. The meteorological residuals at Beypore were noisy because of several nonlinear influences, compared to those at Cochin.

2. Analysis of sea level and corrected sea level records for premonsoon and summer monsoon seasons, indicate that wave phenomena are present during both the seasons at Cochin and Beypore. Similar wave phenomena are also noticed in the atmospheric pressure at both the stations. The wave phenomenon is seen to be distinct in the premonsoon series of observed sea level and corrected sea level, whereas for the atmospheric pressure series, it appears to be sharper during the summer monsoon season.

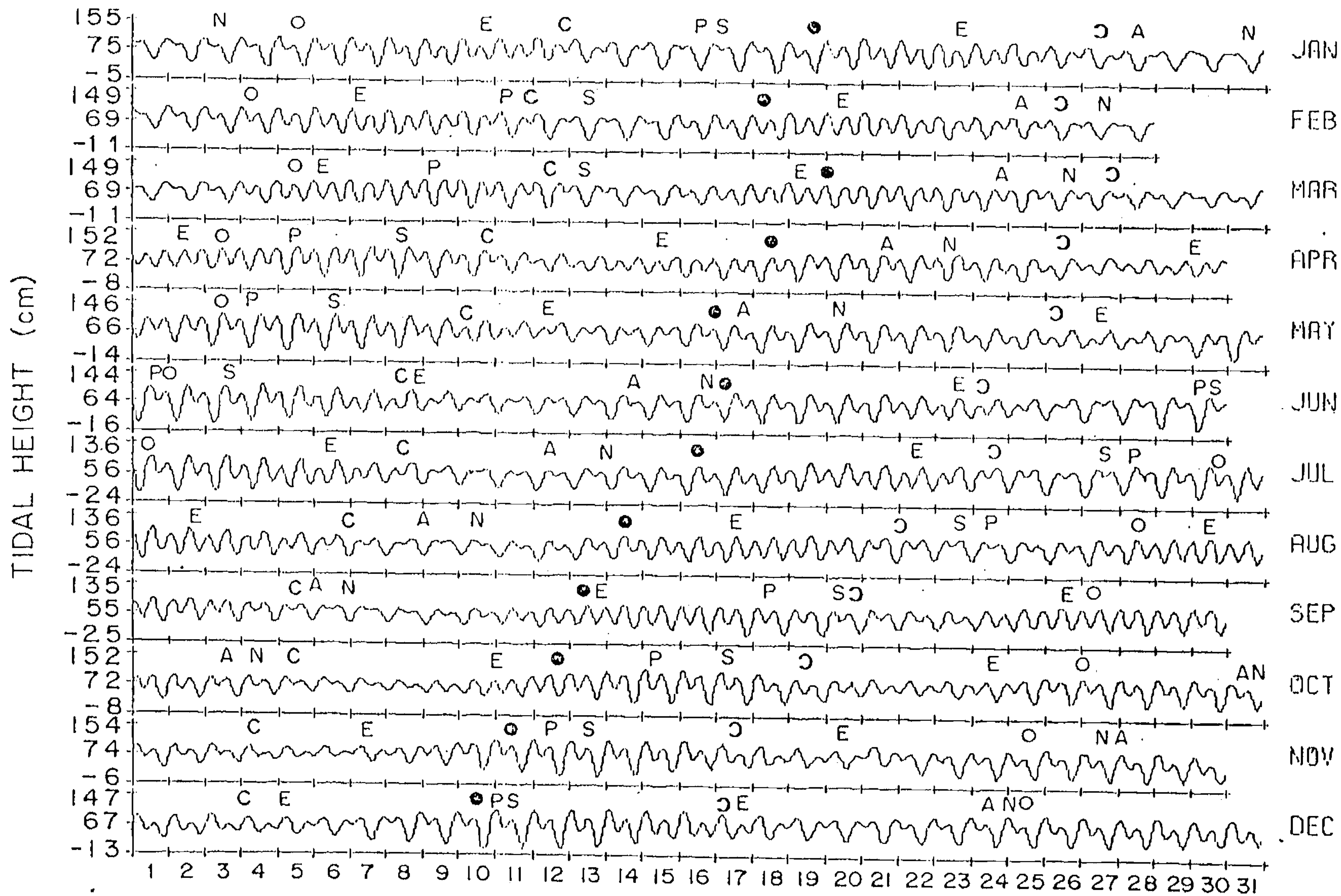
3. The cross-correlograms indicate that Cochin marginally leads Beypore for the observed as well as corrected sea level during the premonsoon as well as summer monsoon seasons. The cross-correlograms do not vary greatly for the observed and corrected series during both the seasons. The spectra of the atmospheric pressure are more or less of synchronous nature for both the seasons.

4. The spectra of observed and corrected sea level show reasonable agreement for most of the frequencies both at Cochin and Beypore, during both the seasons. The hydrostatic sea level response to high frequency atmospheric pressure fluctuations appears to be of minor importance. The energy spectra of the observed sea level and pressure corrected sea level are almost red, signifying the importance of higher period waves.

5. During the premonsoon season, the observed as also corrected sea level at Cochin leads that at Beypore for the most important frequencies (based on the cross spectral analysis). In the case of observed and corrected sea levels during the summer monsoon season, eventhough the important periods (again based on cross spectral analysis) show that Cochin leads Beypore, the phases are much more than those for the premonsoon season. This perhaps could be due to the fact that the Beypore sea levels are under the strong influence of freshwater discharges from the Chaliyar river during the summer monsoon season.

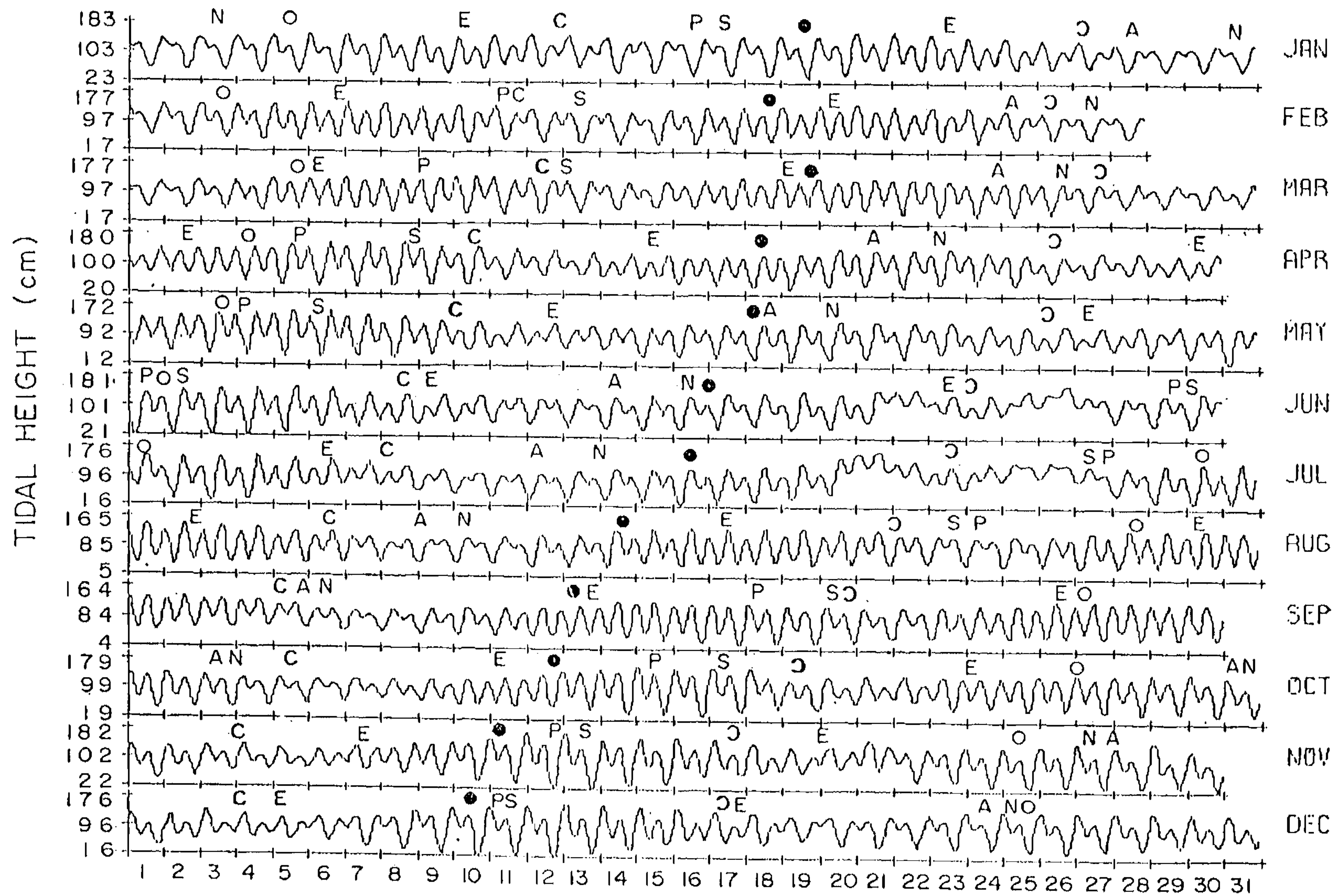
6. The premonsoon and summer monsoon series of atmospheric pressure, when subjected to the cross spectral analysis, show that the lag between Cochin and Beypore is very less. The spectra of the individual time series are also very similar for Cochin and Beypore during both the seasons. This, probably, can be attributed to the fact that the entire region comes under the influence of the same meteorological systems.

7. In general, it appears that northward propagation of coastal trapped waves occurs during premonsoon season. However, during summer monsoon season, this phenomenon is not clear.



P = PERIGEE ; A = Apogee ; ● = NEW MOON ; Ɔ = First Quarter ; O = FULL MOON ; C = Last Quarter ; E = Moon on Equator ; N = MAXIMUM NORTH DECLINATION ; S = MAXIMUM SOUTH DECLINATION ; Lunar phenomena having a superior effect on tides are printed in CAPITALS.

Fig. 6·1 . Observed hourly tidal heights at Cochin during 1977.



P = PERIGEE ; **A** = Apogee ; ● = NEW MOON ; Ↄ = First Quarter ; **O** = FULL MOON ; **C** = Last Quarter ; **E** = Moon on Equator ; **N** = MAXIMUM NORTH DECLINATION ; **S** = MAXIMUM SOUTH DECLINATION ; Lunar phenomena having a superior effect on tides are printed in CAPITALS.

Fig. 6·2 . Observed hourly tidal heights at Beypore during 1977.

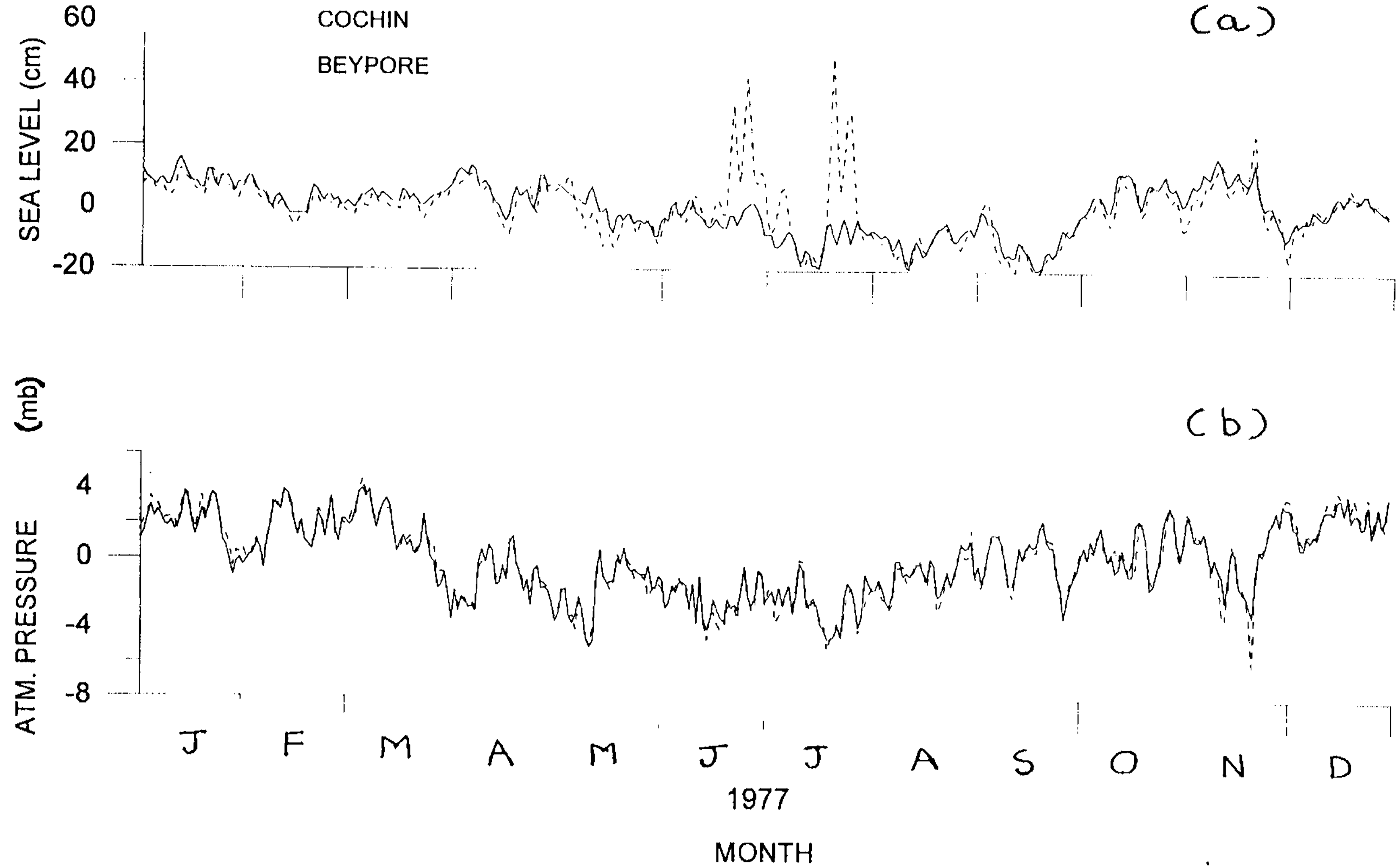


Fig. 6.3. Daily average of (a) sea level and (b) atmospheric pressure at Cochin and Beypore during 1977.

