

Low-Frequency Variability of Sea Level Along the Coast of India

D. Shankar

Thesis

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to *appa* and *amma*

Statement

As required under the University ordinance 0.19.8.(vi), I state that this thesis entitled *Low-frequency variability of sea level along the coast of India* is my original contribution and it has not been submitted on any previous occasion.

The literature related to the problem investigated has been cited. Due acknowledgements have been made wherever facilities and suggestions have been availed of.

D. SHANKAR

*National Institute of Oceanography, Goa
December 1998*

Certificate

This is to certify that the thesis entitled *Low-frequency variability of sea level along the coast of India*, submitted by D. Shankar to Goa University for the degree of Doctor of Philosophy, is based on his original studies carried out under my supervision. The thesis or any part thereof has not been previously submitted for any other degree or diploma in any university or institution.

SATISH R. SHETYE

*National Institute of Oceanography, Goa
December 1998*

Vita

Name Shankar Doraiswamy

Born 9 August 1967, Bangalore

Education

B. Tech. Aerospace Engineering
Indian Institute of Technology, Madras (Chennai)
June 1989

M.Sc. (Engg.) Atmospheric Sciences
Indian Institute of Science, Bangalore
November 1991

Work

Research Fellow Centre for Mathematical Modelling and Computer Simulation
(C-MMACS), Bangalore
November 1991 to August 1994

Scientist Centre for Mathematical Modelling and Computer Simulation
(C-MMACS), Bangalore
September 1994 to January 1995

Scientist National Institute of Oceanography, Goa
January 1995 to date

Address for communication

By post Physical Oceanography Division,
National Institute of Oceanography,
Dona Paula, Goa 403 004,
India.

By e-mail shankar@csnio.ren.nic.in,
shankar@darya.nio.org.

List of Publications

- **D. Shankar**. *Seasonal cycle of the zonally symmetric tropical circulation in a simple climate model*. M.Sc. thesis, Indian Institute of Science, Bangalore, 1991.
- **D. Shankar**, J. P. McCreary, W. Han, and S. R. Shetye. Dynamics of the East India Coastal Current, 1. Analytic solutions forced by interior Ekman pumping and local alongshore winds. *Journal of Geophysical Research*, 101:13,975–13,991, 1996.
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¹See Chapter 4.

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This thesis was typed using $\text{\LaTeX} 2_{\epsilon}$ ². The “style file”, `guthesis.sty`, was hacked from `utthesis.sty` by Dinesh Das; `utthesis.sty` was brought to my notice by N. H. Saji at a time when I was not getting anywhere with a template for the thesis, and it proved an invaluable starting point. And, as the saying goes, well begun is half done.

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D. SHANKAR

National Institute of Oceanography, Goa
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² $\text{\LaTeX} 2_{\epsilon}$ is an extension of \LaTeX , a collection of macros for \TeX . \TeX is a trademark of the American Mathematical Society.

Synopsis

Coastal sea level is one of the better documented oceanic variables, there being several tide-gauge records of hourly sea level that stretch back to the last century. This, together with the fact that geostrophic, low-frequency coastal currents leave their signatures on sea level, makes tide-gauge data an excellent source of information for the study of coastal circulation over a vast range of sub-inertial frequencies. Low-frequency variability of sea level along the coast of India forms the subject of this thesis. “Low” is defined to exclude frequencies higher than those described by monthly sea level. The seasonal cycle is the highest frequency studied in this thesis, which examines the variability of sea level along the coast of India on seasonal through interdecadal time scales and determines the causes of the observed variability.

After the introduction in Chapter 1 of the thesis, the observational and theoretical background is presented in Chapter 2. The focus is on the literature on the seasonal cycle. The seasonal cycle of sea level, corrected for the effect of atmospheric pressure using the Inverse-Barometer approximation, is coherent along the coast; its range is 45 cm on the east coast and 30 cm on the west coast. Along the east coast, the maximum sea level occurs in November and the minimum during March–April; along the west coast, the maximum occurs in December and the minimum during the southwest monsoon. The seasonal cycle of corrected sea level is in good agreement with that of the observed alongshore ship drifts, implying a link between the large-scale coastal circulation and coastal sea level. It does not, however, match that of the local alongshore winds, showing that the circulation along the coast of India is influenced considerably by remote forcing. This inability to model the circulation along the coast of India by invoking purely local causes leads to a theoretical framework, developed over the last decade, for describing the large-scale circulation in the north Indian Ocean.

This theoretical framework merges the Bay of Bengal, the Arabian Sea, and the equatorial Indian Ocean into a single dynamical entity, which must be modelled as a whole even to simulate the circulation in its parts. It is applied in Chapter 3 to the Lakshadweep high and low, a high and low in sea level that form off southwest India during the northeast and southwest monsoons, respectively, and propagate westward. The dynamics of the high and low is modelled using a dynamical $1\frac{1}{2}$ -layer reduced-gravity model. The simulations show that the high and low are explicable by

linear theory and do not owe their existence to nonlinearity. Simple numerical and analytic solutions show that a Kelvin wave propagating along the east coast of India can generate the high and low, implying that the essential elements of the high and low are contained in coastal Kelvin and equatorial Rossby waves, both of which arise from linear dynamics on an equatorial β -plane. They are forced by the radiation of Rossby waves from Kelvin waves propagating poleward along the west coast of India. The Kelvin waves must have a period greater than about 50 days to radiate Rossby waves and force the high and low; at lower periods, they are trapped at the coast. Among the mechanisms forcing these Kelvin waves along the west coast of India, most important are the winds along the east coast of India and Sri Lanka, which by themselves can force the high and low. The winds along the west coast of India and Sri Lanka, especially along the southern margin of the Indian subcontinent, contribute to the formation of the low, but cannot force a high. Other processes contribute marginally to the Lakshadweep high, but they force a westward Southwest Monsoon Current during the southwest monsoon, and the low does not form.

Though the dynamical reduced-gravity model is successful in simulating the essential features of the circulation in the north Indian Ocean, including the currents along the coast of India, it fails to simulate the seasonal cycle of coastal sea level; this is the subject of Chapter 4. The wind-forced model fails to simulate the winter peak along the east coast, and as a result, forces a higher range of the seasonal cycle along the west coast than along the east coast. Simulations in which temperature and salinity vary in the active model layer, these fields being prescribed from a climatology, show that the drop in salinity along the east coast after the southwest monsoon raises steric sea level and is the cause of the maximum in November. This low salinity is the result of runoff from the Ganga and the Brahmaputra into the northern Bay of Bengal during the southwest monsoon. Thus, three mechanisms — atmospheric pressure, winds on the scale of the basin, and salinity — contribute to the seasonal cycle of sea level along the coast of India.

A lower frequency, the annual mean sea level, is the subject of Chapter 5. Levelling observations conducted during the Great Trigonometrical Survey of India (1858–1909) showed that the annual mean sea level is higher along the east coast of India than along the west, the difference between Vishakhapatnam and Mumbai (Bombay) being about 30 cm. Simulations with the $1\frac{1}{2}$ -layer reduced-gravity model show that purely wind-forced circulation accounts for half this difference, the other half being due to the gradient in salinity along the coast.

The variability of annual sea level on interannual and interdecadal time scales is the subject of Chapter 6. Annual mean sea level along the coast is significantly correlated with the annual extrema and seasonal averages. Cross-correlations of annual mean sea level at the stations along the coast are statistically significant, showing that these changes are coherent and are part of a basin-scale response. The annual mean and extrema of sea level are also correlated with annual all-India rainfall, as is the local rainfall at Mumbai with the annual sea level there. These correlations

retain their significance when the rainfall and sea-level data are decimated with a 10-year running mean. The interdecadal changes in monsoon rainfall are reflected in sea-level changes at Mumbai, which has the only century-long tide-gauge record in the Indian Ocean; both increase from a low in the first quarter of this century to a high in the 1950s and decrease thereafter.

Our hypothesis is that the seasonal inflow of the monsoon rainfall into the seas around India and the dynamics of the East and West India Coastal Currents (EICC and WICC) provide the link between monsoon rainfall and coastal sea level, the coastal salinity field playing an intermediate role. The seasonal EICC and WICC spread the runoff along the coast, creating a cross-shore salinity gradient; the time scale associated with this gradient is much longer than an year because mixing is slow in the ocean, which responds as a two-layer system to this quasi-steady cross-shore gradient in salinity. When salinity, and hence, density, decreases coastward in the upper layer, sea level rises at the coast, and this is accompanied by a weak, geostrophic, surface current that flows with the lighter water on its right; below it is an undercurrent. Geostrophy also requires that the pycnocline slope up towards the coast.

There are two main conclusions of this thesis, which is summarized in Chapter 7.

1. There are three causes of the low-frequency variability of sea level along the coast of India.
 - (a) The large-scale wind-forced circulation of the upper ocean.
 - (b) The large changes in salinity that are a result of the high rainfall over the Indian sub-continent and the surrounding seas.
 - (c) Atmospheric pressure.

The first two causes are important at periods ranging from a season to decades; atmospheric pressure contributes significantly only to the seasonal cycle.

2. We propose a hypothesis connecting the interdecadal changes in sea level along the coast of India to the variability of the monsoon, the major aspect of the climate of the region. This hypothesis is different from those generally proposed to link sea level to climate change; these hypotheses invoke the increase in volume due to the change in temperature of the upper ocean and the addition of freshwater because of the melting of polar ice caps.

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Chapter 1

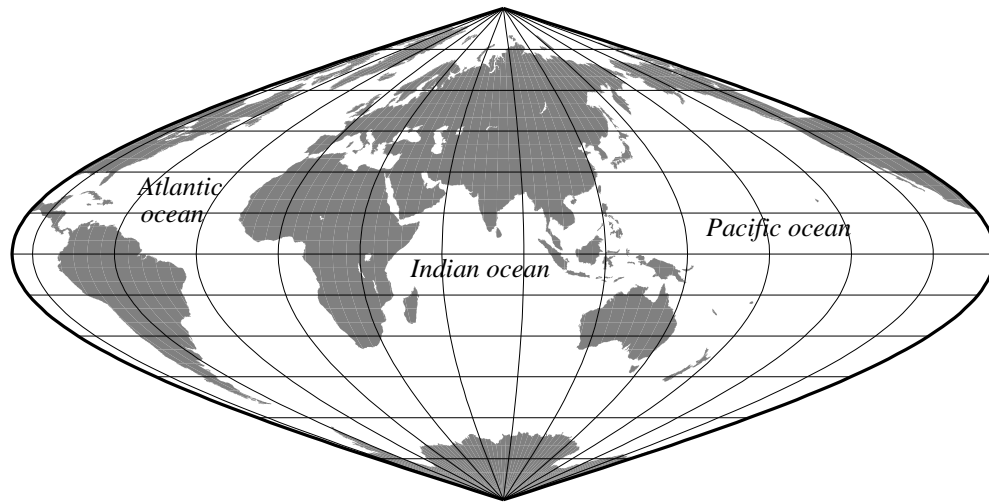
Introduction

The surface of the sea deforms continuously under various influences. Its level, measured relative to an arbitrary datum, is called sea level, which changes with time and is the grossest, and most obvious, indicator of change in the oceans. Changes in sea level are greater in the shallow waters in the vicinity of a coast than they are in the open sea, and since a large fraction of the human population resides in coastal areas, variations in sea level have aroused interest for a long time. A reasonably accurate prediction of sea level was also necessary for safe navigation of boats and ships in harbours. This, and the relative ease of measuring sea level as compared to measuring, say, temperature or currents, has led to it being one of the better documented oceanic variables. Hourly measurements of sea level are available at several places over the globe, some of the records stretching back to the last century.

