

# DYNAMICS OF CIRCULATION OF THE WATERS AROUND INDIA

Satish R Shetye

*National Institute of Oceanography  
Dona Paula 403 004, Goa*

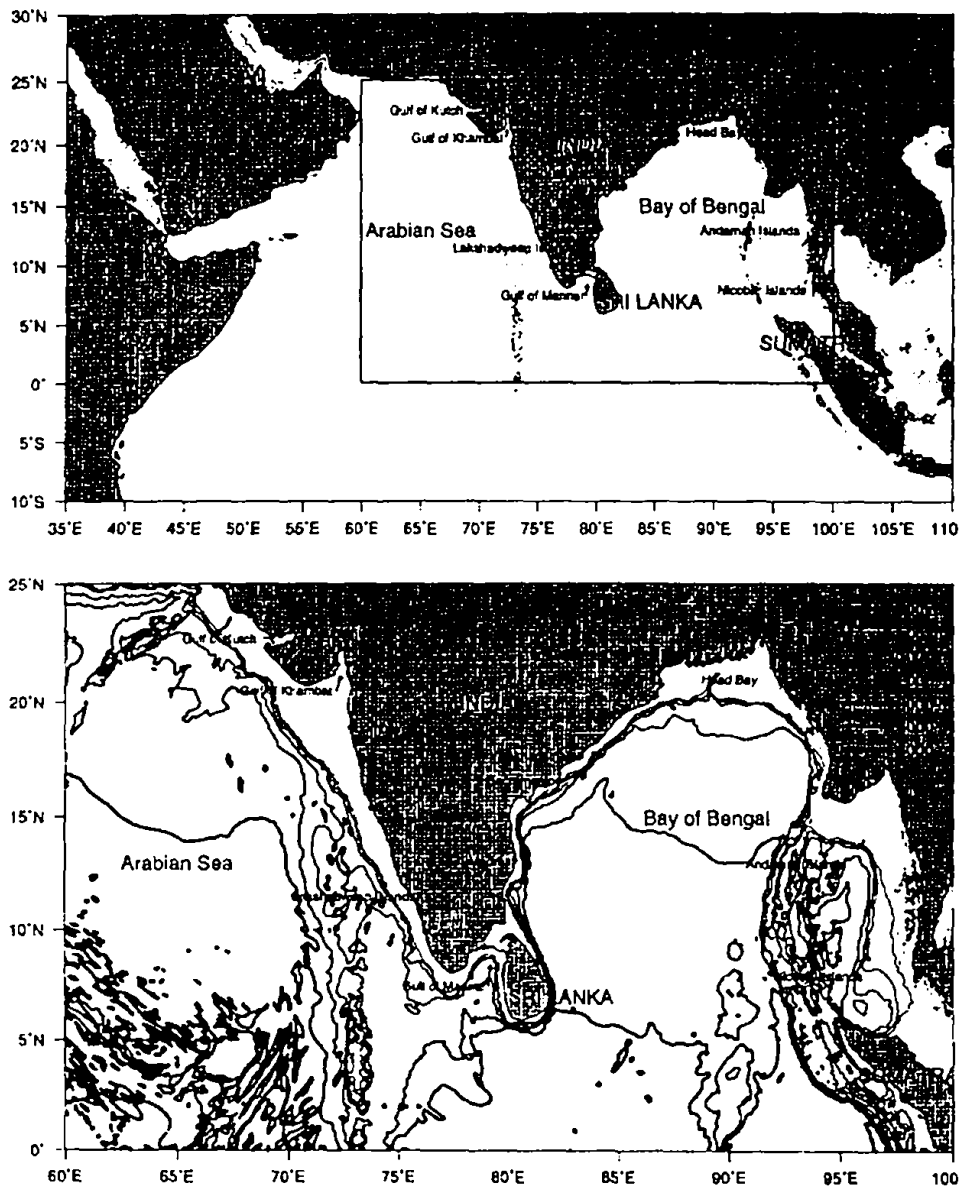
During the last decade the understanding of dynamics of the large-scale seasonal coastal currents around India has markedly improved. However, a number of major issues concerning circulation on the shelf and in the estuaries remain unresolved. An adequate infrastructure to study them is now available, and understanding gained by studying them offers the promise of capability to address environmental issues and to develop new services in the coastal regime. To avail of these opportunities an integrated approach to the generation of postgraduate manpower and its deployment is needed.