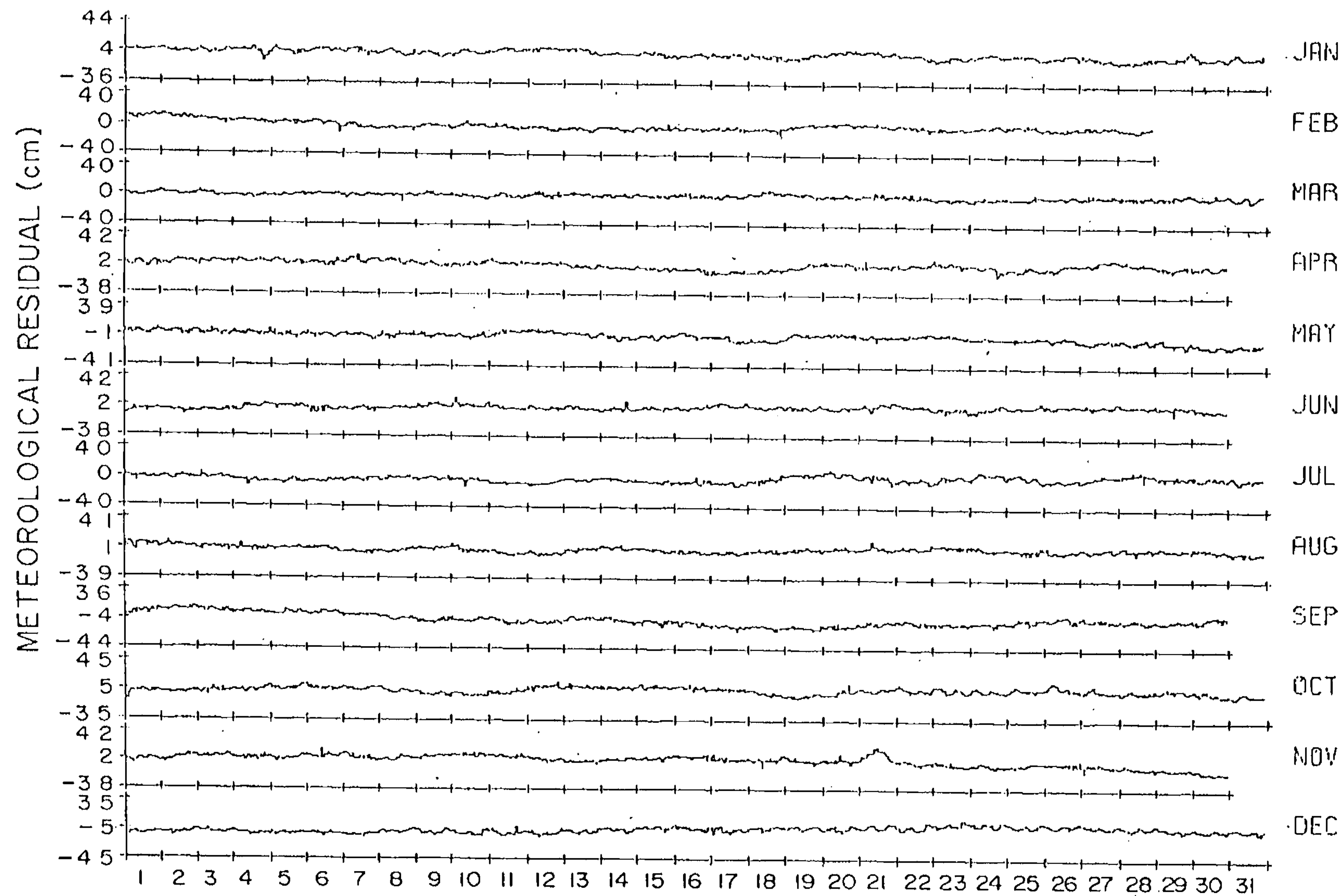


Fig. 6·4 . Hourly meteorological residuals at Cochin during 1977.

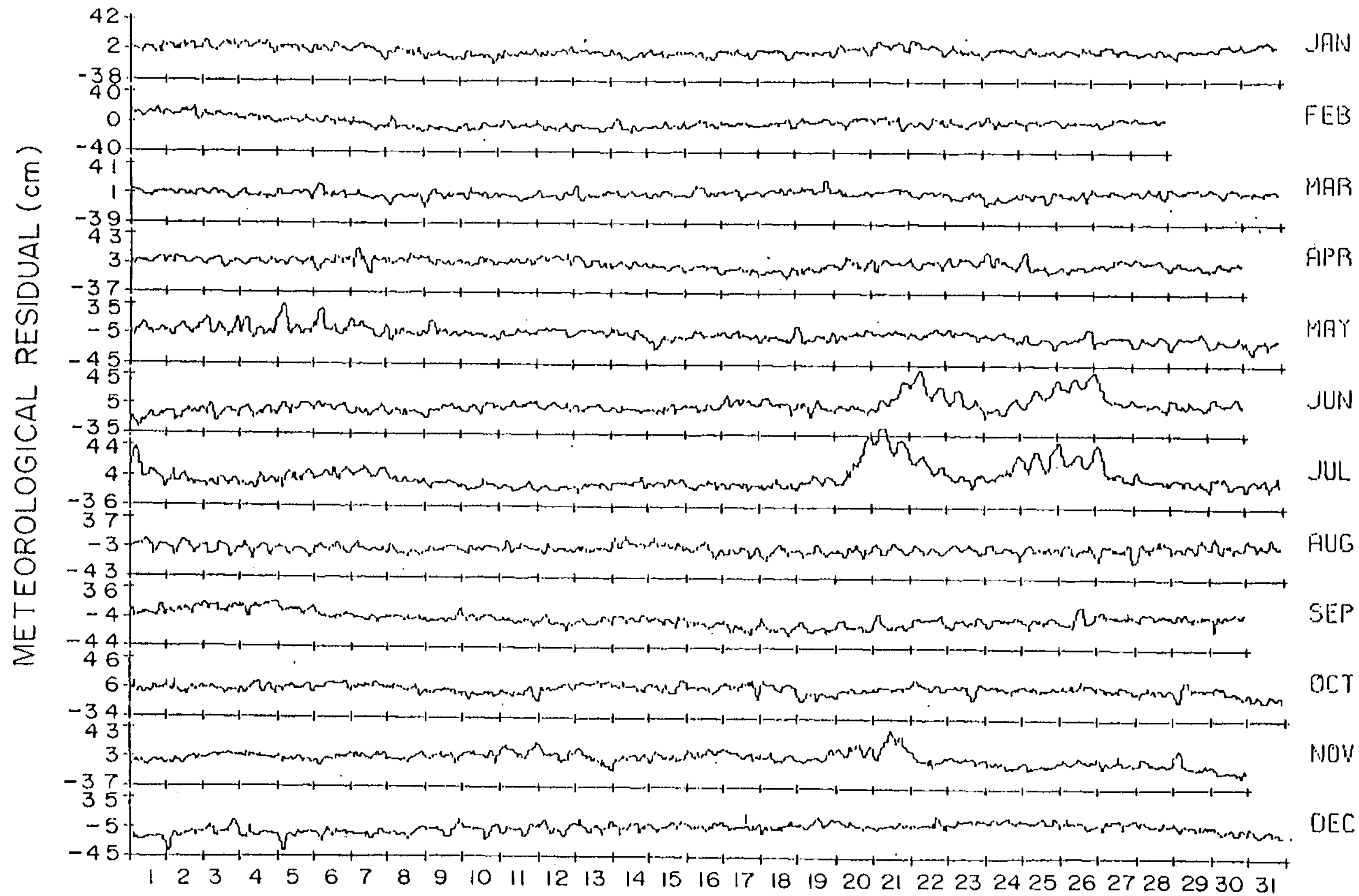


Fig. 6·5 . Hourly meteorological residuals at Beypore during 1977.

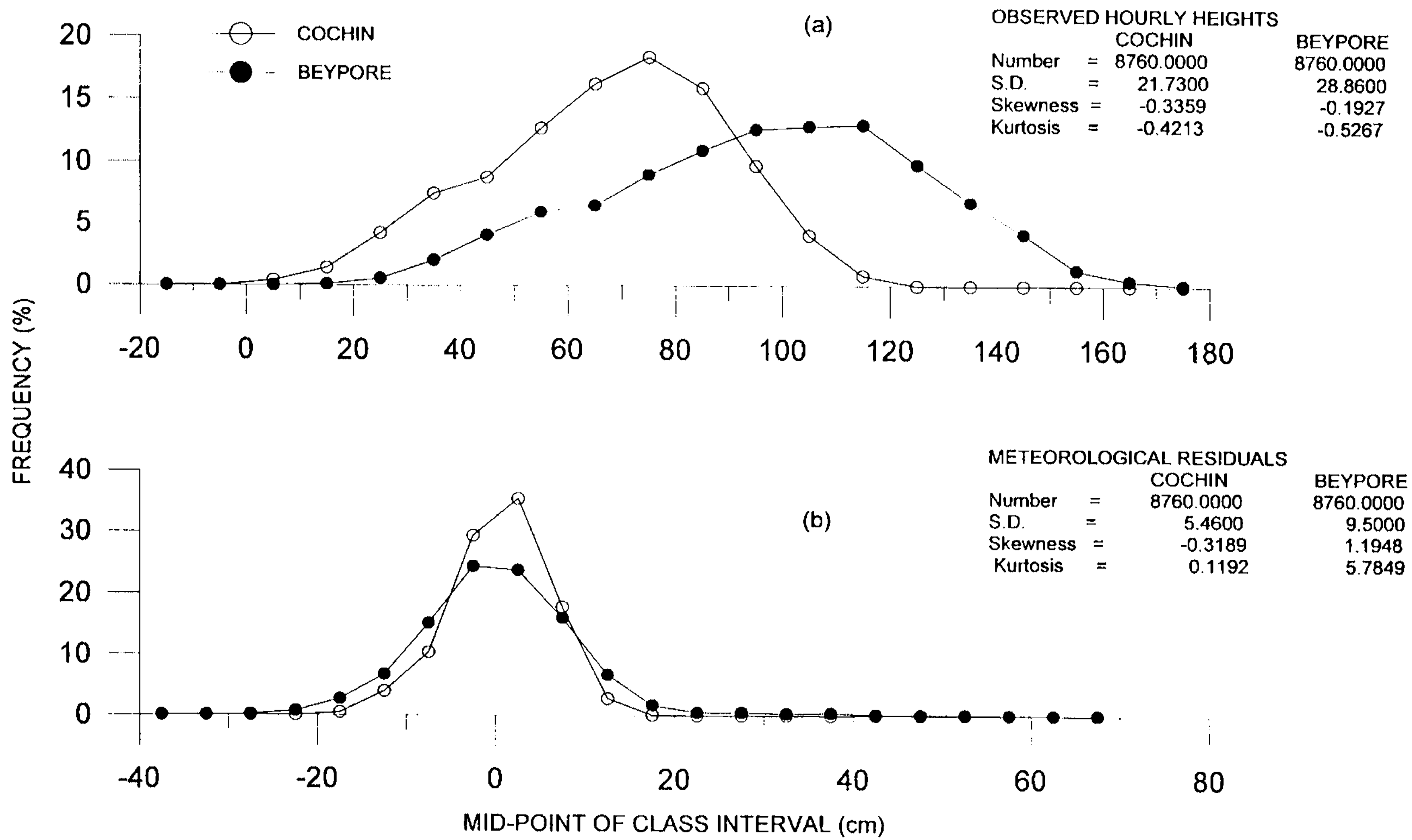


Fig. 6.6. Frequency distributions of hourly (a) observed tidal heights and (b) meteorological residuals at Cochin and Beypore during 1977.