A tide gauge measures sea level relative to land; an increase in sea level may either be due to an absolute rise in sea level, or due to a sinking of land. The largest changes evident in a typical sea-level record are those due to astronomical tides. These regular, periodic patterns are modified by the effects of the weather; exchange of energy between the atmosphere and the ocean occurs at all space and time scales, from the generation of short-period wind-waves to the slow transfer of energy, over a century, from the tropics to the poles by the global ocean circulation. The sea-level record also includes the effect of secular changes in sea level, forced by changes in the volume of ice locked in major ice caps and glaciers.

India, with its long coastline, lies in the Indian Ocean (Figure 1.1), which is much smaller than the Pacific or the north Atlantic. Unlike these two basins, it is bounded in the north by Asia; this makes it a tropical basin. This has profound consequences for the meteorology and oceanography of this region: the land-ocean contrast forces seasonally reversing winds, the monsoons, over the north Indian Ocean (Figure 1.2), unlike in the north Atlantic or the north Pacific. The north Indian Ocean responds to this forcing, resulting in the significant seasonal cycle of sea level seen in the tide-gauge records along the coast of India.

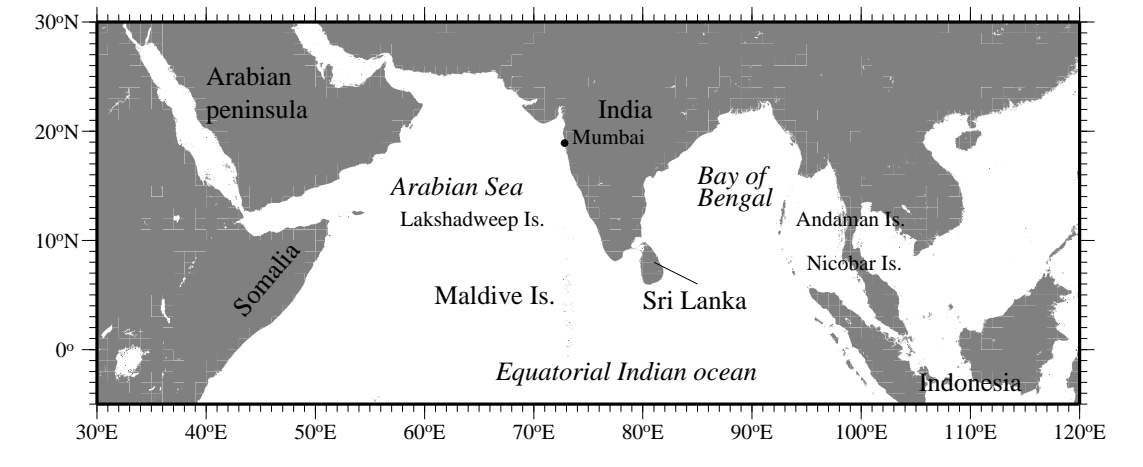
Figure 1.1 The geography of the Indian Ocean. The zonal extent of the Indian Ocean is much less than that of the Pacific or the north Atlantic. Its southern boundary is arbitrary, but is chosen to distinguish it from the Antarctic, or southern, Ocean. Unlike the Pacific and the Atlantic, the Indian Ocean is bounded in the north by Asia; this makes it a tropical basin. This has profound consequences for the meteorology and oceanography of this region: the land-ocean contrast forces seasonally reversing winds, the monsoons, over the north Indian Ocean, unlike in the north Atlantic or the north Pacific. The north Indian Ocean responds to this forcing, resulting in the significant seasonal cycle of sea level seen in the tide-gauge records along the coast of India.



Mumbai, on the west coast of India (Figure 1.2), has the longest tide-gauge record in the Indian Ocean. Like tide-gauge records elsewhere in the world, that at Mumbai exhibits variability over a range of frequencies (Figure 1.3). The change in sea level due to tides is much greater than those related to the weather; the latter are obtained by filtering the hourly sea level with a 3-day low-pass filter [Doodson, 1921]. Tidal and non-tidal sea-level oscillations are usually studied separately because of the vastly different ways in which they are forced. We ignore tides in this thesis, focussing instead on weather-related sea-level changes at “low” frequencies. Though these are much smaller than the tides, the related movement of the thermocline is important. Defining “low” to exclude all frequencies higher than seasonal, we study the variability of sea level along the coast of India on seasonal through interdecadal time scales, mapping one end of the spectrum of sea-level variability. For this, it is necessary to filter the tides and high-frequency oscillations related to the weather out of the sea-level data. This is most easily achieved by averaging the hourly sea level over a month to obtain monthly sea level¹; this does almost as good a job at

¹Throughout this thesis, the term “monthly sea level” is used to denote the mean of hourly sea level over a given calendar month. Likewise, “annual sea level” is used to denote the mean of monthly sea level over a calendar year. What we call monthly and annual sea level are often called monthly mean and annual mean sea level; we drop the “mean”, using it only when its absence can lead to ambiguity.

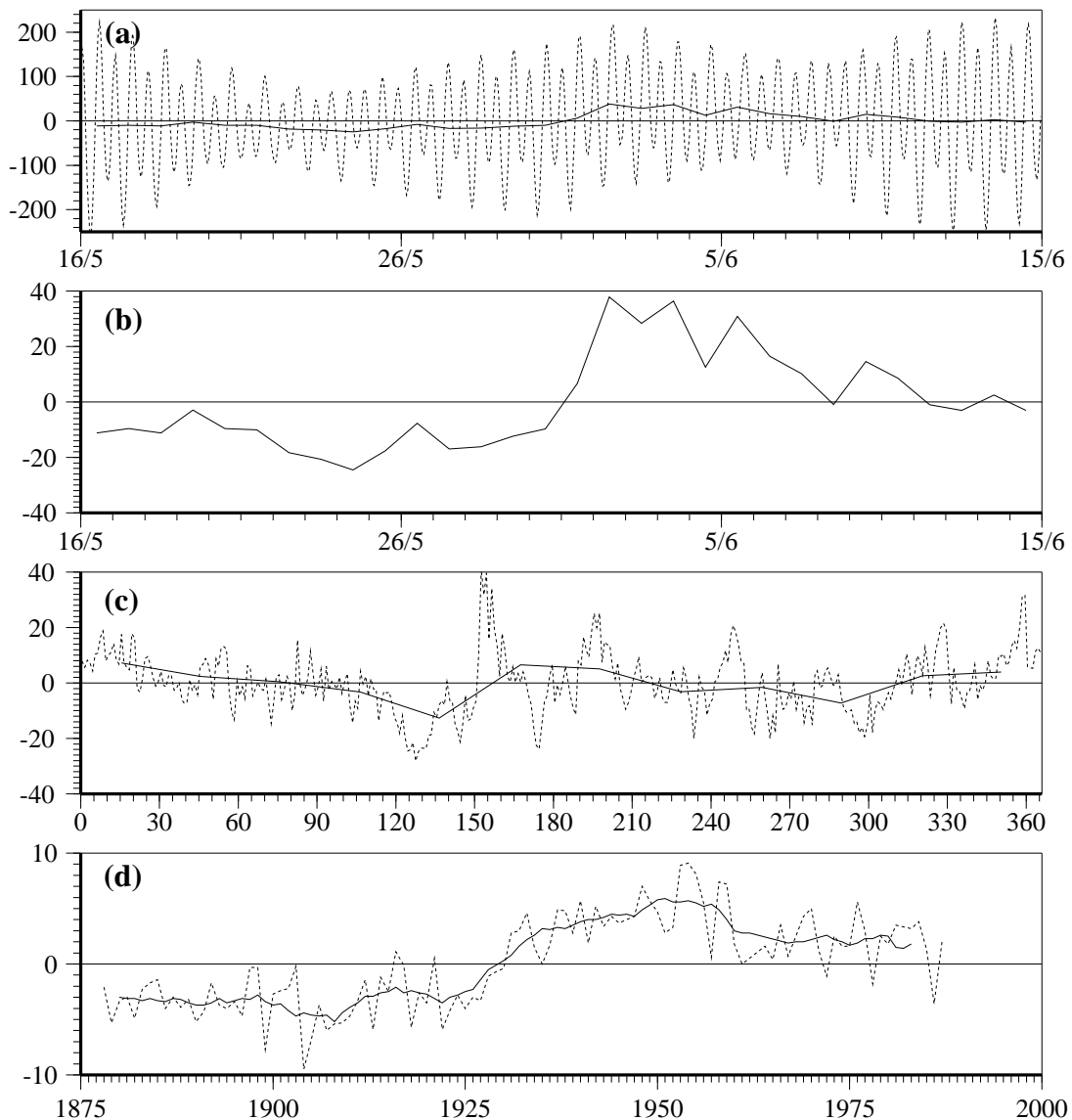
Figure 1.2 The geography of the north Indian Ocean. The north Indian Ocean is split by the Indian peninsula into two parts, the Bay of Bengal in the east and the Arabian Sea in the west. The equatorial Indian Ocean, the Bay of Bengal, and the Arabian Sea are contiguous basins because the southern tip of the Indian subcontinent lies well north of the equator. Together, they form one dynamical entity, the north Indian Ocean.



filtering out the higher frequencies, especially the tides, as do more complex techniques [Pugh, 1987]. In this thesis, we use monthly sea level to study the low-frequency variability of sea level along the coast of India.

The tide gauges along the coast of mainland India are important for estimating low-frequency changes because they represent half of those for the entire Indian Ocean [Emery and Aubrey, 1989]. A brief description of this network of tide gauges is given in Chapter 2, which presents the observational and theoretical background for this thesis. At the low frequencies of interest, the sea level along the coast is related to alongshore currents, which are forced by winds acting on the scale of the basin. This leads to a theoretical framework, developed during this decade, for the wind-forced circulation in the north Indian Ocean. The framework is applied in Chapter 3 to the dynamics of the Lakshadweep high and low, a high and low in sea level that form off southwest India. The next three chapters are devoted to the low-frequency variability of coastal sea level, of which the seasonal cycle is the highest frequency. Since it is the most prominent of the regular oscillations related to the weather, it is seen even in a climatology of monthly sea level; this climatological seasonal cycle is studied in Chapter 4. A lower frequency is described by annual sea level, the mean of monthly sea level over an year. The alongshore variation of annual sea level is the subject of Chapter 5. Departures from climatology and sub-annual changes are studied in Chapter 6. Chapter 7 summarizes and concludes the thesis.

Figure 1.3 Sea level variability at Mumbai on the west coast of India. Hourly, daily, monthly, and annual sea level (cm) are plotted as a function of time to reveal the variability over a range of frequencies; the mean, defined over the duration for which the sea level is plotted, is subtracted before plotting each curve. **(a)** Hourly sea level (dashed curve) and daily sea level (solid curve) during 16 May to 15 June, 1976. Daily sea level, which is mostly related to weather, is computed by de-tiding the hourly sea level with a 3-day low-pass filter. **(b)** Daily sea level, as in (a), but with an increase in the scale of the ordinate. **(c)** Daily sea level (dashed curve) and monthly sea level (solid curve) for 1976. Monthly sea level, obtained by averaging the hourly sea level over a month, essentially describes the seasonal cycle. **(d)** Annual sea level (dashed curve) is the average of monthly sea level over an year. Filtering annual sea level with a 10-year running mean (solid curve) reveals interdecadal changes.