## INTRODUCTION

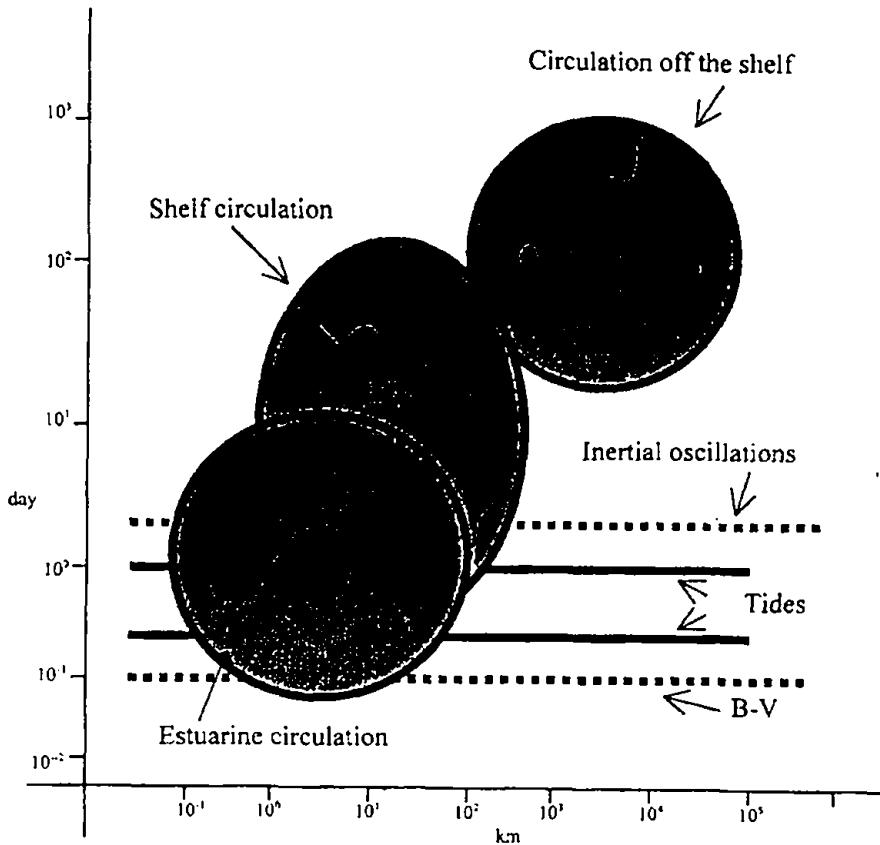
Understanding the dynamics of circulation of the waters along India's coastline is fundamental to the study of a variety of processes that concern this approximately 6000 km long marine zone. Transport of pollutants from marine outfalls of domestic and industrial waste, erosion of beaches, processes such as upwelling that control biological productivity and hence fisheries, processes that control chemistry of the region, etc. are all influenced by characteristics of the circulation. This article examines the status of our understanding of the dynamics of circulation: what is known, what needs to be studied, and what are opportunities and concerns for the future?

The discussion is divided into three parts. The first deals with the large-scale near-surface currents beyond the shelf-edge that is close to the 200 m depth contour (see Fig. 1). The second examines the circulation on the continental shelf, which comes under the influence of not only the large-scale currents, but also tides, local winds, and river runoff. The third part is concerned with estuaries, the interface between saline waters and freshwater carried by rivers, where circulation is determined primarily by tides and river runoff.

These three parts can also be distinguished by the length and time-scales displayed by currents (Fig. 2). The large-scale seasonal circulation has length scales of the order of 100-10,000 km, and time scales of a few tens of days to a few years. The core of this flow is on the continental slope. Circulation on the shelf has length scales ranging between 10-100 km and time scales of 10-100 days. Scales associated with estuarine circulation are shortest of the three, 100 m-100 km and a few hours to a few days.