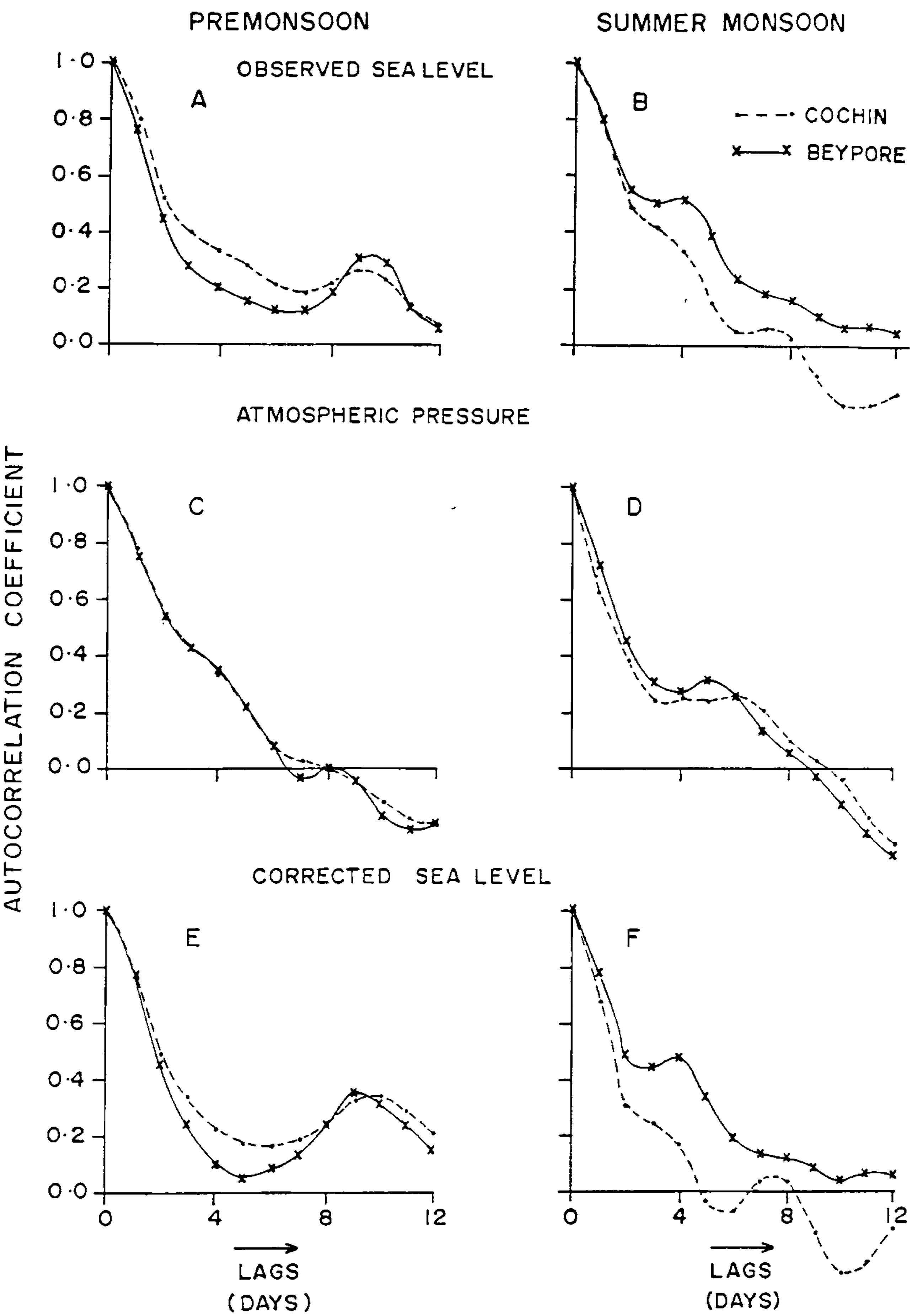


Fig. 6.7. Autocorrelograms for Cochin and Beypore for daily data on :- (a) premonsoon observed sea level; (b) summer monsoon observed sea level; (c) premonsoon atmospheric pressure; (d) summer monsoon atmospheric pressure; (e) premonsoon corrected sea level; (f) summer

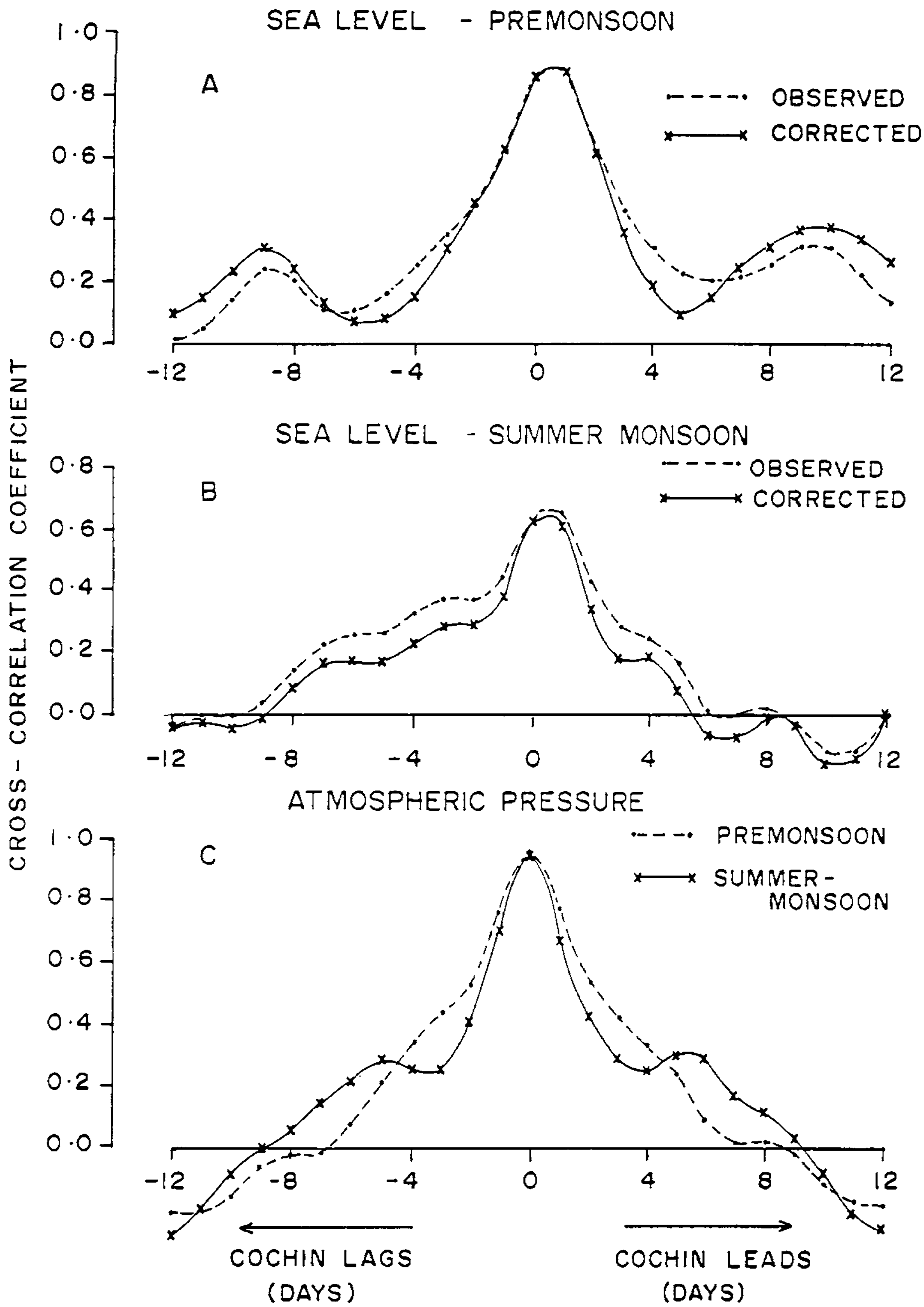


Fig. 6.8. Cross-correlograms between Cochin and Beypore for daily data on :- (a) premonsoon sea level (observed and corrected); (b) summer monsoon sea level (observed and corrected); (c) atmospheric pressure (premonsoon and summer monsoon).

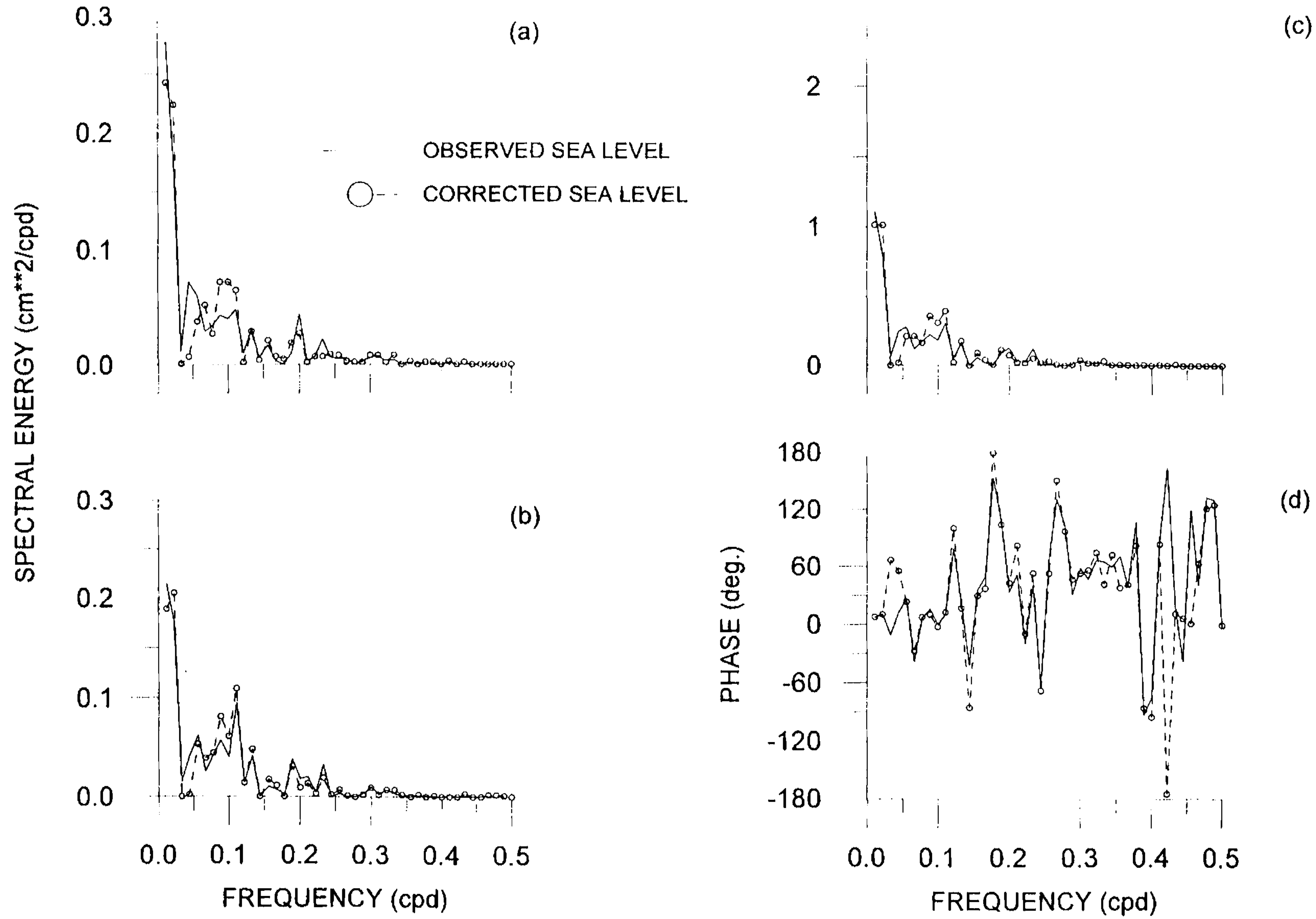


Fig. 6.9. Spectra of sea level (observed and corrected) during premonsoon at (a) Cochin and (b) Beypore. Cross-spectrum of sea level (observed and corrected) during premonsoon between Cochin and Beypore: (c) cross-amplitude spectrum and (d) phase spectrum.

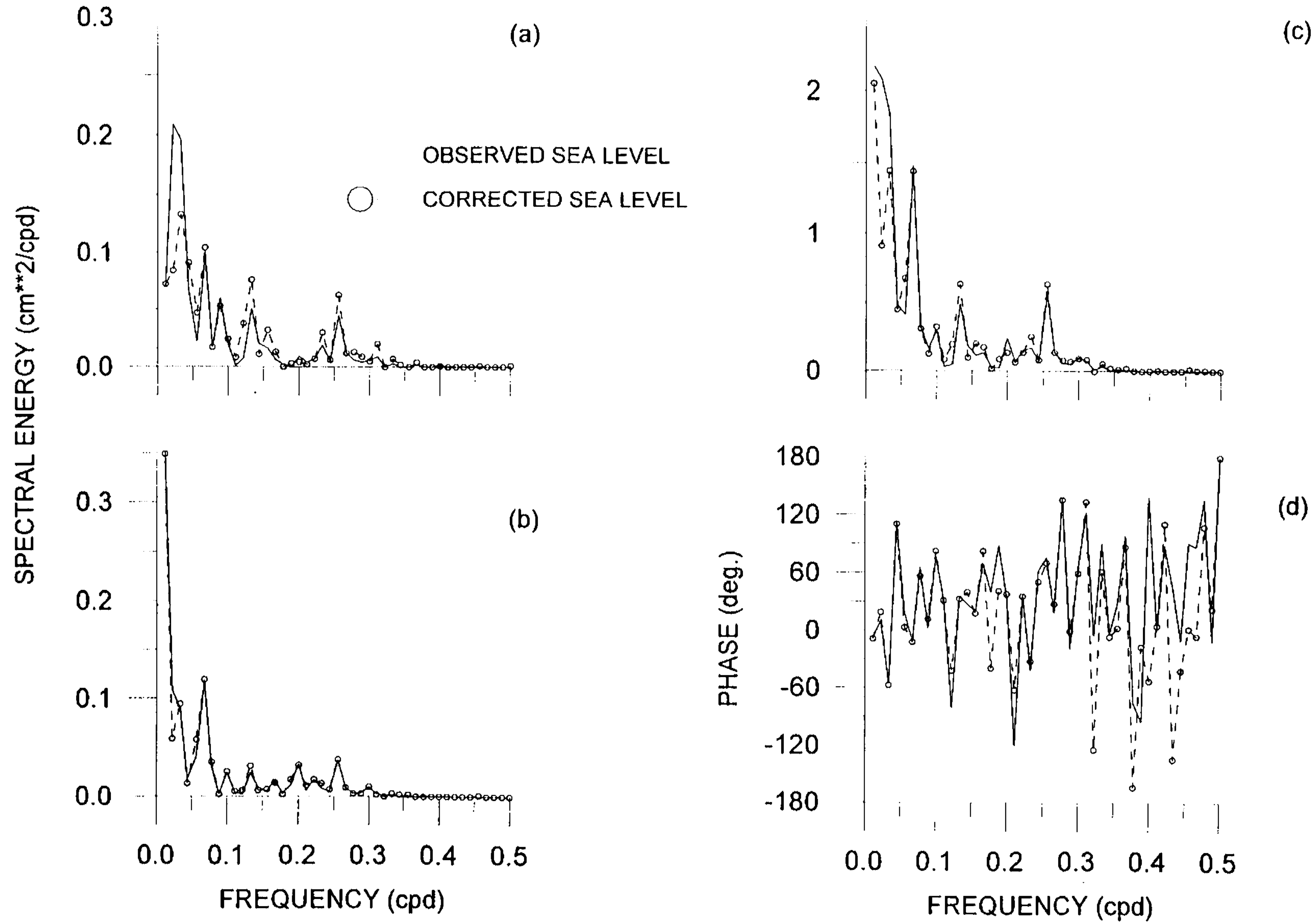


Fig. 6.10. Spectra of sea level (observed and corrected) during summer monsoon at (a) Cochin and (b) Beypore. Cross-spectrum of sea level (observed and corrected) during summer monsoon between Cochin and Beypore: (c) cross-amplitude spectrum and (d) phase spectrum