Chapter 2

Observational and Theoretical Background

In this chapter, we examine the observational and theoretical background for this thesis. Most of the literature on the low-frequency variability of sea level along the coast of India deals with the seasonal cycle, the outstanding low-frequency signal in the sea-level records; hence, before surveying the literature, we describe the observed seasonal cycle of sea level, beginning with a description of the tide-gauge network along the coast of India.

2.1 The Tide-Gauge Network Along the Coast of India

The Geodetic and Research Branch of the Survey of India monitors the network of tide gauges along the coast of mainland India and at a few offshore island stations [Roy, 1994]. The measurements are made using a float-type automatic mechanical tide gauge with an accuracy¹ of 1 cm; since the oscillations studied in this thesis are at least an order of magnitude greater, this accuracy is sufficient for our purpose. The measured sea level is recorded by a stylus on charts, which are later digitised into hourly values of sea level. Monthly sea level is computed from these hourly values by averaging over a month, and annual sea level is obtained by averaging the monthly sea levels over an year. These monthly and annual sea-level data are supplied by the Survey of India to the Permanent Service for Mean Sea Level (PSMSL) along with the datum to which the measurement is referred. Since the datum history is known for the tide gauges of India, a homogeneous series of levels can be prepared. These levels are adjusted by the PSMSL to a Revised

¹Although the hourly sea level may be accurate only to 1 cm, the mean of several hourly values is potentially much more accurate, provided that the error in each reading has a random probability distribution. If this distribution is statistically normal, the mean of n independent readings is more accurate than a single reading by a factor of $n^{-\frac{1}{2}}$. On this basis, 100 readings would reduce the error from 1 cm to 1 mm [Pugh, 1987].

Local Reference (RLR) datum, which is defined relative to the tide-gauge benchmark so that the mean sea level in a specified year² is approximately 7 m. Defining sea levels relative to the tide-gauge benchmark has the advantage of separating the oceanographic and the geodetic aspects of the problem of sea-level trends [Pugh, 1987].

The traditional Indian tide-gauge network has been used primarily for establishing the datum for vertical control network of India and to determine various tidal constituents for tide tables [Roy, 1994]. As a result, many of the records are short, and only 12 [Emery and Aubrey, 1989] are acceptable for estimating sea-level variability on seasonal and higher time scales. Some of these, however, are situated on the banks of major rivers, or in narrow gulfs, making them unsuitable for the study of low-frequency variability on the scale of a basin. Five of these gauges were found by Emery and Aubrey to have acceptable confidence levels; these gauges are located at Mumbai (Bombay), Mangalore, and Kochi (Cochin) on the Indian west coast, and at Vishakhapatnam and Chennai (Madras) on the Indian east coast (Figure 2.1, Table 2.1). In addition, we use data from Marmagao³ on the west coast and Paradip⁴ on the east coast. Apart from the Indian tide gauges, that at Colombo in Sri Lanka is considered because it lies close to the southern tip of the Indian subcontinent, the junction between the Bay of Bengal and the Arabian Sea.

Table 2.1 Tide-gauge stations along the coast of the Indian subcontinent. N_{yr} is the number of years of data available. The monthly mean sea-level data for all stations are with respect to the Revised Local Reference, i.e., all the sea-level data used in this thesis are RLR data. The Permanent Service for Mean Sea Level (PSMSL) is the source for the monthly sea-level data.

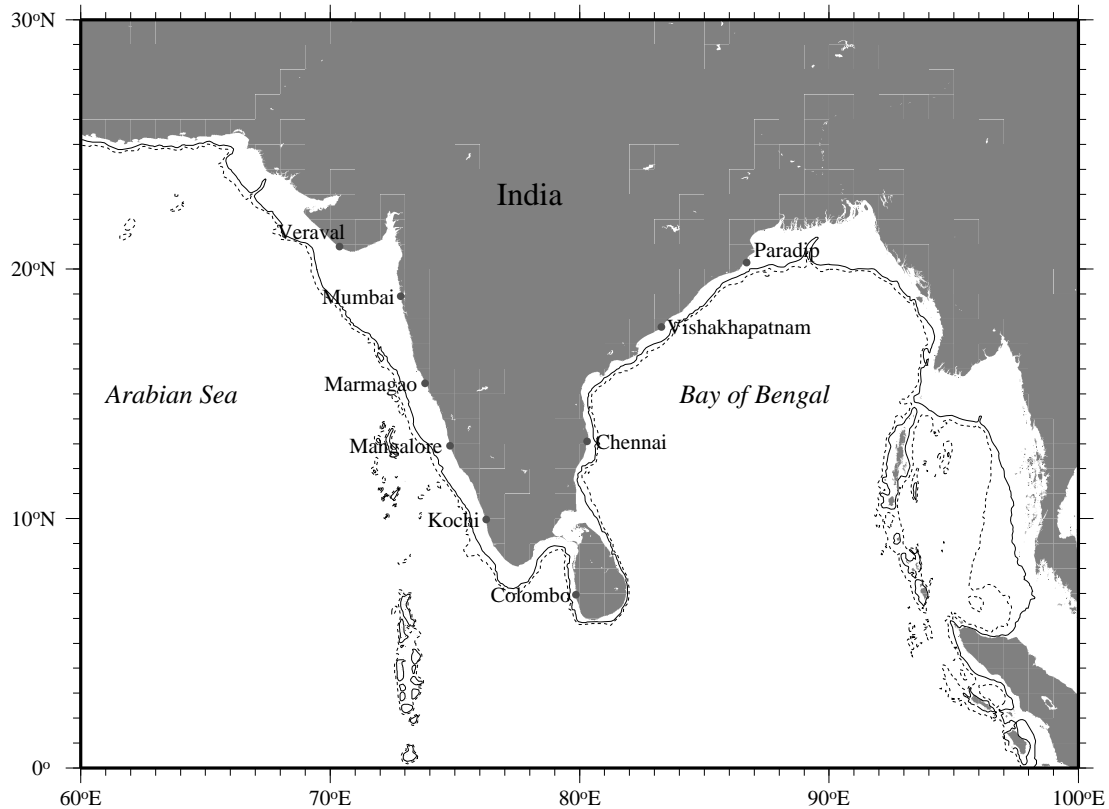
Station	Longitude (°E)	Latitude (°N)	Time span	N_{yr}
Paradip	86.70	20.26	1966–1988	22
Vishakhapatnam	83.28	17.68	1937–1989	52
Chennai (Madras)	80.30	13.10	1916–1989	43
Colombo	79.85	6.95	1953–1965	13
Kochi (Cochin)	76.26	9.96	1939–1989	50
Mangalore	74.80	12.92	1952–1976	23
Marmagao	73.80	15.42	1969–1989	15
Mumbai (Bombay)	72.83	18.92	1878–1988	111

²Henceforth, we refer to such sea-level data as “RLR data”.

³The record at Marmagao was considered too short by Emery and Aubrey, but more data has since become available.

⁴For reasons not known, Paradip was ignored by Emery and Aubrey.

Figure 2.1 Tide-gauge stations along the coast of the Indian subcontinent. “Indian subcontinent” implies India and some neighbouring countries, including Sri Lanka. In the figure, the solid line is the 200 m isobath, which usually marks the shelf-break, and the dashed line is the 1000 m isobath. The shelf is narrow along the east coast of the Indian subcontinent, except in the northern Bay of Bengal; it is wider along the west coast, especially off Mumbai.



2.2 The Climatological Seasonal Cycle of Sea Level

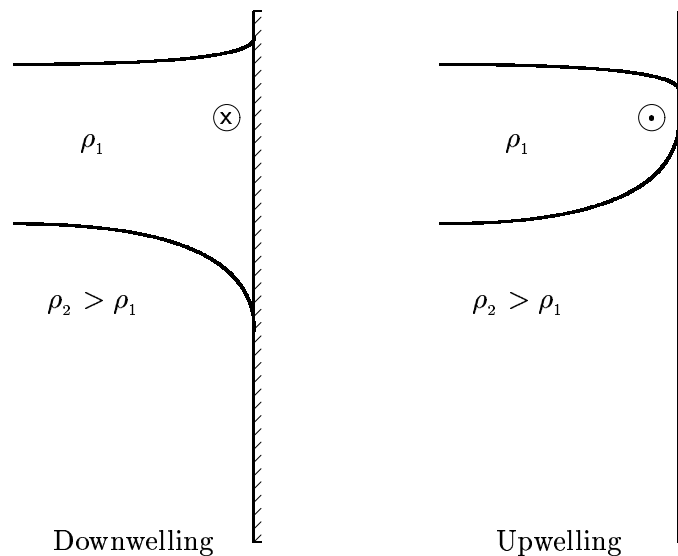
The dominant frequency of the wind-stress forcing over the north Indian Ocean is the annual harmonic [Rao, 1998], a consequence of the seasonally reversing monsoon winds. These large-scale winds force a pronounced seasonal cycle of circulation in the basin, and hence, a seasonal cycle of sea level along the coast of India⁵. The seasonal cycle is the highest frequency adequately resolved by monthly sea level. A climatology is obtained from monthly sea level by averaging the data for a particular month, say January, over all the years of the record. A monthly climatology of anomalies is then obtained by removing the annual mean from the monthly climatology.

There are three causes of the seasonal cycle of sea level at a coast: astronomic tides, atmo-

⁵Strictly, we should say “coast of the Indian subcontinent” because the coast of Sri Lanka forms part of it. With due apologies to the Sri Lankans, we use “coast of India” in the rest of this thesis.

spheric pressure, and “steric oscillations” [Patullo et al., 1955]. Steric oscillations are due to changes in specific volume; the steric sea level is low (high) when the water is cold (warm), or has high (low) salinity. Changes in steric sea level are forced by surface fluxes and horizontal and vertical advection of heat and salt. Even in the absence of horizontal advection and of fluxes across the boundaries of the ocean, coastal currents forced by winds cause changes in the local mass field by forcing coastal upwelling or downwelling, thereby influencing the steric sea level (Figure 2.2). We distinguish between this and the changes in steric sea level caused by horizon-

Figure 2.2 Effect of winds and coastal currents on steric sea level. This schematic of a section normal to the coast shows the relation between winds, coastal currents, and sea level. The ocean is considered a two-layer system, the denser lower layer being much deeper than the shallow upper layer. The interface between the two layers represents the pycnocline, the density-equivalent of the thermocline. In the northern hemisphere, wind blowing with the coast on its right (left) forces Ekman flow into (out of) the coast, causing coastal downwelling (upwelling); sea level rises (falls) at the coast and the pycnocline slopes down (up) towards the coast. This sets up a cross-shore pressure gradient that drives a geostrophic alongshore current. In the figure, the current shown by “x” (“.”) within a circle is into (out of) the plane of the paper. Thus, when there is downwelling (upwelling) at the coast, the current flows with the coast on its right (left), sea level rises (falls) at the coast, and the pycnocline slopes down (up) towards the coast. The change in sea level is given by $\eta = -\left(\frac{\rho_2 - \rho_1}{\rho_2}\right)h$, where h is the change in the thickness of the upper layer from the mean, or undisturbed, state.



tal advection of heat and salt and by the exchange of heat and salt across the boundaries of the ocean; the former are considered the effect of wind-forced coastal currents, and the latter that of thermohaline forcing. Therefore, there are four causes of changes in monthly sea level at a coast:

astronomic tides, atmospheric pressure, wind-forced coastal currents, and thermohaline effects. Of these, the astronomic tides contribute around 1 cm, which is an order of magnitude less than the meteorological effects [Patullo et al., 1955; Shetye and Almeida, 1985]; hence, we ignore their effect.