**Figure 1.** (a) The North Indian Ocean, and (b) The Indian coastal region. Even though the area around the Lakshadweep, Andaman and Nicobar islands form a part of the Indian coastal region, the article discusses only the region around the continental coast line. The contours in (b) give bottom topography.



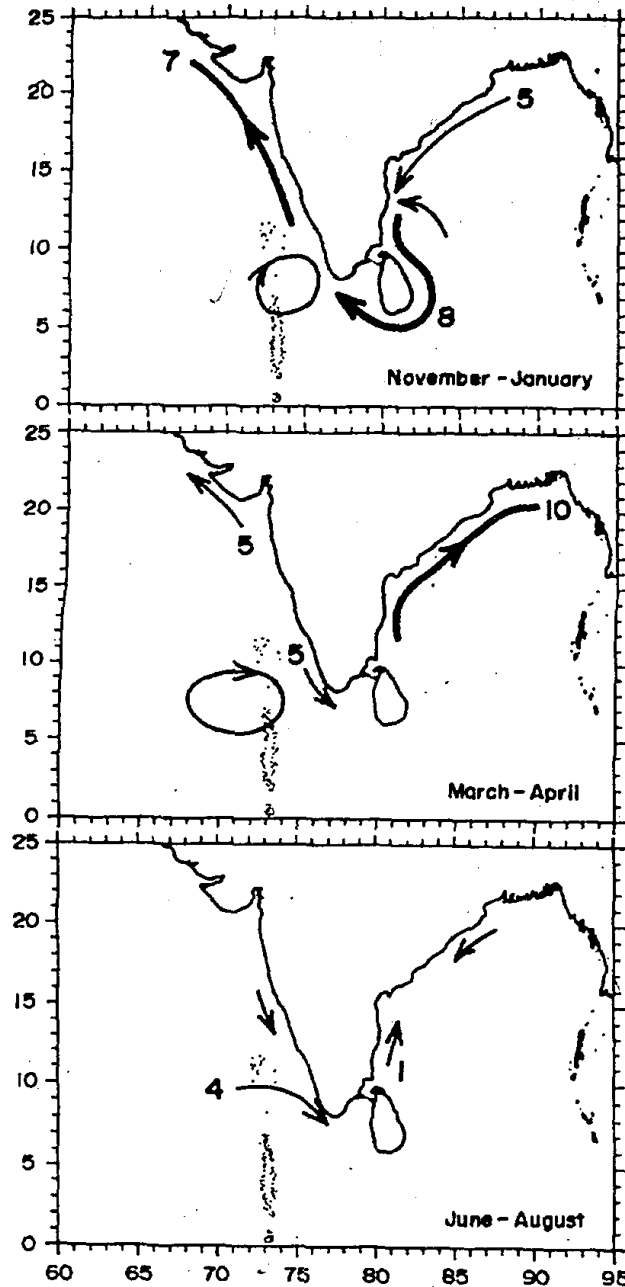
**Figure 2.** Length-and time-scales associated with circulation in vicinity of the Indian coastline. The inertial period has been set at approximately 2 days corresponding to the latitude of  $15^{\circ}$  N. Internal waves can occur with a frequency between the inertial frequency and the Brunt-Vaisala frequency (B-V).

Sections 2, 3 and 4 examine, respectively, the large-scale, the shelf and the estuarine circulation. Section 5 summarizes the key issues that will need to be addressed during the next decade.