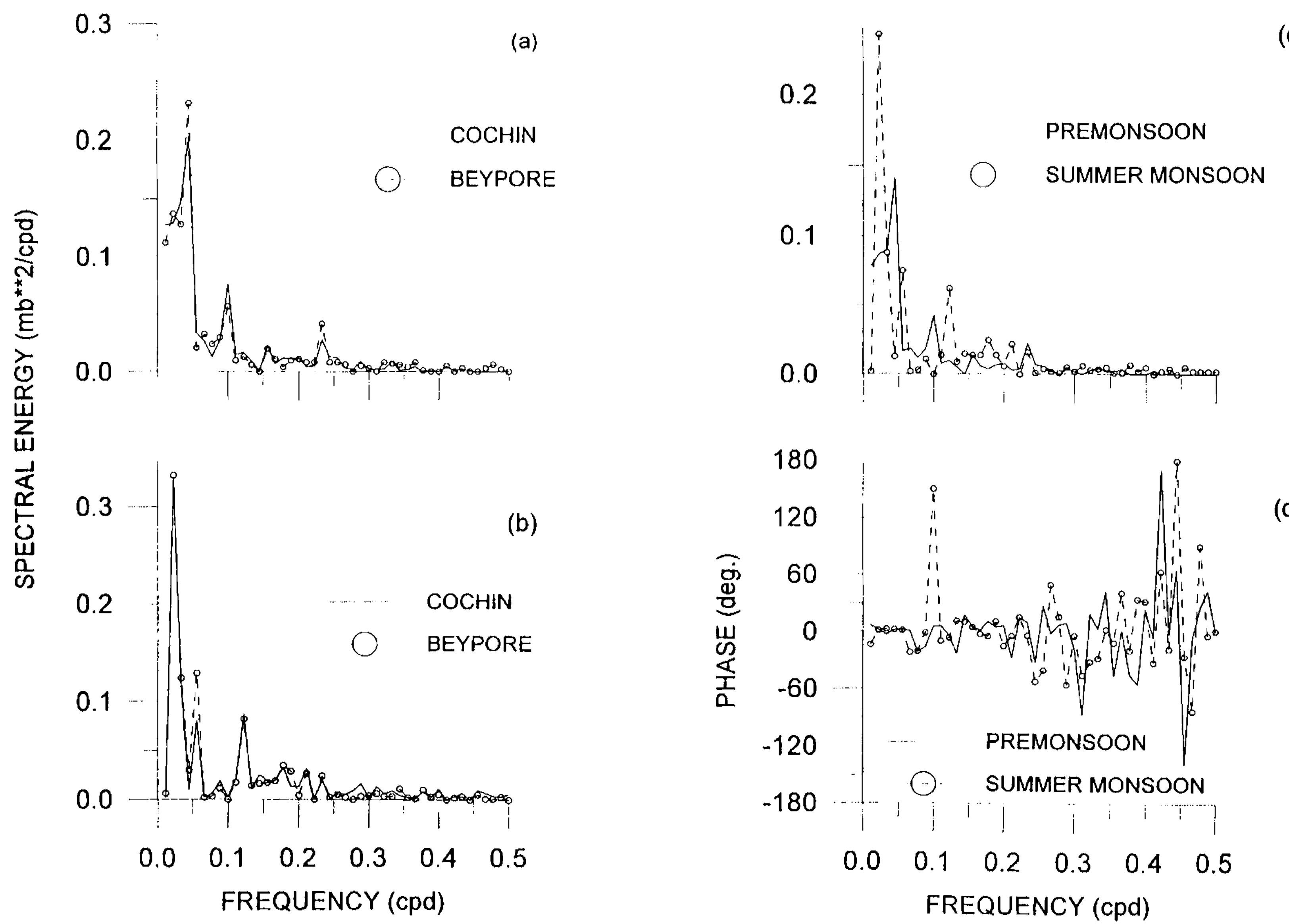


Fig. 6.11. Spectra of atmospheric pressure during: (a) premonsoon at Cochin and Beypore (b) summer monsoon at Cochin and Beypore. Cross-spectrum of atmospheric pressure between Cochin and Beypore: (c) Cross-amplitude spectrum for premonsoon and summer monsoon (d) phase spectrum for premonsoon and summer monsoon.

Table 6.1. Amplitude and phase of the 67 harmonic tidal constituents at Cochin and Beypore for the year - 1977. Z0 is the mean sea level

CONSTITUENT	FREQUENCY (cph)	COCHIN AMPLITUDE (cm)	COCHIN PHASE (deg.)	BEYPORE AMPLITUDE (cm)	BEYPORE PHASE (deg.)
1 Z0	.00000000	66.3611	00.00	95.9668	00.00
2 SA	.00011407	7.6042	23.91	4.4090	36.46
3 SSA	.00022816	3.8452	91.04	3.5351	151.03
4 MSM	.00130978	1.5674	21.29	1.5241	295.78
5 MM	.00151215	1.3690	25.55	3.4185	350.73
6 MSF	.00282193	0.4220	174.35	1.5463	171.61
7 MF	.00305009	1.2402	57.01	2.3442	60.36
8 ALP1	.03439657	0.0607	322.76	0.1184	22.39
9 2Q1	.03570635	0.3525	46.58	0.3718	38.87
10 SIG1	.03590872	0.2200	57.17	0.6601	39.91
11 Q1	.03721850	2.2245	74.46	1.9761	72.19
12 RHO1	.03742087	0.4532	101.89	0.4739	37.27
13 O1	.03873065	8.7552	69.61	10.0544	59.34
14 TAU1	.03895881	0.2778	139.23	0.0333	139.78
15 BET1	.04004044	0.0599	211.15	0.6036	18.24
16 NO1	.04026860	1.5432	297.25	0.2221	214.07
17 CHI1	.04047097	0.2389	15.79	0.5977	322.27
18 PI1	.04143851	0.1822	37.31	1.0149	55.41
19 P1	.04155259	4.5441	61.09	5.3678	62.62
20 S1	.04166667	0.9546	35.12	2.9597	52.85
21 K1	.04178075	16.5641	63.08	20.3245	62.48
22 PSI1	.04189482	0.5366	104.17	0.0555	19.17
23 PHI1	.04200891	0.5023	75.80	0.4845	82.76
24 THE1	.04309053	0.2051	26.90	0.5377	119.93
25 J1	.04329290	1.0287	83.23	1.0057	97.39
26 SO1	.04460268	0.2046	105.76	0.2867	176.81
27 OO1	.04483084	0.4585	120.26	0.5342	124.43
28 UPS1	.04634299	0.2493	213.93	0.4267	117.16
29 OQ2	.07597495	0.1273	173.20	0.3801	129.66
30 EPS2	.07617731	0.0590	268.81	0.2302	351.34
31 2N2	.07748710	0.7144	264.59	0.9544	239.67
32 MU2	.07768947	0.2879	263.06	0.0800	5.30
33 N2	.07899925	4.3321	317.80	5.4741	311.85
34 NU2	.07920162	0.7979	325.51	1.5557	293.90

Contd..

Table 6.1 (continued)

CONSTITUENT	FREQUENCY (cph)	COCHIN AMPLITUDE (cm)	COCHIN PHASE (deg.)	BEYPORE AMPLITUDE (cm)	BEYPORE PHASE (deg.)
35 H1	.08039733	0.2517	343.97	1.8812	181.50
36 M2	.08051140	20.0336	345.60	28.0495	339.69
37 H2	.08062547	0.2650	112.22	1.0379	207.01
38 MKS2	.08073956	0.0697	103.52	1.3246	359.32
39 LDA2	.08182118	0.3483	24.40	0.3461	23.09
40 L2	.08202355	0.6917	14.25	1.1764	332.97
41 T2	.08321926	0.4524	65.48	1.6321	60.10
42 S2	.08333334	7.5078	43.85	10.0997	36.66
43 R2	.08344740	0.1532	37.61	1.1479	45.36
44 K2	.08356149	1.7574	46.39	2.4902	39.86
45 MSN2	.08484548	0.0802	296.27	0.4675	186.87
46 ETA2	.08507364	0.1354	94.30	0.2197	251.44
47 MO3	.11924210	0.0603	112.27	0.9151	32.77
48 M3	.12076710	0.1819	209.44	0.4066	212.54
49 SO3	.12206400	0.3715	187.22	0.5043	71.19
50 MK3	.12229210	0.3492	213.01	0.7416	44.89
51 SK3	.12511410	0.0429	276.81	0.2888	86.66
52 MN4	.15951060	0.2286	53.34	0.1441	35.13
53 M4	.16102280	0.6662	118.18	0.2314	48.08
54 SN4	.16233260	0.0406	93.61	0.1287	292.95
55 MS4	.16384470	0.5655	179.49	0.1240	142.52
56 MK4	.16407290	0.0897	357.51	0.1550	38.95
57 S4	.16666670	0.1344	220.15	0.1927	237.27
58 SK4	.16689480	0.0544	83.50	0.1111	105.48
59 2MK5	.20280360	0.2754	145.93	0.2955	40.74
60 2SK5	.20844740	0.0526	212.23	0.0123	340.04
61 2MN6	.24002200	0.1069	26.56	0.2314	315.81
62 M6	.24153420	0.1825	86.00	0.2683	329.40
63 2MS6	.24435610	0.4017	206.04	0.1974	324.54
64 2MK6	.24458430	0.1207	201.44	0.1353	327.75
65 2SM6	.24717810	0.1083	289.66	0.1484	36.62
66 MSK6	.24740620	0.0390	289.57	0.0470	171.34
67 3MK7	.28331490	0.0091	261.65	0.0991	253.80
68 M8	.32204560	0.1162	16.68	0.0862	178.35

Table 6.2. Percentage contribution of some of the cycles to the total variance.

PARAMETER	STATION	A	B	C	D
		PREMONSOON			
OBSERVED SEA LEVEL	COCHIN	6.3	46.1	76.1	8.7
	BEYPORE	17.8	55.3	72.9	7.9
ATMOSPHERIC PRESSURE	COCHIN	29.2	39.5	77.3	1.4
	BEYPORE	28.5	39.2	77.0	1.2
CORRECTED SEA LEVEL	COCHIN	33.4	52.3	79.6	9.1
	BEYPORE	38.6	60.4	79.0	9.9

PARAMETER	STATION	A	B	C	D
		SUMMER MONSOON			
OBSERVED SEA LEVEL	COCHIN	26.1	45.9	79.6	13.2
	BEYPORE	24.1	43.1	80.8	58.3
ATMOSPHERIC PRESSURE	COCHIN	43.6	54.4	72.6	1.5
	BEYPORE	36.3	50.8	78.8	1.4
CORRECTED SEA LEVEL	COCHIN	39.9	62.0	67.6	11.8
	BEYPORE	27.1	48.4	78.5	56.8

A - Percentage contribution of waves between 2 and 10 days to the total variance

B - Percentage contribution of waves less than 20 days to the total variance

C - Percentage contribution of the first eight predominant cycles to the total variance

D - Variance (cm^2 - for sea level, mb^2 - for atmospheric pressure)

Table 6.3. The percentage contribution of the first eight predominant cycles to the total variance in respect of observed sea level, atmospheric pressure and corrected sea level during premonsoon and summer monsoon seasons.

OBSERVED SEA LEVEL

SEASON	STATION		1	2	3	4	5	6	7	8
PRE	COCHIN	(P)	90.0	45.0	22.5	18.0	9.0	5.0	11.3	10.0
		(E)	27.8	17.6	7.2	6.0	4.8	4.4	4.3	4.0
PRE	BEYPORE	(P)	90.0	45.0	9.0	18.0	11.3	12.9	7.5	22.5
		(E)	21.5	17.6	9.5	6.2	5.7	4.2	4.1	4.1
SUM	COCHIN	(P)	45.0	30.0	15.0	90.0	22.5	11.3	7.5	3.9
		(E)	20.9	19.6	9.8	7.0	6.7	6.0	5.1	4.5
SUM	BEYPORE	(P)	90.0	15.0	45.0	30.0	18.0	3.9	5.0	12.9
		(E)	35.2	11.7	10.8	9.0	4.0	3.7	3.3	3.1

ATMOSPHERIC PRESSURE

SEASON	STATION		1	2	3	4	5	6	7	8
PRE	COCHIN	(P)	22.5	30.0	45.0	90.0	10.0	18.0	11.3	4.3
		(E)	20.3	14.7	12.9	12.7	7.6	3.4	2.9	2.5
PRE	BEYPORE	(P)	22.5	45.0	30.0	90.0	10.0	4.3	15.0	11.3
		(E)	23.1	13.7	12.8	11.2	5.7	4.2	3.3	3.0
SUM	COCHIN	(P)	45.0	30.0	8.2	18.0	5.6	4.7	6.9	9.0
		(E)	33.0	11.5	8.8	8.1	3.4	3.2	2.5	2.1
SUM	BEYPORE	(P)	45.0	18.0	30.0	8.2	5.6	22.5	5.3	4.7
		(E)	33.2	12.9	12.4	8.2	3.5	3.0	2.9	2.7

CORRECTED SEA LEVEL

SEASON	STATION		1	2	3	4	5	6	7	8
PRE	COCHIN	(P)	90.0	45.0	11.3	10.0	9.0	15.0	18.0	7.5
		(E)	24.4	22.4	7.2	7.2	6.5	5.2	3.8	2.9
PRE	BEYPORE	(P)	45.0	90.0	9.0	11.3	10.0	18.0	7.5	12.9
		(E)	20.5	18.9	10.9	8.1	6.1	5.3	4.8	4.4
SUM	COCHIN	(P)	30.0	15.0	22.5	45.0	7.5	90.0	3.9	11.3
		(E)	13.3	10.4	9.1	8.4	7.6	7.2	6.3	5.3
SUM	BEYPORE	(P)	90.0	15.0	30.0	45.0	18.0	3.9	12.9	5.0
		(E)	35.0	11.9	9.4	5.9	5.8	3.8	3.5	3.2

P - Period in days
E - Energy (in percentage contribution to the total variance)
PRE - Premonsoon season
SUM - Summer monsoon season

Table 6.4. Details of the first eight predominant cycles in the cross-spectrum in respect of observed sea level, atmospheric pressure and corrected sea level during premonsoon and summer monsoon seasons.