2.2.1 The Inverse-Barometer Effect

At the low frequencies of interest, the effect of atmospheric-pressure variations in the tropics can be “corrected” by using the Inverse-Barometer (IB) approximation. Following Ponte [1993], the corrected sea level is given by

$$\eta_c = \eta_o + \frac{1}{\rho g} (p_{\text{atm}} - \bar{p}_{\text{atm}}), \quad (2.1)$$

where η_o and η_c are the observed and corrected sea levels. $\rho = 1026 \text{ kg m}^{-3}$ is the oceanic surface density, g the acceleration due to gravity, p_{atm} the local atmospheric pressure, and \bar{p}_{atm} the spatial average of the atmospheric pressure over the global ocean. Since \bar{p}_{atm} is a function of time because of a shift in air mass towards Siberia in winter [Patullo et al., 1955], the IB approximation involves an adjustment of sea level to both local and nonlocal pressure fluctuations [Ponte, 1993]. It is iso-static, i.e., it does not lead to pressure changes in the deeper ocean. The IB effect, computed using climatological monthly atmospheric pressure data from the Comprehensive Ocean-Atmosphere Data Set (COADS), is more pronounced towards the north of the basin and along the east coast of India (Figure 2.3). Seasonal sea-level changes due to variations of atmospheric pressure vary from about 3 cm at Colombo to 13 cm at Paradip. The corrected sea level is lower (higher) than the observed sea level during the southwest (northeast) monsoon⁶, when the local atmospheric pressure is low (high). The seasonal changes observed in the corrected sea level are caused by the two remaining processes: wind-forced coastal currents and thermohaline effects. It is these changes, which are linked to the basin-scale dynamics of the north Indian Ocean, that form the subject of this thesis.

2.2.2 Major Features of the Seasonal Cycle of Sea Level

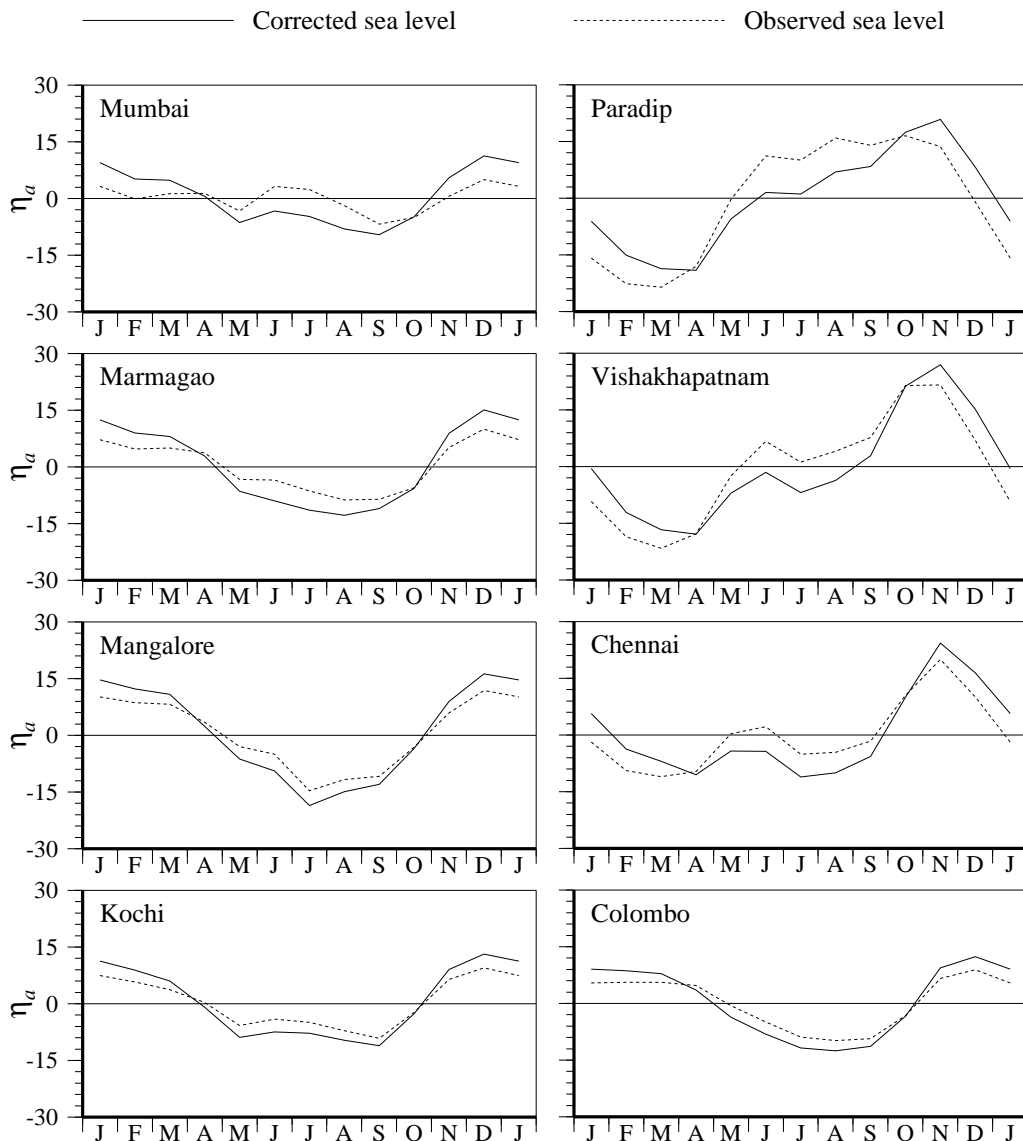
The climatological seasonal cycle of sea level, corrected for the effect of atmospheric pressure⁷, is visually coherent along the east and west coasts of India and shows the following features (Figure 2.3⁸).

⁶The southwest monsoon lasts from June to September, the northeast monsoon from November to January. October and February–May are the transition months, when the winds are weak over the north Indian Ocean.

⁷Hereafter, sea level corrected for the effect of atmospheric pressure is referred to as “corrected sea level”; when the correction is not applied, it is called “observed sea level”, or “uncorrected sea level”, or just “sea level”.

⁸In this figure, as in all subsequent figures of this kind, the variables plotted are monthly anomalies. The local annual mean is subtracted from the monthly values to compute the anomalies. Therefore, the anomalies at one station may be compared with those at another.

Figure 2.3 The climatological seasonal cycle of sea level (cm) along the coast of India. The stations on the right (except Colombo) are on the east coast, and those on the left are on the west coast. The figure shows the monthly anomalies of observed and corrected sea level; the local annual mean has been subtracted from the monthly climatology to compute these anomalies. The correction for atmospheric pressure was applied using the Inverse-Barometer approximation. The effect of atmospheric pressure on sea level varies from 3 cm at Colombo to 13 cm at Paradip. The seasonal cycle of corrected sea level is coherent along the coast. Its range is greater along the east coast (45 cm) than along the west coast (30 cm). Along the east (west) coast, the corrected sea level is maximum in November (December) and minimum during March–April (the southwest monsoon).



1. The range is greater along the east coast (45 cm) than along the west coast (30 cm). The drop in the range from Chennai to Kochi is because of a decrease in the maximum; the minimum does not change as much from the east to the west coast.
2. Along the east coast, there are two maxima, a minor peak during the southwest monsoon and a major peak during November; the winter peak is broad (in time) at Paradip and narrows equatorward along the coast. The minimum occurs during April.
3. Along the west coast, sea level peaks during December, the peak being broader than along the east coast, making the seasonal cycle more symmetric; there is also a minor secondary peak at Kochi and Mumbai during the southwest monsoon, when the minimum occurs along the west coast.

Some hypotheses have been proffered to explain the seasonal and lower frequencies seen in the sea-level records along the Indian coast; the available literature is surveyed in the following section.

2.3 A Brief Survey of the Literature

The first study of the seasonal cycle of sea level along the Indian coast was by Patullo et al. [1955], who examined the climatological seasonal cycle of sea level measured by tide gauges all over the world and compared them to the height of the sea surface arising from seasonal variations in specific volume; these were computed using data from bathythermograms and Nansen bottle casts. There was a good correlation between the tide-gauge sea level and the steric oscillations at low and temperate latitudes. The sea-level anomalies were nearly equal to the sum of the steric anomalies and the atmospheric-pressure effect, implying that a pressure sensor in the deep ocean would show very small seasonal fluctuations; this condition was termed “isostasy”. Patullo et al. also noted that actual current measurements tallied well with currents computed from dynamic topography (or steric heights), implying a link between the large-scale coastal currents and sea level measured by coastal tide gauges.

Varadarajulu et al. [1982] used tide-gauge data for 10 years (1966–1975) at Paradip and concluded that the variations in monthly sea levels were related to variations in heating and cooling during summer and winter, respectively, in addition to the influence of rainfall and the seasonally reversing monsoon winds. Prasad and Reddy [1985] used the same method to study sea-level variability over 10 years (1970–1979) at Chennai. They too linked the observed variability to the physical properties of sea water and the climate in the neighbourhood of Chennai. Both these studies related sea-level changes purely to local causes.

Shetye and Almeida [1985] compared the seasonal cycle of sea level at several stations along the coast of India with those of local rainfall and the large-scale coastal current in the vicinity of the gauge. The seasonal cycle of corrected sea level and that of the alongshore current followed a similar pattern at most stations, Mumbai being an exception; Das [1979] also noted the connection between the seasonal cycle of sea level and that of the alongshore current at Marmagao. Therefore, while not ruling out the possible influence of runoff on the sea level along the east coast, Shetye and Almeida concluded that coastal sea level may be a good tool for monitoring the large-scale, wind-forced geostrophic currents along the coast.

Emery and Aubrey [1989] noted that the monthly sea level at different stations along the Indian coast reveals close relationships. They attributed the maxima in the seasonal cycle to storm surges and to monsoonal floods, or river runoff. Their main focus, however, was on the long-term changes in sea level. Five stations — Mumbai, Kochi, Mangalore, Chennai, and Vishakhapatnam — were found to be reliable indicators of long-term changes. Of these, Mangalore showed a decrease in relative sea level (1.3 mm year^{-1}), while the others showed an increase in sea level relative to land, the rate varying from $0.36 \text{ mm year}^{-1}$ at Chennai to 2.1 mm year^{-1} at Kochi. This indicates either marginal subsidence of land, or a slow rise in sea level. These results are similar to those obtained for Australia [Aubrey and Emery, 1986], where eight acceptable station records averaged 2.2 mm year^{-1} of land subsidence or sea-level rise. This similarity is striking because Australia is known for its tectonic stability and India for its nearness to a belt of tectonic instability. Other coastal regions of the world exhibit more erratic and local changes ascribable to tectonics associated with folding, faulting, melting of ice caps, volcanic activity, and delta growth, only the last of which can be important along the western and southeastern coasts of India and Australia. Hence, Emery and Aubrey concluded that these two regions may be the best indicators of long-term, relative sea-level change.