## 1. LARGE-SCALE NEAR SURFACE CIRCULATION

What is the nature of large-scale near-surface currents around India? A number of studies<sup>1-6</sup> carried out in the last decade have addressed this question. Fig. 3 is a schematic summary of their findings. The figure confirms what has been known earlier: the coastal currents around India reverse seasonally. This is an expected feature because the N. Indian Ocean experiences seasonally reversing monsoon winds. The figure, however, has some surprises. Though winds over the N. Indian Ocean are much stronger during the southwest monsoon (June-September), the circulation along the coast of India is better organized during the northeast monsoon (November-January). Along the western coast of India the transport of West India Coastal Current (WICC) is largest, about  $7 \times 10^6 \text{ m}^3/\text{s}$  during the northeast

monsoon. This estimate was made in the region off the coast of Saurashtra<sup>3</sup>, when the WICC flows northward along the entire coast against weak winds. In contrast, during the southwest monsoon the largest transport of the WICC, about  $4 \times 10^6 \text{ m}^3/\text{s}$ , is observed off the southwest coast of India. It is equatorward, and occurs in the same direction as the local winds. During this season the current weakens rapidly in the north.



**Figure 3.** A schematic summary of the currents around the Indian subcontinent during November-January, March-April, and June-August. The number next to the arrow gives estimate of the transport of the current in unit of  $10^6 \text{ m}^3/\text{s}$ . The anticyclonic circular cell during March-April represents the Lakshadweep High, and the cyclonic cell during June-August is the Lakshadweep Low.

Another surprise in Fig. 3 is that the East India Coastal Current (EICC) is best developed during March-April, when winds in the region of the current are very weak, in fact, weakest of the year. Moreover, like the WICC, the EICC is much weaker and unorganized during the southwest monsoon than in the northeast monsoon when it can be traced all along the east coast using salinity as the tracer. The current carries low-salinity waters that originate in the northern Bay due to river runoff, most notably from the Ganga and the Brahmaputra. The EICC transports these waters all the way to the southwest coast of India after turning around Sri Lanka. From there the WICC carries them northward along the coast. Thus during the northeast monsoon the WICC and EICC together girdle the coast forming a continuous flow from the northern Bay of Bengal to the northern Arabian Sea. This is the only time when the coastal circulation around the Indian coastline takes such a well developed character covering the entire coastline.

Recently<sup>7&8</sup> it has been recognized that the events that occur along the Indian coastline have implications to the circulation offshore of the southwest coast of India. Hydrographic data and satellite altimetry show that in early January, when the EICC and the WICC are well developed, positive anomalies of sea-level spread offshore from the southwest coast of India, and a circular "high" in sea-level forms to the east of the Lakshadweep Islands. We refer to it as the Lakshadweep High. An anticyclonic geostrophic near-surface flow is associated with it as depicted in Fig. 3. In February, the high stretches westward and is no longer circular. Subsequently, it spreads all the way to southwestern Arabian Sea. During the southwest a "low" in sea level forms in a similar fashion. The low is located east of the Lakshadweep islands in July-August, and associated with it is a cyclonic geostrophic near-surface flow (Fig. 3). The low then stretches westward and by October is seen spread across the entire southern Arabian Sea.

The system of circulation as depicted in Fig. 3 is indeed complicated. It cannot be forced by local winds alone, because, as pointed out above, there are times when currents are opposite to the winds. So what drives the circulation? During the last few years a number of studies<sup>8-14</sup> have helped in evolving a new theoretical framework to explain the large-scale seasonal currents in the N. Indian Ocean in general, and the coastal currents around India in particular. The following are the elements of the framework:-