OBSERVED SEA LEVEL

SEASON	DETAILS	1	2	3	4	5	6	7	8
PRE	(ENERGY)	25.2	18.1	7.0	6.3	5.6	5.1	4.1	3.9
	(PERIOD)	90.0	45.0	9.0	18.0	22.5	11.3	10.0	12.9
	(PHASE)	7.0	10.6	10.0	26.6	12.2	16.0	0.0	6.4
SUM	(ENERGY)	17.9	17.1	15.1	12.2	4.6	4.0	4.0	3.4
	(PERIOD)	90.0	45.0	30.0	15.0	3.9	7.5	22.5	18.0
	(PHASE)	-8.1	10.1	-56.2	-11.0	76.1	35.7	112.7	18.5

ATMOSPHERIC PRESSURE

SEASON	DETAILS	1	2	3	4	5	6	7	8
PRE	(ENERGY)	22.0	13.9	13.5	12.1	6.7	3.5	3.0	3.0
	(PERIOD)	22.5	30.0	45.0	90.0	10.0	4.3	15.0	11.3
	(PHASE)	2.0	-3.2	2.0	6.5	4.8	9.3	1.0	-16.4
SUM	(ENERGY)	33.9	12.2	10.5	8.7	3.5	3.0	2.2	2.0
	(PERIOD)	45.0	30.0	18.0	8.2	5.6	4.7	4.3	6.9
	(PHASE)	1.5	2.9	1.5	-7.0	-5.5	-5.4	-4.8	9.8

CORRECTED SEA LEVEL

SEASON	DETAILS	1	2	3	4	5	6	7	8
PRE	(ENERGY)	22.1	22.0	8.6	7.8	6.8	4.6	4.6	3.9
	(PERIOD)	90.0	45.0	9.0	11.3	10.0	15.0	18.0	7.5
	(PHASE)	7.6	10.4	12.5	10.0	-2.4	-27.5	23.5	16.8
SUM	(ENERGY)	18.3	12.9	12.9	8.2	6.0	5.7	5.6	4.0
	(PERIOD)	90.0	30.0	15.0	45.0	18.0	3.9	7.5	22.5
	(PHASE)	-8.9	-57.6	-12.5	18.7	2.8	70.1	32.7	110.0

ENERGY - Energy in the cross-spectrum (based on the contribution of the cycle to the total sum)
PERIOD - Period in days
PHASE - Phase in degrees (positive value indicates lead by Cochin series)
PRE - Premonsoon season
SUM - Summer monsoon season

CHAPTER 7

CHAPTER 7

SUMMARY, CONCLUSIONS, LIMITATIONS AND RECOMMENDATIONS OF THE PRESENT STUDY

7.1. SUMMARY AND CONCLUSIONS

Sea level in a port area is an important consideration in the management of port traffic. Its abnormal deviation will drastically affect the operations at the port. Further, together with the other associated surface meteorological and oceanographic parameters like rainfall, sea surface temperature, air temperature, atmospheric pressure, winds, density of sea water, currents, etc., it has considerable implications on the eco-system. With these aspects in view, the study concerning the variability in sea level together with the associated oceanographic and surface meteorological parameters was undertaken for Cochin, which is important as a port and also as an estuarine ecosystem on the southwest coast of India. The important conclusions of the study are given below.

Tides are an important form of sea level variation. Harmonic analysis of the hourly sea level data was carried out to determine the harmonic tidal constituents (amplitudes and phases of 67 constituents) for Cochin. The M_2 constituent showed the maximum amplitude, followed by K_1, O_1, S_a, S_2, P_1, N_2, S_{sa}, Q_1 and K_2. The amplitudes of the constituents M_2, S_2, N_2, K_2, K_1, O_1 and P_1 were found to manifest small variability over the 1988-1993 period. The amplitudes of most of the other components, particularly shallow water ones, showed higher degree of variability for the same period. The analysis revealed that based on the Form Number, the observed tide is of a mixed but predominantly semi-diurnal type. The diurnal contribution was higher during June and December, and semi-diurnal contribution was higher during March and September, mainly due to sun's movements. The tides showed large spring-neap variation and also large monthly variation in the semi-diurnal forcing. The tidal constituents K_1 and S_2 were found to be responsible for the seasonal cycle of tides at Cochin.

The seasonal march of the sea level and some of the surface meteorological and oceanographic parameters (that are known to drive the sea level) at Cochin was studied. The three types of sea level (viz. observed one, the one corrected for global atmospheric pressure and the other for local atmospheric pressure), rainfall, sea surface temperature (SST), air temperature, relative density, atmospheric pressure, wind speed, and cross-shore/along-shore components of wind were studied. The seasonal march of all the three types of sea level showed a concave pattern with a mild peak during June, with maximum occurring in the month of December and minimum in July-September period. The seasonal cycle of rainfall showed a weak bimodal distribution, with the primary peak in June and the secondary peak in October. The SST and air temperature also showed a bimodal distribution with the primary maximum in April. Relative density of the sea water showed a sharp drop from May to July, associated with the summer monsoon, followed by a gradual increase upto December. Atmospheric pressure showed a concave pattern, with low values in May and high values in premonsoon and postmonsoon periods. The wind speed showed uniformly high values during the summer monsoon season. The cross-shore component of wind showed predominance of onshore component. The along-shore component showed a predominance of equatorward wind, but the postmonsoon months of November-December showed very small equatorward values. The along-shore wind showed more seasonal variance than the cross-shore wind or the scalar wind speed. Harmonic analysis was performed on the climatological mean data (12 months) of the elements, and the amplitudes and phases of the first three cycles were determined. Air temperature was the only parameter that showed dominance of the semi-annual cycle over the annual cycle. The first three cycles (annual, semi-annual and ter-annual) together explained more than 96% of the total variance in the case of all the parameters. The seasonal signal was observed to be stronger than the interannual signal in the case of sea level, rainfall, air temperature, atmospheric pressure, relative density of sea water and along-shore wind. Scalar wind speed and cross-shore wind showed greater interannual variability. The long time series of monthly data clearly exhibited that the cross-shore wind showed the least (33.7%) and the relative density the maximum (83.5%), seasonal signal. The maximum interannual variability for the three types of sea level occurred during the postmonsoon months of November-December, while for most other parameters it was during summer monsoon months. The effect of the summer monsoon was conspicuous in the seasonal cycle of many of the parameters.

A study of wind direction has shown that the direction is in agreement with the orientation of the Western Ghats indicating that the latter had a profound influence on the wind direction. The highest steadiness of wind is observed in August and the lowest in December.

A regression analysis was carried out to study the effect of some of the oceanographic and surface meteorological parameters on the observed sea level using non-seasonal component of the data. The non-seasonal data for Cochin on winds, SST, air temperature, atmospheric pressure, rainfall and relative density have shown to have significant correlation with the sea level. Among the parameters considered, the effect of along-shore wind was particularly strong followed by the cross-shore wind. An increase of 1 cm in rainfall is found to increase the sea level by 0.1 cm. An increase of 1° C in SST is associated with an increase of 1.39 cm in the sea level, while for cross-shore and along-shore winds it is 3.85 cm and 6.12 cm respectively per m/s. Scalar wind and relative density showed negative effects, with the former showing a decrease of 3.19 cm per m/s, while the latter 0.34 cm per unit.

As compared to the normal years of 1981 and 1984, for the El Nino period of 1982-83 (one of the strongest ones reported during this century), the anomalies are found to be positive in respect of relative density, air temperature, SST, atmospheric pressure, and negative in the case of sea level. A correlation analysis with SOI (Southern Oscillation Index) series has shown that during El Nino periods, more northerly winds and lower sea levels are to be expected. The SO influence was strong on the atmospheric pressure followed by relative density.

Forecasting techniques were tried out to study their suitability for forecasting the monthly march of the different parameters at Cochin. Of the three techniques tried, viz., autoregressive, sinusoidal and EWMA models, EWMA has yielded estimates closer to the actually observed values. However, the seasonal variations in the observations were prominently brought out by all the three techniques.

A comparative study on sea level of nine stations on the west coast (Cochin included) and seven stations on the east coast of the Indian subcontinent, using long monthly mean time series was conducted. From the long time series of monthly data, the seasonal variance (in percentage) contained in the time series was determined. For the west coast, the seasonal variance varied from 29.41 at Kandla to 77.96 at Bhavnagar and for the east coast stations, it varied from 39.03 at Tuticorin to 82.49 at Nagapatnam. Interestingly, the stations close to each other, showed maximum and minimum seasonality for both the coasts, which could be due to purely local phenomena. The seasonal signal of sea level was found to be stronger than the interannual signal.

Interannual variability in the sea level was maximum on the west coast during summer monsoon months, and in November on the east coast. Climatological mean seasonal cycle revealed that during summer monsoon season, the sea level is more than the annual mean in the northern stations and less during other months, while for southern stations reverse is the case, for both the coasts.

The available climatological mean seasonal data on rainfall, atmospheric pressure and along-shore current were examined for the 16 stations, for understanding their effects on the sea level.

The rainfall data shows, except for Cochin, the data are unimodal with the mode occurring in summer monsoon months on the west coast, and during October-November on the east coast. Atmospheric pressure showed a concave pattern on both the coasts with minima in summer monsoon and maxima during premonsoon and postmonsoon seasons.

The along-shore currents along the west coast, at the more exposed stations, showed that there are southerly currents during the summer monsoon season and northerly currents during the postmonsoon season, the transition in direction taking place rather quickly. Along the east coast, at the more exposed stations, there are northerly currents during summer monsoon season and southerly currents during the postmonsoon season. The seasonal variance of the coastal currents is more on the east coast than on the west coast, indicating that the alongshore current is more energetic along the east coast as compared to the west coast. During the summer monsoon season, the coastal currents along the southwest coast behave as eastern boundary currents whereas those along the east coast of India behave as western boundary currents, which are characteristically fast and intense.

Most of the stations along the Indian subcontinent showed a strong negative relationship with the SOI. This suggests that during the El Nino periods the sea level is anomalously low along the Indian subcontinent. The variance accounted by the relationship between SOI and sea level is more along the east coast stations which could probably be due to reduced rainfall, atmospheric pressure and anomalous northerly currents.

For climate monitoring purposes, the subseasonal (annual and semi-annual) frequencies together give most of the information. In the present study, the amplitude and phase of the ter-annual cycle has also been determined along with those of the annual and semi-annual cycles. This has been done for the sea level and associated surface meteorological and oceanographic parameters at the tide gauge stations covered in the study.

A study on propagation characteristics of coastal trapped waves at Cochin (with reference point at Beypore, north of Cochin) using non-tidal sea level corrected for the effects of the atmospheric pressure, showed that the propagation is northward of Cochin during premonsoon months. Further, a comparative study of the tidal heights for Cochin and Beypore has shown that the tidal amplitudes at Beypore are higher than those at Cochin. The meteorological residuals at Beypore were noisy because of several nonlinear influences, as compared to those at Cochin.

The above, among others, are the important conclusions arrived at in this study.

7.2. LIMITATIONS OF THE PRESENT STUDY

Despite the vast number of methodologies of tidal analysis (Doodson, harmonic, response, least squares, etc.) used nowadays to obtain tidal constituents, none of the most employed methodologies is based on non-linear time series analysis. Among these, the least squares method is the most popular (Pugh, 1987; Foreman, 1993; Emery and Thomson, 1998) and can be applied to irregulary sampled data also (Zetler et al., 1965; Foreman and Henry, 1993). The least squares method has been used in the present study, for the determination of tidal harmonic constituents. Marone and Mesquita (1994), however, opined that spectral estimators that follow a second order non-linear model appear to be an accurate tool to assess the non-linear energy of time series data.

Semi-diurnal tides are relatively easy to predict because high tides tend to occur at a regular time after the moon has crossed the meridian for that location. Mixed tides are not as easy to predict as the semi-diurnal tides, because the timing of the high and low tide "stands" (also referred to as Slack Water, when there is no appreciable change in the height of the tide) does not bear a simple relationship to the passage of the moon over the meridian of the location (Gross, 1982). This aspect could probably lead to small errors in the predictions at Cochin, because of the mixed nature of tides at this station.

In the present study on tides at Cochin, the data have been collected at a single site only. Eventhough water level records obtained near the mouth of the estuary may accurately represent the driving force for periodic and quasi-periodic estuarine shelf exchanges, there is some question regarding how representative these measurements are of tidal conditions, a short distance along the coast in either direction from the estuary.

The complex interaction of a daily temporally fixed sampling design with seasonal, tidal and diurnal cycles can result in serious aliasing and reduced usefulness of estuarine data (Hutchinson and Sklar, 1993). This, however, does not seem to affect the results of the present study for Cochin, because of the low tidal range and low seasonal ranges of the studied parameters. These errors could increase as we proceed northwards.

Eventhough there is a good correlation between the along-shore current and corrected sea level along the Indian subcontinent, the suitability of using sea level for predicting along-shore current needs to be treated with caution. Fukumori et al.(1998), for e.g., opined that there is no uniformly applicable pointwise correspondence between sea level and instantaneous circulation at depth, indicating the difficulty in inferring circulation from sea level measurements alone. They also concluded that although some relation with latitude exists, it is strongly modulated by effects of coastal geometry, bottom topography, and stratification that result in strong inhomogeneities and anisotropy.