Tsimplis and Woodworth [1994] updated the work of Patullo et al. [1955], using three times the quantity of data used in the earlier work. They decomposed the climatological seasonal cycle into annual and semiannual harmonics, presenting the worldwide distribution of the amplitudes and phases of both. There is a difference in annual phase between the east and west coasts of India; the annual phase progressively increases from the east to the west coast. The annual amplitude is much larger than the semiannual amplitude. A large semiannual amplitude, however, may not imply a realistic semiannual oscillation, but can be the result of irregularities in the annual cycle, caused, for example, by the sudden onset of the monsoon.

Clarke and Liu [1994] used monthly sea level along the Indian coast to study interannual variability. They found a significant correlation between the sea level at Vishakhapatnam and that at Chennai, Kochi, and Mumbai. The correlation is maximum at non-zero lags, hinting at the possibility of wave propagation along the coast. Based on a model study, they concluded that

an interannual sea-level signal occurs along more than 8000 km of the Indian Ocean coastline, extending from southern Java to Mumbai, and is generated remotely by zonal interannual winds along the equator. Clarke and Liu [1993] used the same model to study the annual and semiannual sea levels along the eastern boundary of the equatorial Indian Ocean. They concluded that atmospheric pressure, local alongshore winds, and remote forcing by equatorial Kelvin waves were the causes of the observed oscillations.

Thus, these studies show that the sea levels at different stations along the Indian coast reveal close relationships. However, the causes of the observed variability, seasonal or interannual, are not clear. Atmospheric pressure has an effect on sea level, but this is easily accounted for by the Inverse-Barometer approximation. There is also some similarity between the seasonal cycle of local rainfall, and hence of river runoff, and that of sea level. Most crucial, however, is the striking resemblance of the seasonal cycle of coastal currents to that of sea level along the Indian coast. This, and the significant correlation between interannual variations in sea level at Vishakhapatnam and at other stations, suggests that the low-frequency variability of sea level along the Indian coast is linked to the large-scale circulation in the north Indian Ocean. This is not surprising, given that a similar relationship has been noted elsewhere too [Patullo et al., 1955].

2.4 The Large-Scale Circulation Along the Coast of India

Oceanographers have traditionally relied on hydrographic data to estimate currents in the ocean [Pickard and Emery, 1982]. The first major hydrographic survey of the north Indian Ocean was made during the International Indian Ocean Expedition (IIOE) in the late 1960s [Wyrcki, 1971]. Several hydrographic surveys have been carried out in the north Indian Ocean since then, and a coherent picture of the large-scale coastal circulation around India emerged during the 1990s⁹. We use the data collected during six hydrographic surveys during 1987–1994 in the Exclusive Economic Zone (EEZ) of India, in conjunction with ship drifts, to describe the large-scale circulation off the Indian coast. Each of these methods has its own drawbacks. Dynamic topographies constructed from hydrographic data assume a level of no motion, typically 1000 m, and are therefore unreliable in the vicinity of a coast. Ship drifts, on the other hand, are influenced by wind and usually are too noisy to yield a coherent picture of the basin-scale circulation. Nevertheless, in the absence of direct current-meter measurements, these are the only means of estimating currents along the Indian coast.

⁹An extensive bibliography for the Bay of Bengal is given by Varkey et al. [1996].

2.4.1 Hydrography of the Coastal Waters of India

Three cruises surveyed the coastal waters off the Indian west coast during June–August 1987 [Shetye et al., 1990], December-1987–January-1988 [Shetye et al., 1991a], and March–April 1994, and three cruises surveyed the coastal waters off the Indian east coast during July–August 1989 [Shetye et al., 1991b], March–April 1991 [Shetye et al., 1993], and November–December 1991 [Shetye et al., 1996]. These cruises¹⁰ followed near-identical tracks, measurements being made along sections (also called legs) normal to the coast or to the shelf-break.

The dynamic topography with respect to 1000 dbar for these six cruises is shown in Figure 2.4. The dynamic height field is a measure of the geostrophic transport in the top 1000 m of the water column; the smaller the spacing between the contours of dynamic height, the larger is the transport of the associated current, which, in the northern hemisphere, flows with the higher dynamic height on its right. The dynamic topographies in Figure 2.4 are but snapshots, representative of the large-scale circulation during the period of the survey, but they provide the only coherent hydrographic observations in the region. The schematic in Figure 2.5 shows the transports associated with these coastal currents over the top 1000 m of the water column. Interannual variability is expected to cause changes in the transports of these current systems, but they still provide a rough picture of the climatological seasonal cycle of the coastal currents around India.

The currents along the coast of India change direction with season. From November to January, the current along the east coast, the East India Coastal Current (EICC), is equatorward all along the coast [Shetye et al., 1996]. It bends around Sri Lanka to flow along the Indian west coast [Shetye et al., 1991a] as a poleward West India Coastal Current (WICC). Off southwest India, the poleward flow is along the western flank of an anticyclonic high that forms in the region; a geostrophic current completes the circulation around the high, forcing an equatorward WICC off southwest India¹¹. The EICC reverses in February, and it flows poleward during March–May, forming the western boundary current of a basin-wide anticyclonic gyre [Shetye et al., 1993]. The anticyclonic high off southwest India persists through March–April, weakening thereafter and giving way to a cyclonic low during the southwest monsoon (June–September); during this period, the WICC flows equatorward along most of the Indian west coast [Shetye et al., 1990]. The EICC is weak during the southwest monsoon; it is poleward in the south, but is equatorward in the north [Shetye et al., 1991b].

Since the dynamic heights do not represent a climatology, we refrain from comparing them with tide-gauge sea level; this has been done elsewhere, and the agreement found to be good

¹⁰Hereafter, we refer to these six cruises as the “EEZ cruises” because they surveyed the Exclusive Economic Zone (EEZ) of mainland India. A summary of these observations is available in Shetye and Gouveia [1998].

¹¹Shetye et al. [1990, 1991a] do not define the WICC the way we do; they compute the transport by integrating across the high. Therefore, the transport estimates given here are different. So are the current widths; for example, Shetye et al. describe a coastal current that is 400 km wide off southwest India. We define the EICC and WICC more precisely in the next chapter.

[Patullo et al., 1955]. A better comparison is afforded by ship drifts because the far larger number of observations, spread over several years, makes it possible to define a climatology. This was done by Shetye and Almeida [1985] and we repeat the exercise, but with a more extensive ship-drift data set.

2.4.2 Coastal Sea Level, Coastal Currents, and Local Alongshore Winds

We use the ship-drift climatology compiled by Rao et al. [1989], which was not available to Shetye and Almeida [1985], to compute the alongshore coastal current. Since the ship drifts are averaged over $2^\circ \times 2^\circ$ bins, the alongshore coastal currents computed from them represent the large-scale coastal circulation. The climatological seasonal cycle of corrected sea level and that of the alongshore coastal current computed from ship drifts are shown in Figure 2.6. The agreement between the two is excellent, except at Colombo. The only major discrepancy is that the alongshore current peaks a month before the sea level does on the west coast. The seasonal cycle of surface circulation in the north Indian Ocean, as revealed by ship drifts (Figure 2.7), also agrees fairly well with the current systems outlined in Figure 2.5.

Since the local alongshore coastal currents match tide-gauge sea level very well, it is possible that the local winds, which must play a role in forcing these currents, also play a role in forcing the seasonal cycle of sea level. The seasonal cycle of corrected sea level is compared with that of the local alongshore wind stress, computed from the climatology of Hellerman and Rosenstein [1983], in Figure 2.8. The annual mean of the wind stress at each location is removed to obtain the monthly anomalies that are plotted in the figure; this is done because the sea-level data plotted are also anomalies. The mean wind-stress field, which is not negligible, can set up a steady alongshore sea-level gradient, but it cannot force time-dependent changes in sea level.

The local alongshore winds and corrected sea level are in phase along most of the west coast, but are in phase only during winter along the east coast, where the strongest upwelling-favourable winds blow during the southwest monsoon, but sea level is lowest earlier in the year. The sea-level range along the east coast is about twice that along the west coast, but the range of alongshore wind stress along the east coast is about 5–6 times that along the west coast. Along the west coast, the range of sea level does not change significantly from Colombo in the south to Mumbai in the north, but there is a large change in the wind stress, especially from Colombo to Kochi. The wind stress at Colombo matches that along the Indian east coast, but the sea level cycle at Colombo is more akin to that along the Indian west coast; the ship drifts at Colombo are influenced more by the strong local winds than by the currents, leading to the mismatch between ship drifts and sea level there (Figure 2.6). These discrepancies imply that the seasonal cycle of sea level along the coast of India is not forced merely by local winds. The coherence in the seasonal cycle of sea level and ship drifts along the coast points to organization on the scale of the basin; it also suggests that

Figure 2.4 Dynamic topography in the coastal waters of India, based on six cruises in the Indian EEZ during 1987–1994. The contour interval is $5 \text{ cm}^2\text{s}^{-2}$. The minimum and maximum dynamic height for each cruise are listed in the figure. The “+” indicate the locations at which the hydrographic profiles were obtained. The time of the cruises are mentioned in addition to the months they are considered representative of.

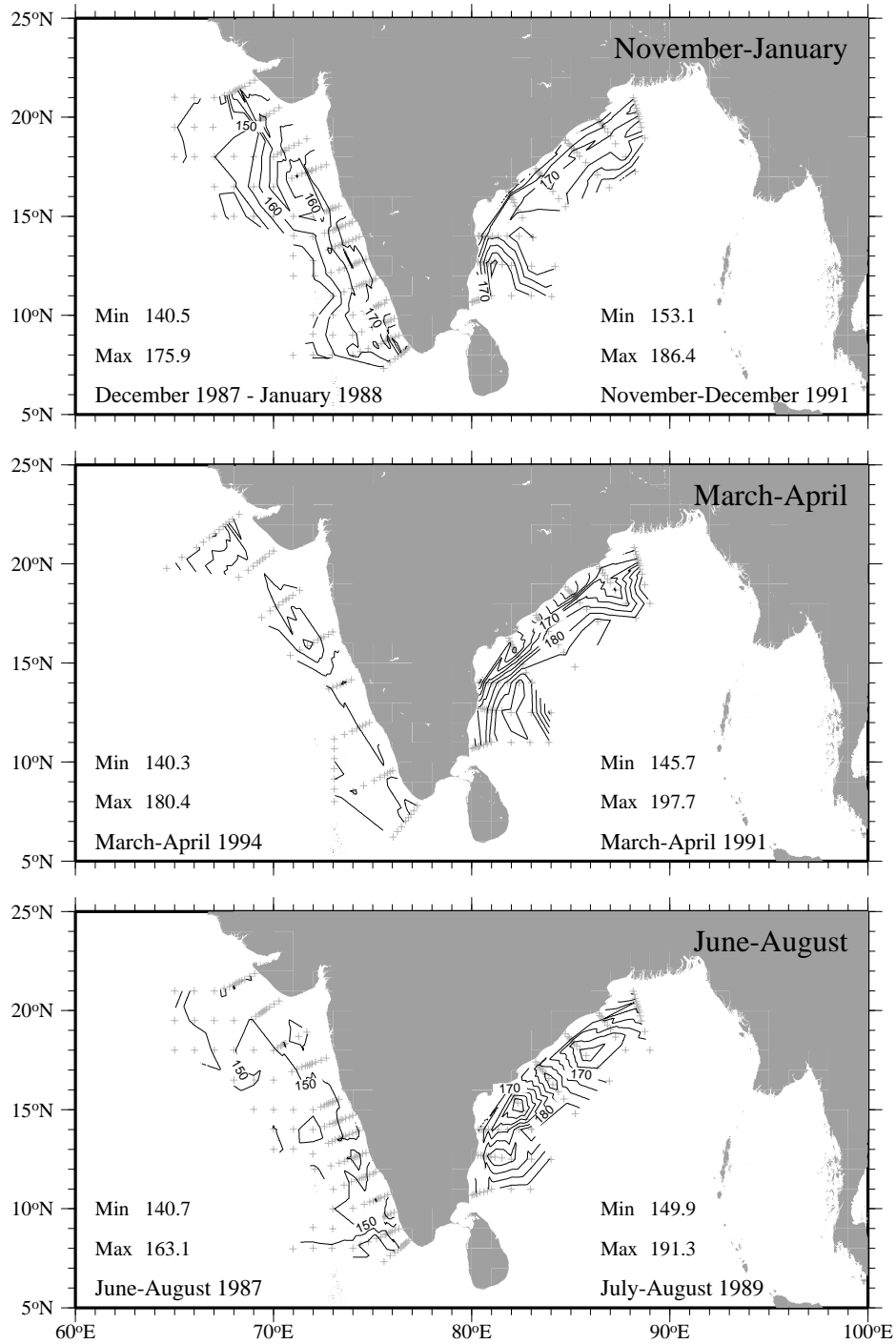


Figure 2.5 A schematic of the current systems along the coast of India. The number against each current indicates the transport (in Sv; $1 \text{ Sv} = 10^6 \text{ m}^3 \text{ s}^{-1}$) associated with it in the top 1000 m of the water column. These estimates, based on the six EEZ cruises, provide but an idea of the coastal circulation off India; interannual variability will change the magnitude of these currents, and in the case of the weak currents, even the direction.