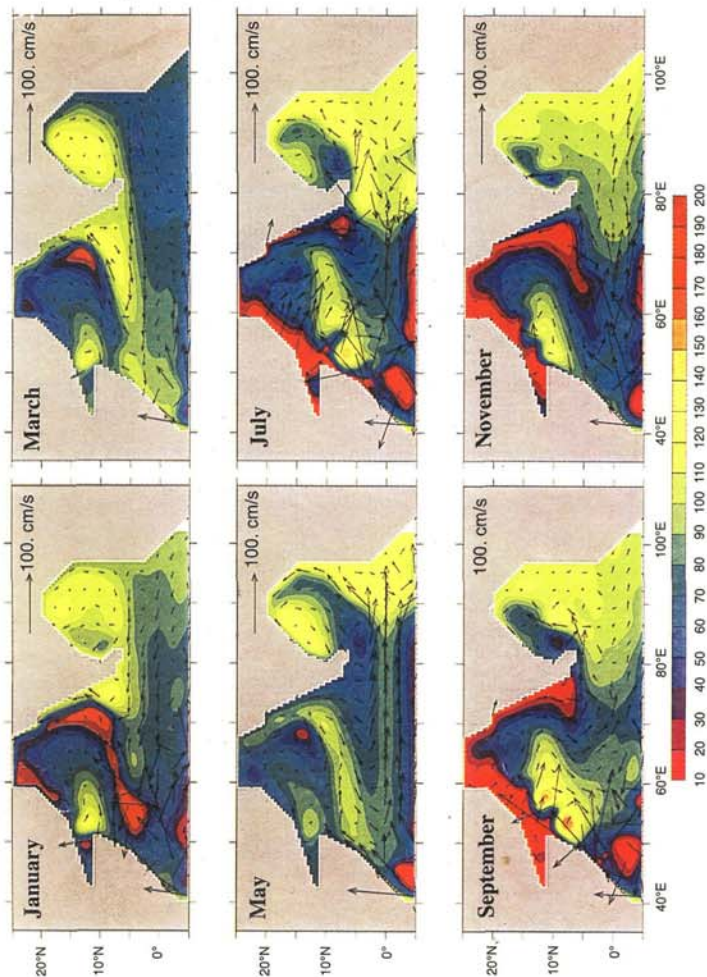
- (1) The coastal currents around India form an integral part of the circulation that encompasses the entire N. Indian Ocean basin. Hence to understand the coastal currents, it is not sufficient to look at the coast alone, but the entire basin needs to be considered.
- (2) The currents in the basin are primarily due to free and forced tropical Rossby waves, equatorial Kelvin waves, and coastal Kelvin/shelf waves triggered by the monsoons whose winds can be represented as the sum of annual and semi-annual components. Hence, the waves that make up the circulation also have annual and semi-annual periods.

- (3) There are three driving mechanisms to trigger these waves:
  - (a) coastal winds generate coastal Kelvin waves which travel large distances and influence the circulation remotely. Whenever the waves propagate along eastern margin of a basin, they radiate westward propagating Rossby waves which drive the circulation in open sea. The small size of the Bay of Bengal and of the Arabian make the waves an effective way of driving the circulation. The importance of this mechanism was first pointed out by McCreary *et al.*<sup>9</sup> This study played a pivotal role in evolution of the new theoretical framework.
  - (b) winds along the equator trigger Equatorial Kelvin Waves that, on impinging on the coast of Sumatra in the east, generate coastal Kelvin waves that move along the periphery of the Bay of Bengal. As they propagate northward, they also radiate Rossby waves that influence circulation in the open bay. This mechanism was highlighted by Yu *et al.*<sup>10</sup> and by Potemra *et al.*<sup>11</sup>
  - (c) divergence of Ekman transport over the open sea regime of the N. Indian Ocean trigger Rossby waves that influence the open sea. This mechanism was highlighted by Shetye *et al.*<sup>5</sup>

Development of this new theoretical framework was largely triggered by numerical model calculations<sup>8-14</sup> with realistic basin geometry and wind forcing. Even the simplest of these models showed impressive ability to simulate features seen in the observations. Fig. 4 depicts the annual cycle of currents simulated in one such model, a one and half layer reduced gravity model<sup>8</sup> driven by the monthly mean wind stress climatology of Hellerman and Rosenstein.<sup>15</sup>

Shankar *et al.*<sup>12</sup> and McCreary *et al.*<sup>13</sup> have examined the contribution of each of the three forcing mechanisms to the driving of the EICC. They concluded that the strong northeastward flow during March-April results from a combination of all the three forcing functions, whereas the weaker northeastward flow during June-September is primarily the result of local winds. It was further determined that the southward EICC during October-January is forced by Ekman pumping and by local along-shore winds.