The results of eigen analysis (Principal Component Analysis) can depend on differences in noise variance, noise correlation, and period of observation among the records and not on the information rich component of the records only (Solow, 1987). In the present study, for the sea level, climatological seasonal cycle were based on data non-uniform with regard to the number of years used for determining the mean seasonal cycle as also the period of the data (i.e. starting and ending years).

No attempt has been made to compute the long term trends, because large interannual and decadal basin wide fluctuations can overshadow the sea level rise signal in tide gauge data spanning less than 40 years (Sturges, 1987; Peltier and Tushingham, 1989; Hendricks et al., 1996). Tropical asia tide gauge data show high decadal and interannual variability (Watson et al., 1998). Very large differences in sea level variation exist for Indian guages over any common time interval (Douglas, 1992).

7.3. RECOMMENDATIONS

The spatial variation of the tidal harmonic constants in the immediate vicinity of an estuary would depend on a number of factors-e.g. geometry, surface area, and the depth. These factors are of primary importance in determining the internal reflection of the tidal wave (Smith, 1980).

No information on the tidal harmonic constituents at other sites in the Cochin estuary is available. The estuary is quite complex with a number of rivers draining into it. Tsimplis (1997) in his study on tides and sea level variability at the strait of Euripus, detected that the amplitude of the semi-diurnal tides at the north side of the strait is four times the amplitude at the south side of the strait, located a few hundred metres away.

Observations of tidal propagation in the Mandovi-Zuari estuarine system showed that the amplitude in the channels remains unchanged over long distances (ca. 40km) from the mouths of the main channels and then decays rapidly over approximately 10km near the head (Shetye et al, 1995). The decay of the tidal amplitude at the upstream end was more rapid during the southwest monsoon in the estuarine system. A similar study in the Cochin estuary would enhance our knowledge of the tidal characteristics and would be useful for a variety of problems, from pollution studies to harbour development. The sampling strategy should be carefully designed for the Cochin estuary, because the waterbody is quite complex with regard to shape, bathymetry and riverine influence. These problems are less complex for Beypore, which is a typical estuary, having a funnel shaped mouth.

The relative importance of non-tidal variance could increase from low values near the mouth of the estuary to high values in the interior of the estuary (Smith, 1983; Walters and Gartner, 1985).

Tidal choking which occurs if the inlet is narrow, implies a decrease of the tidal range and a corresponding phase lag within the basin compared to the tide outside (Oliveira and Kjerfve, 1993; Hill, 1994; Rydberg and Wickbom, 1996). At some sites, the choking coefficient - (ratio of tidal range inside the basin to that outside the basin) can be as low as 0.25 (Rydberg and Wickbom, 1996). It is not known whether any choking occurs inside the Cochin and Beypore estuaries.

The strength of tidal currents near to the mouth of estuaries depends on the volume of water that flows through the opening and its size. Thus it is not possible to predict the strength of the tidal current, given only the tidal range. Large tidal ranges are accompanied by weak tidal currents (e.g., Gulf of Maine) and small tidal ranges are accompanied by strong tidal currents (e.g. Nantucket Sound). However, at a given location, the relative strength of the tidal currents is generally proportional to the relative tidal range for that day-spring tide is usually accompanied by stronger tidal currents than a neap tide (Gross, 1982).

The above information has some relevance to Cochin. At Cochin, eventhough the tidal ranges are below 1m, the currents associated with them are quite strong. Speeds at times reaching 150-160 cm/s, especially during ebb tides and comparatively lesser values during flood tide, have been reported (e.g. Rama Raju et al., 1979). The characterization of the tidal currents, similar to what has been attempted for the tidal heights, should be carried out through the deployments of current meters for atleast one week, at different depths inside and outside the estuary.

The survey of India, Dehra Dun, on a routine basis predicts the tide for 30 Indian stations among which Cochin and Beypore are also included (Surveyor General of India, 1997). The low and high water predictions at Cochin are based on the observed tidal data for the year 1989, whereas for Beypore, it is based on the observed tidal data for 1883-84. Some of the predictions are based on 9 years of data, e.g. Madras (Chennai), but these data are not continuous time series. Many European ports, however, predict tides based on continous observations collected over at least 19 years (e.g. Germany). These predictions are bound to be very accurate as compared to the predictions based on one year of observations. An attempt should be made to compare the tidal characteristics (amplitude and phase) for the oldest, good quality record with that of a recent, good quality record to appreciate the possible changes in tidal characteristics as discussed by Eisma (1995), Warrick et al. (1994). Such studies could be done for many of the stations, where tidal information is not being collected now, by reinstalling tide gauges and recording the sea level for atleast one year. This is definitely bound to reveal many interesting results. At present out of the 30 stations only 13 are operational.

An attempt to understand the seasonal and interannual variability of the tides on similar lines is necessary for Bhavnagar, Kandla and Sundarbans area [known for their high tidal ranges (Shetye, 1998)] followed by other stations along the west and east coasts of India. Such an attempt would enable us to have a clearer picture of the tidal exchanges. From the de-tided series, contribution of other factors (meteorological, oceanographic and hydrological) can also be studied.

More modelling studies are required to understand the tidal characterestics (Carter and Devoy, 1987; Cann, 1990; Xie et al., 1990; Brooks, 1992; Rydberg and Wickbom, 1996; Sinha and Pingree, 1997; Unnikrishnan et al., 1997; Davies and Philip, 1998; Sinha et al., 1998). Kantha (1995) and Kantha et al. (1995) studied the semi-diurnal, and diurnal tides in the Arabian Sea and Bay of Bengal using models assimilating even altimetric tides.

It is important to evaluate the effects of sea level rise on estuarine physics on time scales of decades or a century. If the sea level rise exceeds the rate of filling of the estuary, the system may develop a more linear response to tidal forcing (Aubrey and Speer, 1985). This could be examined for the estuarine tide gauge stations along the Indian subcontinent.

It is commonly believed that most meteorological and oceanographic parameters exhibit unchanged annual cycles within natural variability whereas conspicuous changes in the annual cycles are observed for plant nutrients - phosphate, nitrate, nitrite and silicate (Radach et al., 1990). For most of the meteorological parameters, such a study is not difficult in contrast to the oceanographic parameters. Monthly data are not collected on a routine basis for the physico-chemical parameters in the open ocean, far away from the main land, because of the expense involved in such an exercise. However, for an estuarine study, the expense and time involved for such work is comparatively less and these regions are, in fact, under more stress than the open ocean. Collecting information over a 25 hour period for each month at strategic sites inside the estuary (in the lower as well as upper reaches) on a continuous basis would generate a wealth of information, from which many important conclusions can be drawn. Only continuous monitoring at crucial sites will enable us to understand the effects of anthropogenic changes in the estuarine ecosystem (Mc Alice and Jaeger, 1983).

In the present study, the monthly mean sea level, and associated meteorological and oceanographic parameters at Cochin have been statistically modelled using the autoregressive, sinusoidal and exponentially weighted moving average techniques. Many recent studies on sea level variability, however, involve multiple regression analysis also and hence future studies for sea level variability along the Indian coastline should approach on these lines.

In the present study on sea level variability, only tide gauge data have been used. Satellite altimetry is an important aid, because it allows regular, long term monitoring of ocean surface height over a range of scales in space and time. These data can be directly related to surface currents via geostrophy (Qiu, 1992; Hendricks et al, 1996; Snaith and Robinson, 1996; Woodworth et al., 1996; Stammer, 1997; Yanagi et al. 1997; Iudicone et al., 1998; Prasanna Kumar et al., 1998).

There are numerous studies correlating satellite altimetric data to tide gauge data (Cheney and Miller, 1990; Miller and Cheney, 1990; Chao et al., 1993 and Arnault and Le Provost, 1997). The general result is that altimetric data compare well with tide gauge data for time scales longer than few months, and that the correlation is better when tide guage data at islands are used. This should be examined for the tide gauge stations along the Indian subcontinent.

At present, the Topex/Poseidon data are of 8 years duration (1992-continuing) and Geosat data are of 4.5 years duration (1984-1989). These are too short to discuss interannual variability (Wang et al., 1998). The TOPEX/POSEIDON data reveals a degree of interannual variability that is similar to the amplitude of the annual cycle itself, rendering a climatological annual cycle nearly nonexistent. The results of Stammer (1997) clearly illustrate the truly global character of the interannual large amplitude changes in the ocean. Studying them can be a major step towards the understanding of short-term climate variability (order of 10 years).

For the Indian waters, continuous information on the hydrographic characteristics, especially on an interannual basis (sometimes even on a seasonal basis) is lacking. Normally, the cruises of the research vessels are such that the same track is not covered during the different seasons. This information is very important for understanding the density structures from which steric sea level can be computed. Reverdin et al. (1997), for example, in their study on the decadal variability of hydrography in the northern North Atlantic, attributed the strong surface current mainly to the baroclinic changes. They also concluded that the interannual variability of steric height contributes to a large interannual variability in the baroclinic components of currents.

Continuous data on sea level at the stations along the Indian coastline will be helpful in climate monitoring, because the longer term variability of the extremes of sea level may be connected to regional climatic variability (Tsimplis and Blackman, 1997). Watson et al. (1998) suggest that changes in hydrology and water resources for the Indian subcontinent are likely to cause changes in the seasonal sea level.

Modelling studies are to be carried out to understand non-tidal sea level using meteorological and oceanographic data (Perigaud and Delecluse, 1992; Chao and Fu, 1995; Enfield and Harris, 1995; Ezer et al., 1995; Paraso and Valle-Levinson, 1996;

Beier, 1997; Fukomori et al., 1998). Such studies have to be undertaken for Cochin and the other sea level stations along the Indian subcontinent.

Low frequency variations in coastal sea level and winds are important forcing mechanisms for long-term circulation patterns in estuaries (Walters and Gartner, 1985). The subtidal volume exchange with the adjacent continental shelf is important to the long term transport and flushing of the estuaries (Wong, 1993). Studies on similar lines will be an important aid in understanding the flushing characteristics of many estuaries (which are experiencing anthropogenic pressures) along the Indian subcontinent.

7.4. PROGRAMMES OF RELEVANCE TO SEA LEVEL STUDIES IN INDIA

In this context, it is worthwhile to know the long term programmes of some research organisations relevant to sea level studies in India.

7.4.1. MOORED BUOYS

The Department of Ocean Development (DOD) has initiated a National Data Buoy Programme in 1996, which involved the deployment of 12 met-ocean moored data buoys at selected locations in the seas around India. Eight of these buoys were moored in the shallow water regions along the Indian coast and the remaining four were deployed in deeper waters (two each in the Arabian Sea and Bay of Bengal). These data buoys are equipped with sensors for measurement of some meteorological and oceanographic elements - air temperature, wind speed and direction, atmospheric pressure, sea surface temperature, current speed and direction, salinity and wave height and direction. Deployment of another ten of these in the deeper waters of the Arabian Sea, Bay of Bengal and equatorial Indian Ocean is planned for the next ten years under the Indian Climate Research Programme.

Thomson and Ware (1996) have suggested that the daily record of pressure-corrected sea level can be used to derive the record of prevailing longshore current for the eastern boundary regions of the coastal ocean dominated by wind-driven upwelling dynamics. This could be examined with the availability of continuous along-shore current data at Cochin (and other stations), from NIOT buoys.

7.4.2. COASTAL AND ISLAND TIDE GAUGES

With the support of DOD and Department of Science and Technology, the existing 13 functional tidal observatories maintained by the Survey of India (Dehra Dun) along the Indian coastline (including islands), are being equipped with modern tide gauges (with accuracy of 3 mm). Acoustic tide gauges with higher accuracy are being installed at selected stations.

A National Tidal Data Center has been established by the Survey of India for archiving and disseminating data to the user agencies. The analysis and interpretation of historical data alongwith associated mathematical modelling is thus gaining importance in the Indian context.

7.4.3. EXPENDABLE BATHYTHERMOGRAM (XBT) / CONDUCTIVITY TEMPERATURE DEPTH (CTD) SURVEYS

National Institute of Oceanography (NIO), with the support of Department of Science and Technology (DST), launched in 1990 a long term XBT observation programme for routine monitoring of the upper ocean thermal structure (upper 800 m), along a few selected shipping lanes in the tropical Indian Ocean. The observations are being monitored along the Madras-PortBlair-Calcutta, Bombay-Mauritius and Visakhapatnam-Singapore routes. Surface meteorological data are also collected along with upper ocean thermal data at one degree intervals along these routes at least once in two months. It is proposed to use XCTD probes (upper ocean thermal as well as haline structure will thus be available) and extend the observations to two additional routes: Cochin-Muscat and Bombay-Mombasa. These data will be of immense use for studies on the evolution of upper ocean thermal and haline structure on seasonal and interannual time scales. The steric information thus generated from the above programmes will be of great use for studies on sea level variability on seasonal and interannual time scales.

7.4.4. OCEAN SATELLITE PROGRAMMES

Future Indian OCEANSAT satellite series are expected to carry altimeters on board alongwith other oceanographic sensors. One can, therefore, expect a wealth of sea level data in the near future. By updating the network of tide gauges along the Indian coastline and islands on the lines suggested, one can compare the data generated by the two instruments and validate the satellite data.

7.5. CONCLUDING REMARKS

A co-ordinated effort consisting of tide gauge measurements, altimetric data, meteorological data and oceanographic data (water column density observations) will be of immense value in climate modelling (Wyrtki and Mitchum, 1990; Kilonsky and Caldwell, 1991; Douglas, 1992; Emery and Thomson, 1998). With the various programmes of the Research Organisations in India, it is expected that sea level studies in our country will receive greater impetus. Supply of these data products to the user organisations will be an important step in the years to come.

APPENDIX

APPENDIX I
(CHAPTER 2)

A1.1. TYPES OF TIDES

The coastal waters respond in different ways to tide producing forces and consequently, various types of tides are formed. The representation of the tidal variations as the sum of several harmonics, each of different period, amplitude and phase is facilitated by harmonic analysis.

A1.2. THE IMPORTANT PARTIAL TIDES

The part of the tide that is solely due to the tide producing force of the sun is termed the solar tide, and that due to the moon, the lunar tide. Lunisolar tides are those derived partly from the lunar forces and partly from the solar forces. Some of the important relevant aspects of partial tides are given below.