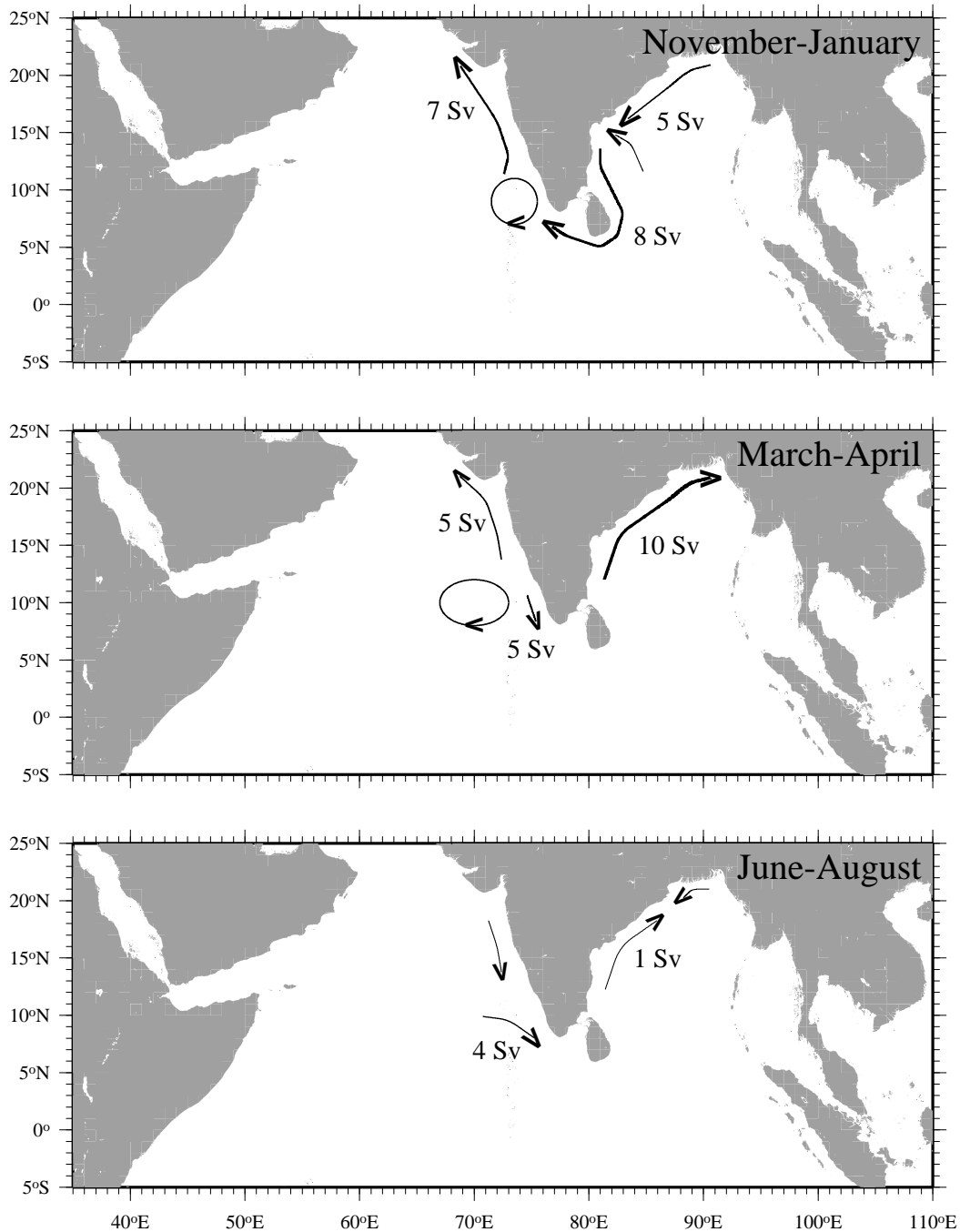


Figure 2.6 Seasonal cycle of corrected sea level (cm) and alongshore ship drifts (cm s^{-1}) along the coast of India. The ship drifts are from the climatology of Rao et al. [1989]. These data are not available at Mumbai and Paradip. The annual mean of the ship drift at each location has been removed to obtain the monthly anomalies that are plotted; this was done because the sea level data plotted are also monthly anomalies. Downwelling- (upwelling-) favourable anomalies are positive (negative); these currents flow with the coast on their right (left) in the northern hemisphere. The ship drifts match the sea level at the coast, except at Colombo, where the strong local winds (see Figure 2.8) influence the ship drifts more than the currents do.

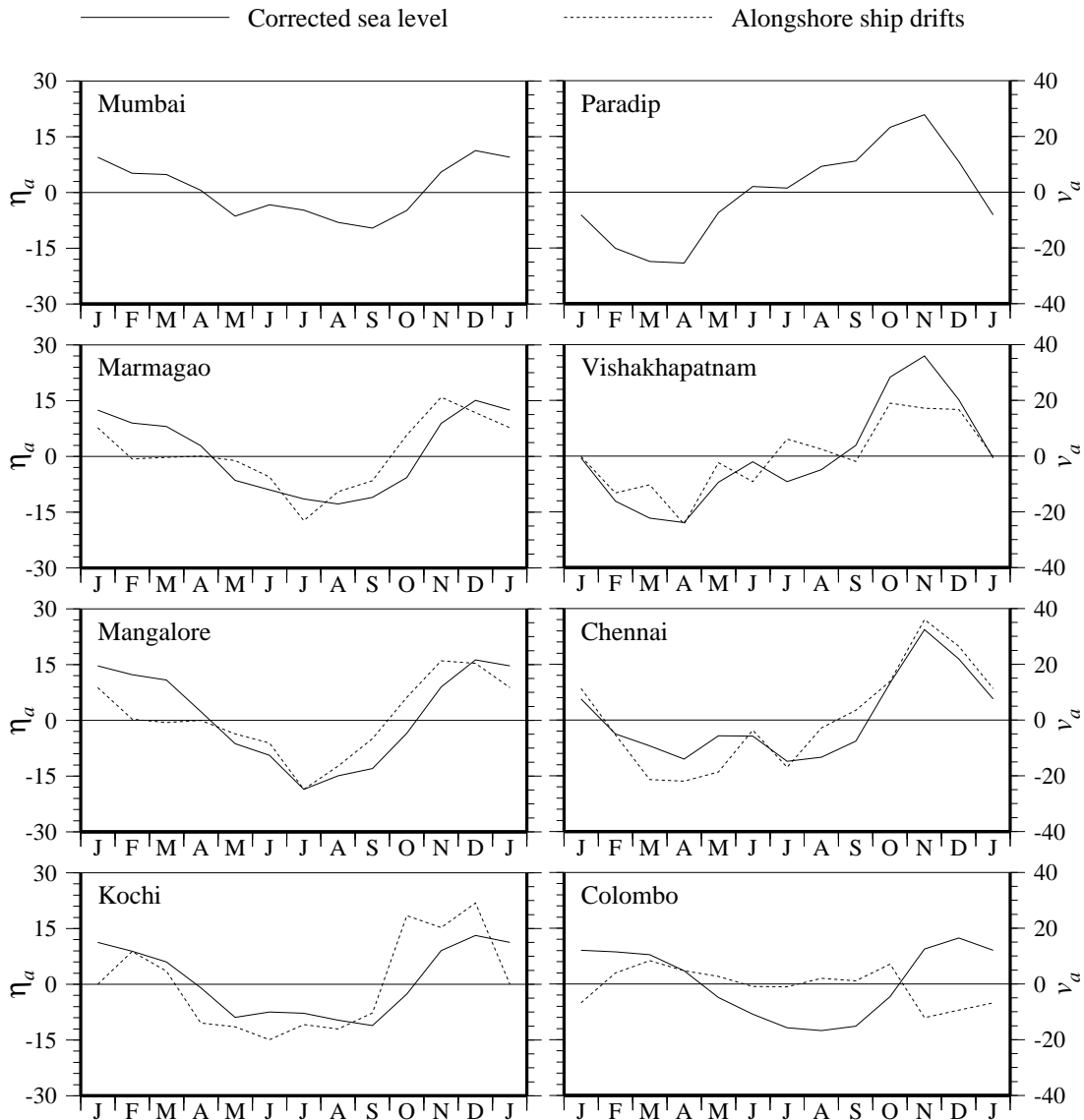


Figure 2.7 Seasonal cycle of surface circulation in the north Indian Ocean, as revealed by ship drifts [Rao et al., 1989]. The currents (cm s^{-1}) were interpolated to the grid used by the numerical model (see Chapter 3) from the original $2^\circ \times 2^\circ$ bins. In January, the EICC is weak; during February–May, it flows poleward and forms the western boundary current of a basin-wide anti-cyclonic gyre. The WICC is poleward during January–April, except off southwest India, where it flows equatorward to close the geostrophic circulation around a high. The westward Northeast Monsoon Current (NMC) connects the EICC and the WICC.