Numerical experiments by McCreary *et al.*<sup>9</sup> suggested that the WICC is mainly forced remotely by Kelvin waves that reach the west coast from the Bay of Bengal. Shankar and Shetye<sup>8</sup> have carried this idea further to propose that these Kelvin waves are also responsible for the formation of the Lakshadweep High/Low. The authors argued that the high/low arise when annual and semi-annual Kelvin waves radiate Rossby waves while propagating northward along the southwest coast of India after turning around the coast of Sri Lanka. It was further shown that any Kelvin wave that reaches the west coast can generate a high/low, provided the period of the wave exceeds a critical value which is about 40 days. Waves with smaller periods stay trapped at the coast as they propagate northward.



**Figure 4:** The annual cycle of circulation in the North Indian Ocean simulated in a reduced gravity one and half layer model (see ref. 8). Upper layer thickness (m, bar on the bottom) and velocity (cm/s, arrows, scale in right of panels) are shown. Contour interval is 10 m.

The period-dependent behaviour of the Kelvin waves along the west coast is of interest because it is now well established that winds over the N. Indian Ocean exhibit variability on a wide range of periods including biweekly<sup>16</sup> and 30-60 days.<sup>17</sup> These winds are expected to trigger coastal waves with similar periods. There is evidence for existence of the waves in the daily sea level along the coast of India (Fig. 5). In addition to seasonal variability, the figure shows presence of oscillations with periods ranging from 10 to 100 days. It is expected that the oscillations are the manifestation of locally- and remotely-forced coastal/shelf waves. In Fig. 5 the amplitude of the oscillations is of the same order as the seasonal amplitude.