A1.3. SPECIES DETAILS

The tidal periods fall into three principal "tidal species" - long period, diurnal and semi-diurnal, represented by 0,1 and 2, respectively. In shallow waters, third-diurnal, fourth-diurnal and higher order species are also generated in the harmonic analysis, which are represented by 3, 4, etc., respectively. Each tidal species contains "groups" of harmonics which can be separated by analysis of at least a month of observations. In turn, each group contains "constituents" which can be separated by the analysis of atleast a year of observations.

A1.3.1. LONG PERIOD ASTRONOMICAL TIDES

The largest term in the long period species is usually S_a, followed by S_{sa}. They reflect annual and semiannual variations in the mean sea level caused by seasonal meteorological effects. The two constituents account for the non-uniform changes in the sun's declination and distance (Hicks, 1984). The lunar monthly (M_m) and fortnightly (M_f) tides are the lunar equivalent to S_a and S_{sa}, but there are no radiational or meteorological effects at these periods. The M_m constituent tide expresses the effect of irregularities in the moon's rate of change of distance and speed in orbit and the M_f constituent expresses the effect of departure from a sinusoidal declinational motion. M_{sf} (Lunisolar synodic fortnightly constituent) has a frequency, which is the difference between M_2 and S_2. The absence of significant energy at M_{sf} is an indication that nonlinear contributions from semi-diurnal tides are unimportant.

A1.3.2. DIURNAL CONSTITUENTS

Diurnal tides are produced mainly by the K_1, O_1 and P_1 constituents and have one high water and one low water each lunar day. The "Lunisolar diurnal constituent" represented by K_1 along with "Lunar diurnal constituent" represented by O_1 expresses the effect of the moon's declination. They account for diurnal inequality and at extremes, diurnal tides. The K_1 constituent along with the "Solar diurnal constituent" represented by P_1 expresses the effect of the sun's declination.

A1.3.3. SEMIDIURNAL CONSTITUENTS

The dominant tidal pattern in most of the oceans is such that it takes 12 hrs. 25 min. for each tidal cycle and since this cycle occupies roughly half a day, it is called semi-diurnal tide (Pugh, 1987). The semi-diurnal tides are produced mainly by the M_2, S_2 and N_2 constituents. These have two nearly equal high waters and low waters in a lunar day. Since tides are always gettng higher or lower at any location, due to the spring-neap tide sequence, successive high tides and successive low tides can never be exactly the same at that location. Semi-diurnal tides have a range that increases and decreases cyclically over a 14-day period. The maximum ranges (called spring tides) occur a few days after the full and new moon, whereas the minimum ranges (called neap tides) occur shortly after the times of the first and third quarters. At the times of spring tides the lunar and solar forces combine together, but at neap tides the lunar and solar forces are out of phase and tend to cancel the effect of each other.

The partial tide representing the rotation of the earth with respect to the moon, is called the "Principal lunar semi-diurnal constituent" and is represented by M_2. The partial tide representing the rotation of the earth with respect to the sun, is called the "Prinicpal solar semi-diurnal constituent" and is represented by S_2. The "Larger lunar elliptic semi-diurnal constituent" represented by N_2 alongwith the "Smaller lunar elliptic semi-diurnal constituent" represented by L_2 modulates the amplitude and frequency of M_2 for the effect of variation in the moon's orbital speed due to its elliptical orbit. The "Lunisolar semi-diurnal constituent" represented by K_2 modulates the amplitude and frequency of M_2 and S_2 for the declinational effect of the moon and sun, respectively.

A1.4. TIDAL HEIGHTS

For the surface elevations, the objective of harmonic analysis is to minimise the residuals, e_i, in the equation (A1.1) (Foreman et al. 1994; Emery and Thomson, 1998).

$$e_i = y_i - A_0 + \sum_{J=1}^{M} A_j \cos(\sigma_j t_i - \phi_j) \qquad \text{...(A1.1)}$$

where A_j, σ_j and ϕ_j are the respective amplitude, frequency and phase of the constituent j, and y_i is the observation at time, t_i. Each equation can be made linear in the new unknowns C_j and S_j by rewriting

$$A_j \cos(\sigma_j t_i - \phi_j) = C_j \cos(\sigma_j t_i) + S_j \sin(\sigma_j t_i) \qquad \text{...(A1.2a)}$$

where

$$A_j = (C_j^2 + S_j^2)^{1/2} \quad \text{and} \quad \phi_j = \arctan(S_j/C_j) \qquad \text{...(A1.2b)}$$

Assuming the number of observations, N, is greater than the number of unknowns, 2M+1, the system of equations is solved by minimising the residuals by the least square technique. With short records, it is not advisable to include all possible constituents in a harmonic analysis because close frequencies in combination with the presence of non-tidal noise or tide gauge errors can produce a large change in the solutions.

As the potential tidal theory predicts the existence of hundreds of tidal frequencies and as many are so close that several years of data are required to separate neighbours by one cycle, it is not practicable to include all constituents in every analysis (Foreman et al, 1994). In most of the studies concerning harmonic analysis of tides, it is convenient to do annual analysis with 8760 or 8784 hourly values. In tidal analyses, some workers have used even 29 days' data while some others have used 18.6 years of data. It has, however, been established universally, that the best data set for routine predictions is the hourly data for an year, which is relatively easy to procure.

Most harmonic analysis programs require the time series to have a uniform sampling interval. Foreman and Henry (1993) developed a program that can analyse either irregularly sampled data, or observations that were made at only the high or low tide. Franco and Harari (1988) developed programs based on Fourier analysis. These programs, unlike conventional harmonic analysis techniques, require uniformly sampled series with no data gaps. A disadvantage of this procedure is that Fourier frequencies do not generally correspond to the tidal frequencies, post Fourier processing is required to reassign energy to the tidal constituents. However, this approach is computationally faster because of Fast Fourier Transform techniques. Foreman and Neufeld (1991) developed programs that could extract 500 constituents from a tidal time series that is atleast 18.6 years long in duration covering a nodal cycle.

APPENDIX II
(CHAPTERS 3 & 5)

A2.1. HARMONIC ANALYSIS OF THE SEASONAL CYCLE

At any tide gauge station, the seasonal cycle of the mean sea level is usually described as the sum of several harmonics as annual, semi-annual and ter-annual etc., components (Maul et al., 1990; Enfield & Harris, 1995; Emery & Thomson, 1998). The seasonal cycle of other oceanographic and meteorological parameters can also be studied using the same technique. Eventhough parameterising the monthly values for each station as the sum of annual and semi-annual components appears to be adequate, the ter-annual component has also been considered in the present study. The phase ϕ_1 is represented as the number of months from the beginning of the year to the time at which the annual cycle is maximum. Similarly ϕ_2 (and ϕ_2+ 6 months) represents the months when the semi-annual (6 month) cycle peaks, and ϕ_3 (and ϕ_3 + 4 months, ϕ_3 + 8 months) represents the months when the ter-annual (4 months) cycle peaks. For each month 'j' (j=1 to 12), an average of the monthly means i.e. the climatological mean from the N years of available data is computed.

$$\mathrm{AVG}(J) = (1/N)\cdot\left[\sum_{i=1}^{N} \mathrm{MSL}(j,i)\right] \qquad \ldots(\mathrm{A2.1})$$

where "MSL(j,i)" is the monthly mean sea level for month j and year i. A least square fit was made in order to determine the amplitudes A_1, A_2 & A_3 and the phases ϕ_1, ϕ_2 & ϕ_3 of the annual, semi-annual and ter-annual cycles.

$$AVG(J) = A_1 \cdot \cos\left[\frac{2\pi}{12}(t-\phi_1)\right] + A_2 \cdot \cos\left[\frac{2\pi}{6}(t-\phi_2)\right] + A_3 \cdot \cos\left[\frac{2\pi}{4}(t-\phi_3)\right] \quad \ldots(A2.2)$$

for j = 1 to 12

and t = j - 0.5 to account for avg(j) being the average of the jth month.

The RMS error (∂) is obtained following Wyrtki and Leslie (1980)

$$\partial^2 = (1/12) \cdot \sum \left[AVG(j) - CALC(j)\right]^2 \quad \ldots(A2.3)$$

where 'CALC(j)' is the value for the month j determined from the parameters of the Fourier expansion. CALC(j) has been determined using the annual plus semi-annual as well as for annual plus semi-annual plus ter-annual harmonic parameters.

A2.2. ATMOSPHERIC PRESSURE CORRECTIONS

The pressure correction factor to be applied to the observed sea level (to account for the inverted barometer effect causing the sea level to depress by about 1 cm for an increase of 1 mb in atmospheric pressure and vice-versa) has not been considered for the tropical region in many of the earlier studies. This correction factor becomes important nearer to the limits of the tropics. Two types of corrections are required to be applied to account for isostasy. The first correction is due to the mean pressure change over the oceans, caused by a shift in the air mass towards Siberia in winter (Pattullo et al., 1955; Lisitzin, 1974; Hendricks et al., 1996). This global mean pressure change varies from 1012 mb in December to 1014 mb in July. To compute the contribution of the atmospheric pressure variations to the changes in sea level, data on the global and the local monthly mean atmospheric pressure at sea level are needed. The global monthly mean atmospheric pressure at sea level has been generated by Pattullo et al. (1955), who have also defined a procedure for correcting the sea level for atmospheric pressure changes. The procedure is as follows:

The mean monthly atmospheric pressure in the general vicinity of the tide gauge station (P_g), and the mean pressure over all the oceans for the same month (P_o) are made use of for this correction. $C' = P_g - P_o$ then represents the amount by which the water surface in this area is depressed relative to the mean global sea level. The recorded sea level has to be raised by this amount to correct for the effect of the atmospheric pressure. It is more convenient to use the correction factor $C = C' - \overline{C}'$, whose mean annual value is zero. This procedure for isostatic adjustment for atmospheric pressure changes would not be valid for quick changes in atmospheric pressure, because there would be be no time for the water to move.

The second correction is due to local atmospheric pressure. The corrected series is generated by adding the atmospheric pressure (in mb) to the sea level (in cm) (Brown et al., 1985; Varadarajulu and Bangarupapa, 1984; Ramp et al., 1997).

A2.3. ALONGSHORE COMPONENT OF CURRENT AND SEA LEVEL

The theoretical background for examining this relationship has been discussed in detail by Shetye and Almeida (1985). The following description has been adopted from the same.

Pattullo et al. (1955) examined the effect of (1) atmospheric pressure and (2) "steric" fluctuations on the recorded cycle. The contribution to the sea level change due to atmospheric pressure change (inverted barometer effect) depends on the difference between the local pressure and the mean global sea surface pressure. The annual cycle of this contribution could be important for stations located at higher latitudes.

The most important finding of Pattullo et al. (1955) is that the variations in the recorded monthly mean sea level at a location agree very well with the "steric" departures (Z_α) in the vicinity of the location

$$Z_\alpha = (1/g) \cdot \int_{P_a}^{P_o} \Delta\alpha \; dP \qquad .....(A2.4)$$

and $$\Delta\alpha = \frac{1}{\rho(T,S,P)} - \frac{1}{\rho(\bar{T},\bar{S},P)} \qquad .....(A2.5)$$

ρ is the density, T and S are the temperature and salinity, $\bar{T}$ and $\bar{S}$ being their respective annual means, g is the acceleration due to gravity, P_a is the atmospheric pressure, and P_o is the pressure at a depth where all seasonal effects are assumed to be small.

Pattullo et al. (1955) did not examine the implications of the above result to the circulation in the vicinity of the tide gauge. This aspect was examined by Shetye and Almeida (1985) as the mass field (which determines Z_α), the sea surface topography, and the geostrophic velocity fields are interrelated.

A coastal current, the motion of which is restricted upto a distance R from the coast (R- being of the order of a Rossby radius of deformation - approximately 100 kms), flows southward along a north - south coastline (Fig. A2.1). Assuming that the pressure gradient normal to the coast is in geostrophic equilibrium with the velocity field, we get

$$f v_l^s = g \frac{\partial Z_s}{\partial x} \qquad ...(A2.6)$$

where f and g are the Coriolis parameter and the acceleration due to gravity, v_l^s is the alongshore component of

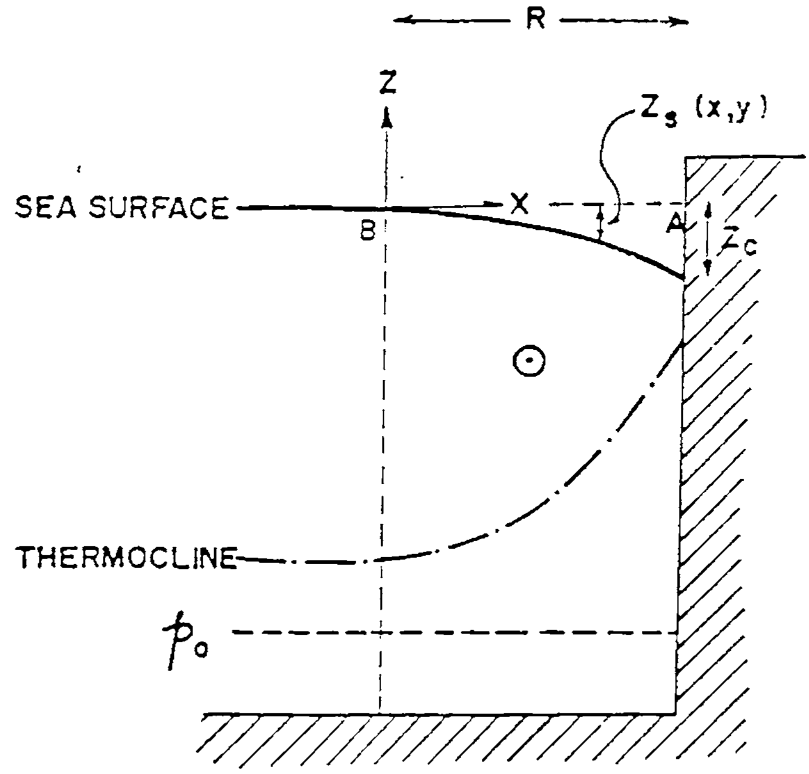


Fig. A2.1. An idealized coastal current. The coastline stretches along the north-south direction. The current is southward, and the motion extends up to a distance R from the coast. Z_S (x,y) is the sea surface. X, Y and Z are the eastward, northward and upward axes, respectively. The sea surface tilts down by Z_C at the coast. The thermocline tilts upward towards the coast. P_o is the pressure at the level of no motion.
(from Shetye and Almeida, 1985)

the surface geostrophic velocity, and $Z_s(x,y)$ is the topography of the ocean surface. Variations in Z_s near a coast can be determined from sea level data. We can write Z_s in terms of variations in dynamic height normal to the coast,

$$fv_1^s = \frac{\partial}{\partial x}\left[\int_{P_o}^{P_a} \delta \, dP\right] \qquad ....(A2.7)$$

where

$$\delta = \frac{1}{\rho(T,S,P)} - \frac{1}{\rho(0,35,P)} \qquad ....(A2.8)$$

is the specific volume anomaly. P_o is the pressure at the depth of no motion. The term in square brackets is proportional to Z_α. The observation made by Pattullo et al. (1955) that variations in Z_α closely match sea level changes, when viewed in isolation, bears no particular implication to the dynamics of the currents in the vicinity of the tide gauge. A static ocean, heated or cooled uniformly at the surface, will show variations in Z_α which will match the sea level variations. If we impose the restriction that the changes in mass field are mainly due to advection, the Pattullo et al. (1955) result becomes a powerful tool to monitor coastal geostrophic currents.