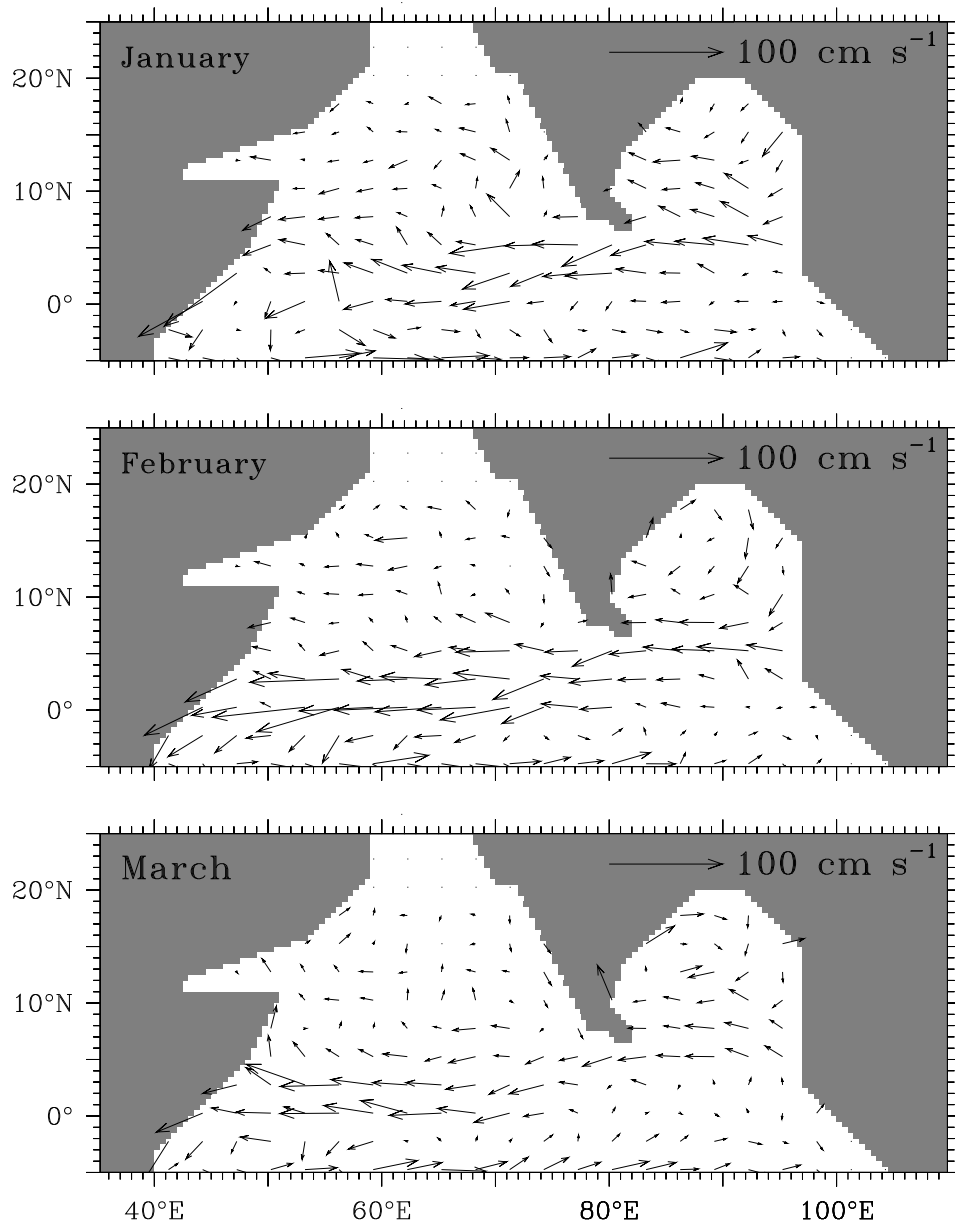


Figure 2.7 (continued) Seasonal cycle of surface circulation in the north Indian Ocean, as revealed by ship drifts [Rao et al., 1989]. The currents (cm s^{-1}) were interpolated to the grid used by the numerical model (see Chapter 3) from the original $2^\circ \times 2^\circ$ bins. During February–May, the EICC flows poleward, forming the western boundary current of a basin-wide anticyclonic gyre. The gyre breaks up in May and the EICC weakens, but it continues to flow poleward till September. The WICC reverses to flow equatorward during the southwest monsoon. The monsoon winds bring about dramatic changes, forcing an eastward jet at the equator during April–May and a strong, poleward current off Somalia during May–September.

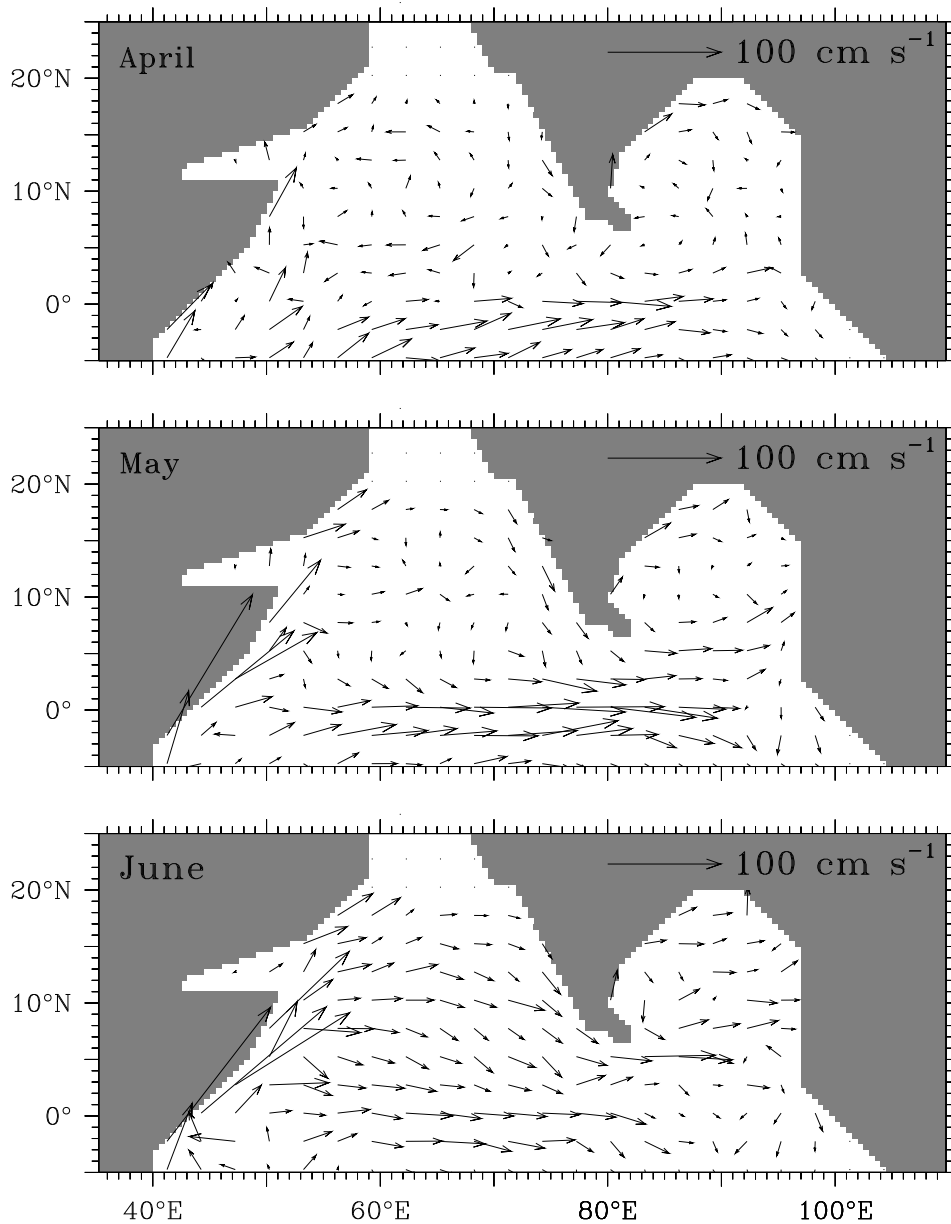


Figure 2.7 (continued) Seasonal cycle of surface circulation in the north Indian Ocean, as revealed by ship drifts [Rao et al., 1989]. The currents (cm s^{-1}) were interpolated to the grid used by the numerical model (see Chapter 3) from the original $2^\circ \times 2^\circ$ bins. During the southwest monsoon, the strong, poleward Somali Current feeds into the the Southwest Monsoon Current (SMC), which spans the basin, flowing across the Arabian Sea and the southern Bay of Bengal. In the Bay of Bengal, a weak EICC flows poleward, but the Ekman drift dominates the ship-drift data. The WICC flows equatorward.

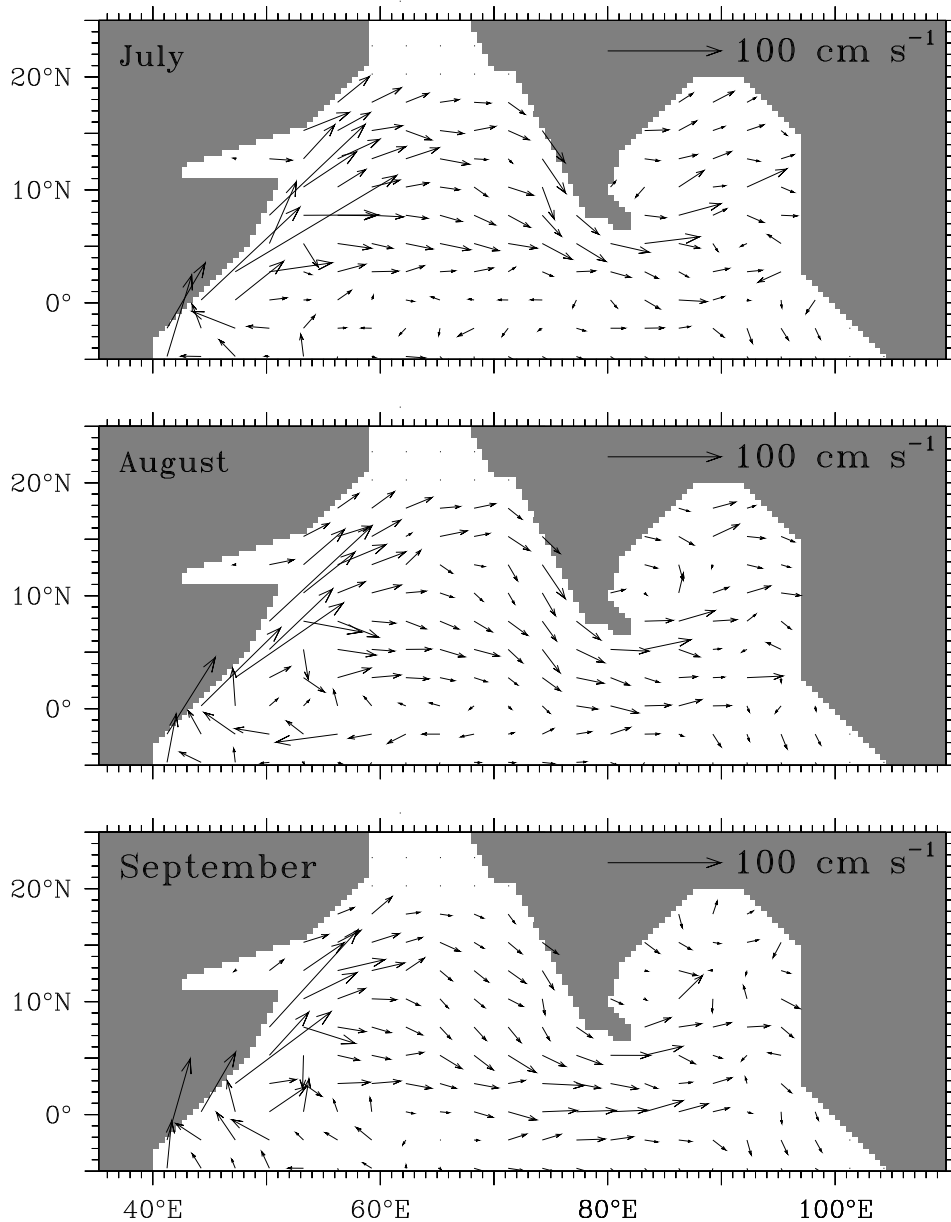


Figure 2.7 (continued) Seasonal cycle of surface circulation in the north Indian Ocean, as revealed by ship drifts [Rao et al., 1989]. The currents (cm s^{-1}) were interpolated to the grid used by the numerical model (see Chapter 3) from the original $2^\circ \times 2^\circ$ bins. With the collapse of the south-west monsoon winds in September, the major currents in the north Indian Ocean reverse direction. The EICC reverses to flow equatorward, the WICC reverses to flow poleward. The Somali Current weakens and reverses in November, when an eastward jet forms again at the equator. By December, the NMC appears in the southern bay.

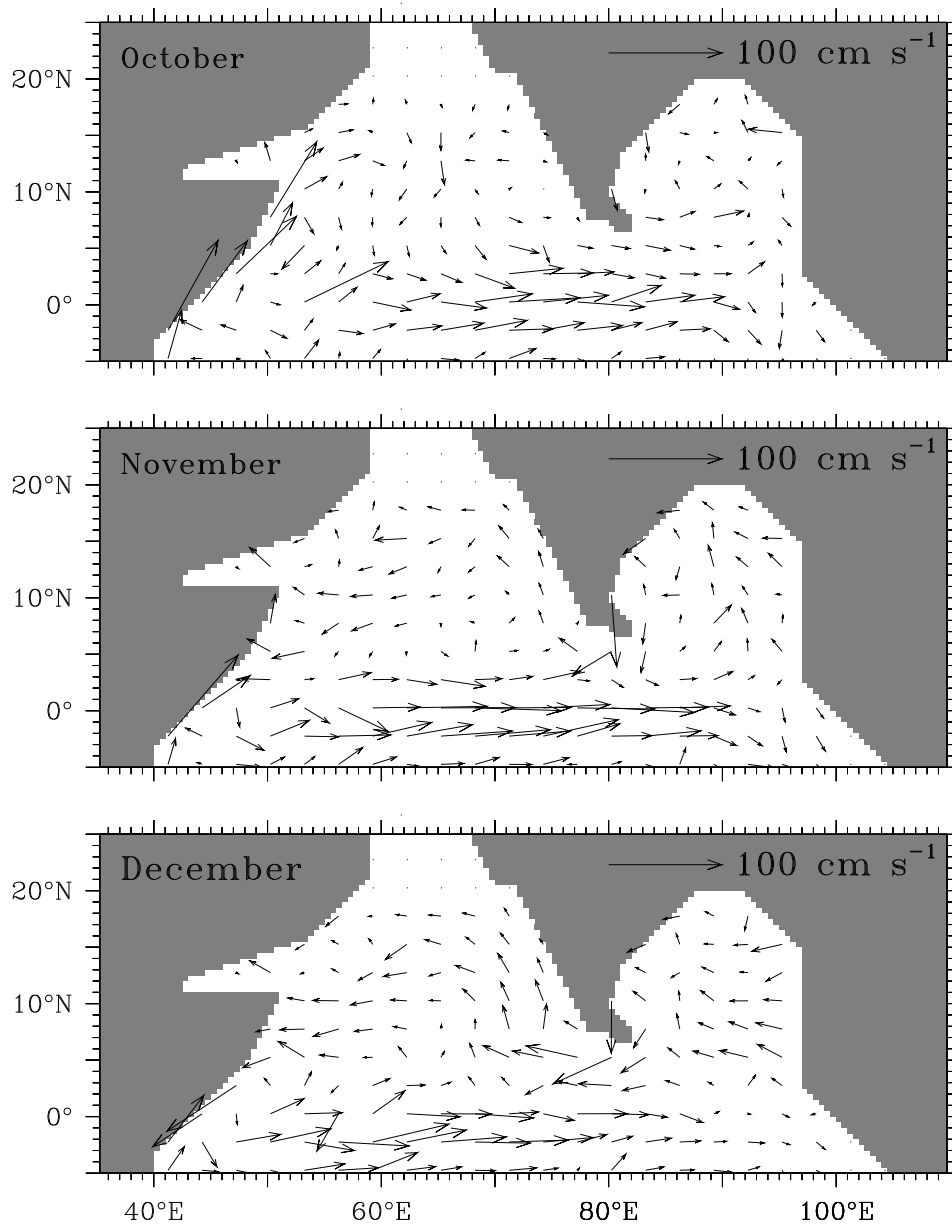
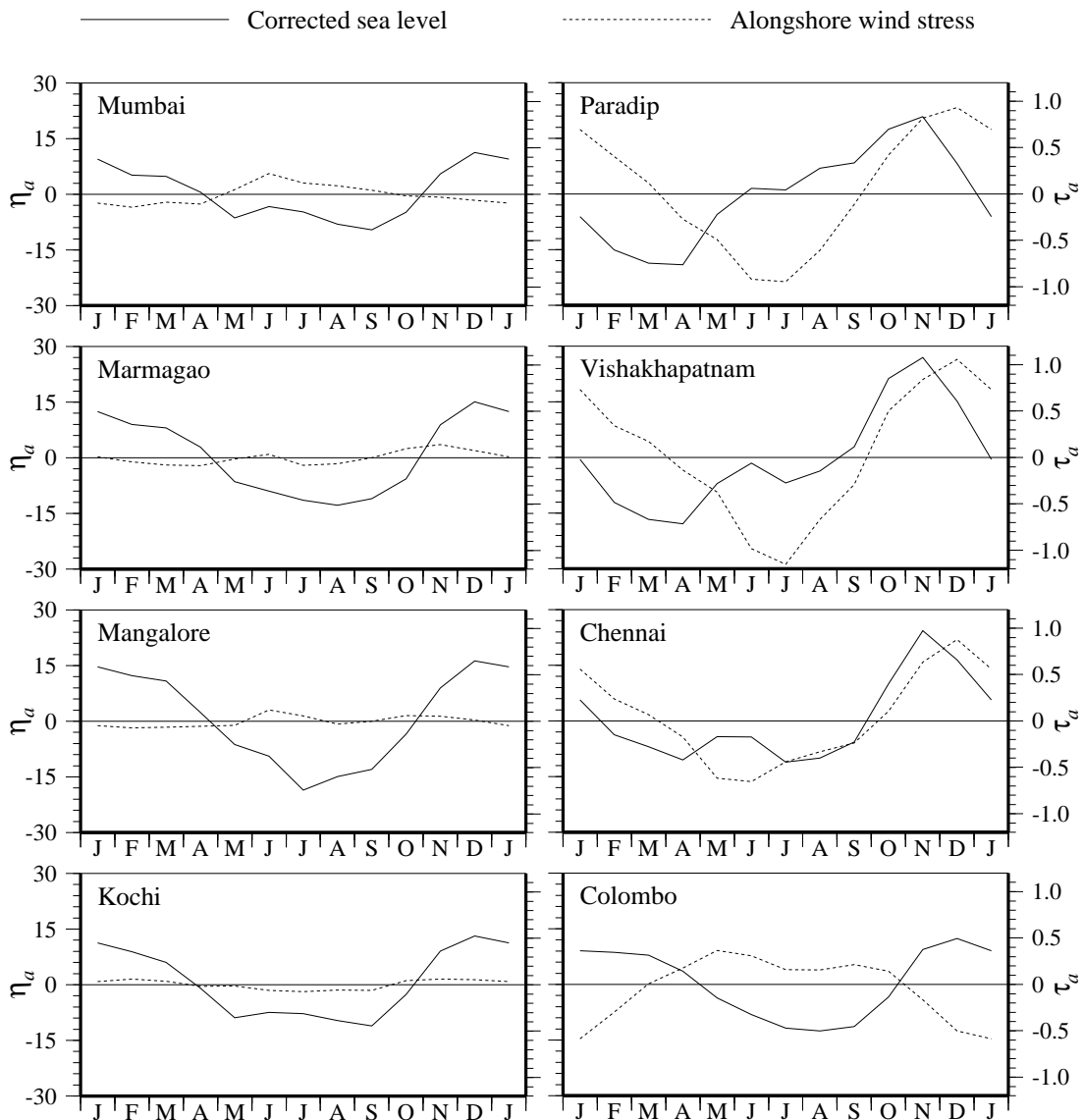


Figure 2.8 Seasonal cycle of corrected sea level (cm) and local alongshore wind stress (dyne cm^{-2}). The wind-stress data are from Hellerman and Rosenstein [1983]. The annual mean of the wind stress at each location has been removed to obtain the monthly anomalies that are plotted; this has been done because the sea-level data plotted are also monthly anomalies. The mean wind-stress field, which is not negligible, can set a steady alongshore sea-level gradient, but it cannot force time-dependent changes in sea level. Downwelling- (upwelling-) favourable anomalies are positive (negative); looking downwind, these winds blow with the coast on their right (left) in the northern hemisphere. The lack of agreement between the local winds and sea level implies that remote forcing is important for the seasonal cycle of sea level and currents along the coast of India.



the circulation along the coast of India is, at least in part, forced remotely.

2.5 Basin-Scale Dynamics of the North Indian Ocean

The need to explain the seasonal cycle of circulation off the Indian coast led, during the 1990s, to the development of a framework involving long baroclinic waves, which had been invoked earlier to explain the sea-level variability along the west coast of the American continent. Anomalies of monthly sea level along the eastern boundary of the Pacific are visually coherent and statistically well-correlated from Valparaiso in Chile to the Canadian border [Enfield and Allen, 1980; Chelton and Davis, 1982], the anomalies propagating poleward in both hemispheres. These anomalies are linked to El Niño, whose domain extends across the equatorial Pacific Ocean. The link is provided by equatorial Kelvin and Rossby waves and coastal Kelvin waves, which propagate long distances, carrying information across the equatorial Pacific and forcing changes in locations far removed from the winds that force these changes in the ocean.

The success of this theory in the Pacific Ocean appears to have prompted its application in the Indian Ocean; this development was synchronous with the hydrographic surveys described earlier. Since these waves communicate changes in sea level or currents forced by winds in one region to remote locations, they merge the equatorial Indian Ocean, the Bay of Bengal and the Arabian Sea into a single dynamical entity, the north Indian Ocean, whose dynamics must be modelled as a whole even to simulate the circulation in its parts. The numerical models developed in the 1990s have been fairly successful in simulating the basic features of the observed circulation in the north Indian Ocean; their success implies that the circulation along the Indian coast must, at least in part, be remotely forced. Though there are some studies using Ocean General Circulation Models (OGCMs), most have used reduced-gravity models¹², which had been used with success in studying the El-Niño phenomenon in the Pacific Ocean.

In the following chapter, we use a reduced-gravity model to simulate the circulation in the north Indian Ocean. We focus our attention on the high and low that form off southwest India (see Section 2.4.1) because these cannot be explained without invoking the long baroclinic waves¹³ and the connection they establish between the Bay of Bengal, the Arabian Sea, and the equatorial Indian Ocean. Called the Lakshadweep high and low after the islands in whose vicinity they form (Figure 1.2), they also have the benefit of novelty, having been discovered recently by Bruce et al. [1994]¹⁴. Shankar and Shetye [1997] studied the dynamics of the Lakshadweep high and low, and the following chapter is based largely on their work.

¹²The reduced-gravity model is described in Appendix A.

¹³See Appendix B for a brief description of these waves.

¹⁴Bruce et al. used the name “Laccadive”, an anglicized form of “Lakshadweep”, which literally means “a hundred thousand islands”. Lakshadweep is the official name of this group of islands.