Approximating equation (A2.6), we obtain

$$f v_l^s = \frac{g}{R} \left[Z_c - Z_o \right] \qquad \text{....(A2.9)}$$

where Z_c is the sea level at the coast (point A in Fig. A2.1), Z_o is the sea level at the point B, at a distance R which is the offshore boundary of the coastal current. The variations in Z_α would be small in comparison to those in Z_c because point B is located in a regime which is quiescent in comparison to that at A. Under these conditions, variations in Z_α, Z_c and v_l^s will match.

Along the west coast, the alongshore component of current is taken as positive if the flow is northward and along the east coast, the alongshore component is taken as positive if the flow is southward. This choice is made to ensure that the sign of sea level change and that of change in v_l^s would be the same, if geostrophic balance as given in equation A2.9 holds.

APPENDIX III
(CHAPTER 6)

A3.1. FILTERING

To remove the tides from the records and to focus attention on other periodicities, numerical tapering is required. "Tapering" denotes operations in the time domain and "filtering" denotes equivalent operations in the frequency domain. Traditionally tides were supressed by using a Cosine-Lanczos taper on the hourly tide gauge readings (Mooers and Smith, 1968)

Breaker (1986) used a Godin low passed digital filter to remove diurnal and semi-diurnal tidal components. The low pass filter, which is most simple, is a 24-hour running mean which is convolved over the hourly time series. This boxcar filter should be avoided as it fails to remove 3.5% of the M_2 amplitude, 8.2% of O_1 and 5.4% of N_2 (Godin, 1972), as well as energy from all constituents except S_2 and its harmonics. A 25 hour running mean filter will remove more of the M_2 signal, but pass significant portions of K_1, S_2 and other constituents.

Godin (1972) suggested that the energy leakage problem may be avoided by running average filters in succession. His $A_{24}A_{24}A_{25}$ filter is applied by initially convolving the time series with a 24 hour running mean. A second 24 hour running mean is then applied to the output of the first filter and a final 25 hour running mean is applied to the output of the second. Although negligible tidal energy remains after these passes, considerable energy at low frequencies is also removed (Thompson, 1983; Foreman et al., 1994). The amplitude of the original signal is reduced to one-half at a period of about 4 days, and the half power period is close to 3 days. At a period of 8 days, about 10% of the amplitude is removed. However, the moving average filter is easy to program and is useful where signals at periods less than 10 days are not needed (Breaker, 1986). Walters and Heston (1982) found that the Godin filter, in addition to removing tidal variations, also attenuates variations in the 2 to 4 day range.

A3.2. DETRENDING

For detrending, the first exercise is to find the equation of the straight line that best fits the points (Spiegel, 1981). The equation could be used to find corresponding 'y' values for points on the x - axis (should be between x_1 and x_n). The least squares method can be used to find the equation of the straight line that best fits the experimental points. We will fit the points (x_1, y_1), (x_2, y_2),...............(x_n, y_n) to the straight line : $y = m*x+ c$

where m (the slope) and c (the y intercept) are given by the following formulae:

$$m = \frac{N*SUM_{xy} - SUM_x * SUM_y}{N*SUM_{x^2} - (SUM_x)^2} \qquad ....(A3.1)$$

$$c = \frac{SUM_{x^2} * SUM_y - SUM_x * SUM_{xy}}{N * SUM_{x^2} - (SUM_x)^2} \qquad ....(A3.2)$$

N is the total number of points

SUM_{xy} is sum of x*y product for each point: i.e., $x_1*y_1 + x_2*y_2 + ...+ x_n*y_n$

SUM_x is the sum of the x's, i.e., $x_1+x_2+..........x_n$

SUM_y is the sum of the y's, i.e., $y_1+y_2+..........y_n$

SUM_{x^2} is the sum of all x's squared, i.e., $x_1^2+ x_2^2+ ....+x_n^2$

A3.3. DATA WINDOWS

Fourier series apply to infinite-duration periodic data sets. If we examine only a finite size record of data (this period is called the data window), the Fourier analysis implicitly assumes that the data is periodic and thus repeats itself both before and after our limited period of measurement.

Even after detrending, the sharp edges of the data window cause what is known as leakage, where spectral estimates from any one frequency are contaminated with some spectral amplitude leaking in from neighbouring frequencies. To reduce leakage, a modified data window with smoother edges is recommeneded. Although a variety of smoothers can be used, a common one utilizes sine or cosine squared terms near the beginning and ending 10% of the period of record, and is known as a bell taper:

$$W(k) = \begin{cases} \sin^2(5\pi k/N) & \text{for } 0.0 \leq k \leq 0.1N \\ 1 & \text{elsewhere} \\ \sin^2(5\pi k/N) & \text{for } 0.9N \leq k \leq N \end{cases} \qquad \ldots.(A3.3)$$

When the window weight, W(k), is multiplied by the time series, A(k), the result yields a modified time series with fluctuations that decrease in amplitude at the beginning and at the end of the series. The Fourier transform can then be performed on this modified time series.

The process of detrending, despiking (removing erroneous data points), filtering and bell tapering is known as conditioning the data. Conditioning should be used with caution, because anytime data is modified, errors or biases can be introduced. It is best to do as little conditioning as is necessary.

A3.4. DISCRETE FOURIER TRANSFORM

Any continous function can be described by an infinite Fourier series, namely the sum of an infinite number of sine and cosine terms. In the case of discrete time series with a finite number of points, we are required to have only a finite number of sine and cosine terms to fit our points exactly.

Using Euler's notation, i.e., $\exp(ix) = \cos(x) + i \cdot \sin(x)$, (where i is the square root of -1) as a shorthand notation for the sines and cosines, we can write the discrete Fourier series representation of A(k) as :

Inverse Transform

$$A(k) = \sum_{n=0}^{N-1} F_A(n)\ e^{i2\pi nk/N} \qquad \text{........(A3.4)}$$

where n is the frequency, and $F_A(n)$ is the discrete Fourier transform. We see that a time series with N data points (indexed from k=0 to n-1) needs not more than N different frequencies to describe it.

There are a number of ways to describe frequency:

n = number of cycles (per time period P)

$\tilde{n}$ = cycles per second = n/P

f = radians per second = $2\pi n/P = 2\pi n/(N\Delta t)$

A frequency of zero (n=0) denotes a mean value. The fundamental frequency, where n=1, means that exactly one wave fills the whole time period, P. Higher frequencies correspond to the harmonics of the fundamental frequency. For example, n=5 means that exactly 5 waves fill the period P.

$F_A(n)$ is a complex number, where the real part represents the amplitude of the cosine waves and the imaginary part is the sine wave amplitude. It is a function of frequency because the waves of different frequencies must be multiplied by different amplitudes to reconstruct the original time series. If the original time series, A(k), is known, then these coefficients can be found from :

Forward Transform

$$F_A(n) = \sum_{k=0}^{N-1} \left[A(k)/N \right] e^{-i2\pi nk/N} \qquad \text{...(A3.5)}$$

This is the same as

$$F_A(n) = 1/N \sum_{k=0}^{N-1} A(k)\cos(2\pi nk/N) - i/N \sum_{k=0}^{N-1} A(k)\sin(2\pi nk/N) \qquad \text{...(A3.6)}$$

The two equations (A3.4) and (A3.5) are called the Fourier transform pairs. The second equation performs the forward transform, creating a representation of the signal in phase space (another name for the frequency or spectral domain). This process is also known as Fourier decomposition. The first equation performs the inverse transform, converting from frequencies back into physical space.

If we have a total of N data points, then the highest frequency that can be resolved in the fourier transform is $n_f = N/2$, which is called the Nyquist Frequency.

A3.5. DISCRETE ENERGY SPECTRUM

The square of the norm of the complex Fourier transform for any frequency n is:

$$|F_A(n)|^2 = [F_{real}(n)]^2 + [F_{imag}(n)]^2 \qquad .....(A3.7)$$

When $|F_A(n)|^2$ is summed over frequencies n = 1 to N-1, the result yields the total biased variance of the original time series :

$$\sigma_A^2 = 1/N \sum_{k=0}^{N-1} (A_k-\bar{A})^2 = \sum_{n=1}^{N-1} |F_A(n)|^2 \qquad ....(A3.8)$$

Thus, we can interpret $|F_A(n)|^2$ as the portion of the variance explained by waves of frequency n. We also notice that the sum over frequencies does not include n=0, because $|F_A(0)|$ is the mean value and does not contribute any information about the variation of the signal about the mean. We define $G_A(n) = |F_A(n)|^2$. The ratio $G_A(n)/\sigma_A^2$ represents the fraction of the variance explained by component n, and is very much like the correlation coefficient squared, r^2.

The discrete spectral intensity (or energy), $E_A(n)$, is defined as $E_A(n) = 2|F_A(n)|^2$, for n=1 to n_f, when N is odd. When N is even, $E_A(n)=2|F_A(n)|^2$ is used for frequencies from n = 1 to (n_f-1), along with $E_A(n)=|F_A(n)|^2$ at the Nyquist frequency. This presentation is called the discrete variance(or energy spectrum).

Theoretical concepts assume that there is a spectral energy density, $S_A(n)$ that can be integrated over n to yield the total variance.

$$\sigma_A{}^2 = \int S_A(n)\ dn \qquad ......(A3.9)$$

The spectral energy density has units of A squared per unit frequency.

We can approximate the spectral energy density by

$$S_A(n)=E(n)/(\Delta n) \qquad ......(A3.10)$$

Where Δn is the difference between neighbouring frequencies, when n is used to represent frequency, $\Delta n = 1$.

A3.6. CROSS-SPECTRA

Cross-spectrum analysis relates the spectra of two variables. We have defined $G_A=|F_A(n)|^2$ as the spectral energy for variable A and frequency, n. We rewrite this definition as $G_A= F_A^*\cdot F_A$, where F_A^* is the complex conjugate of F_A, and where the dependance on n is still implied.

To demonstrate this last definition, let $F_A = F_{Ar}+i\cdot F_{Ai}$, where subscripts r and i denote real and imaginary parts, respectively. Thus, the complex conjugate is simply F_A^* =

$F_{Ar}-i\cdot F_{Ai}$. The expression for the spectral energy can now be written as :

$$G_A = F_A^* \cdot F_A = (F_{Ar}-iF_{Ai})\cdot(F_{Ar}+iF_{Ai})$$

$$= F_{Ar}^2+i\cdot F_{Ai}\cdot F_{Ar}-i\cdot F_{Ai}\cdot F_{Ar}-i^2\cdot F_{Ai}^2$$

$$= F_{Ar}^2+F_{Ai}^2 = |F_A(n)|^2 \qquad ...(A3.11)$$

Similarly, we define the spectral intensity, $G_B = F_B^* \cdot F_B$, for different variable B. We can now define the cross-spectrum between A and B by

$$G_{AB} = F_A^* \cdot F_B = F_{Ar}F_{Br}+iF_{Ar}F_{Bi}-iF_{Ai}F_{Br}-i^2F_{Ai}F_{Bi} \qquad ...(A3.12)$$

Upon collecting the real and imaginary parts, the real part is defined as the cospectrum , Co, and the imaginary part is called the quadrature spectrum, Q:

$$G_{AB} = Co - iQ \qquad ...(A3.13)$$

where

$$Co = F_{Ar}\cdot F_{Br}+F_{Ai}\cdot F_{Bi} \quad \& \quad Q = F_{Ai}\cdot F_{Br}-F_{Ar}\cdot F_{Bi} \qquad ...(A3.14)$$

Although not explicitly written in the equations above, F_A and F_B are functions of n, making both the cospectrum and quadrature spectrum functions of n too: Co(n) and Q(n). The sum over frequency of all cospectral amplitudes, Co, equals the covariance between A and B.

Two additional spectra can be constructed from the quadrature and co-spectra.

An amplitude spectrum, Am, defined as

$$Am = G_{AB}^{*} \cdot G_{AB} = Q^2 + Co^2 \qquad \ldots(A3.15)$$

and

Phase spectrum, ϕ, defined as

$$\tan \phi = Q/Co \qquad \ldots(A3.16)$$

This can be interpreted as the phase difference between the two series A and B that yields the greatest correlation for any frequency, n. In other words, the phase gives the time displacement of one record with respect to the other as functions of frequency. The phase difference can give useful information even when the spectrums of the separate time series are relatively featureless (Hamon, 1962).

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