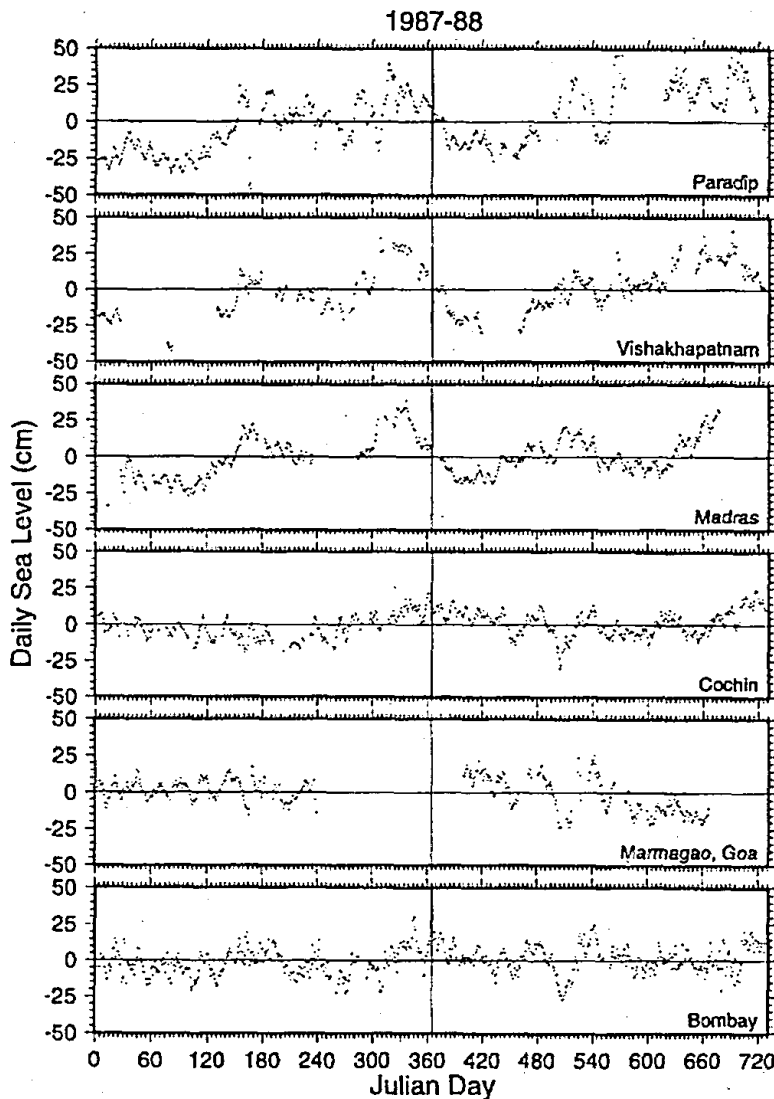


Figure 5. Deviation from the mean of daily sea level (cm) during 1987-88 at Paradip, Visakhapatnam, Madras, Cochin, Goa, and Bombay (see Fig.1 for locations) Julian day 1 is 1 January 1987. The solid line in each frame separates 1987 from 1988. To compute the daily sea level hourly values tide-gauge records were subjected to a 72 h low-pass filter. Gaps are due to missing data.



This fact raises an important question. Do the data mean that currents with periods of 10-100 days are as important as the seasonal ones in determining the circulation along the coast of India? What are the implications to vertical velocity, i.e. to upwelling along the coast? The upwelling determines concentration of dissolved oxygen and of nutrients on the inner shelf, and hence has considerable impact on the chemistry, biology, and fishery of the region.

At present we do not have answers to these questions. But we do have an adequate theoretical framework to address them. It is likely that during the next decade the data base on intra-seasonal variability will improve substantially because of improved observational capability. Most promising in this regards is the array of moored buoys that are now being installed under a programme funded by the Department of Ocean Development (DOD). Equally promising are the satellite altimeter data that are now available.

## 2. SHELF CIRCULATION

The width of the shelf along the Indian subcontinent varies considerably. It is only a few tens of kilometres along the central part of the east coast (Fig. 1), more than 100 km in the northeastern part of the same coast, and more than 200 km off Bombay on the west coast. The shelf includes three gulfs: Kutch, Khambat, and Mannar. What determines the characteristics of circulation on the shelf? There has not been much discussion on this question. It is expected that the following factors play a crucial role: (a) the large-scale wind-driven currents discussed in the previous section; (b) tides; (c) local winds; (d) river runoff. The influence of (a) ought to be most pronounced near the shelf-edge, and decrease as depth decreases towards the inner shelf. The importance of (b), (c), and (d) is expected to be the largest at the coastline and to decrease from the inner to the outer shelf. The wider the shelf, the greater should be the contribution of (b), (c), and (d) near the coast. The contribution of each of the four processes to the circulation on the shelf has not been determined for any location on the Indian shelf. There is a need, however, to take up studies of this kind and to evolve a conceptual framework to analyze currents on the shelf. Below we briefly discuss how (a), (b), (c) and (d) may contribute to circulation on the shelf in those areas where some information is available.

Both semi-diurnal and diurnal constituents contribute to the tides along the coast of India. The most prominent of the semi-diurnal constituents is the  $M_2$  (principal lunar) whereas the most important diurnal constituent is the  $K_1$  (principal lunar/solar). Variation in amplitude of the constituents along the coast is determined by basin-wide propagation characteristics of the global tide. In Fig. 6 the amplitude of  $M_2$  and of  $K_1$  in the coastal waters of India is plotted to bring out the areas where tides are particularly high. One of these is the Gulf of Kutch. Spring tidal range as high as 7 m occurs at the

eastern end of the gulf. A few direct current measurements that have been made here suggest that the tidal currents almost exclusively determine the tidal circulation in the gulf. River runoff into the gulf is negligible, and it appears that tides here are much too strong for the local winds and for large-scale coastal currents to have significant impact. Why are the tides so large in the Gulf of Kutch? Do the tides amplify merely due to geometric confinement, or do other effects, such as resonance, play a role? Though the latter has been suggested, there has not been much discussion on it in the literature and the questions are unanswered. The Gulf of Khambat is another area where equally large tides occur (Fig. 6) and our understanding of them is equally poor. This gulf receives freshwater influx from River Narmada, but it is not known if this has a significant impact. Offshore of the Gulf of Khambat is the Bombay High, India's largest offshore oil-field. We have no idea what are the dominant factors controlling the circulation here.

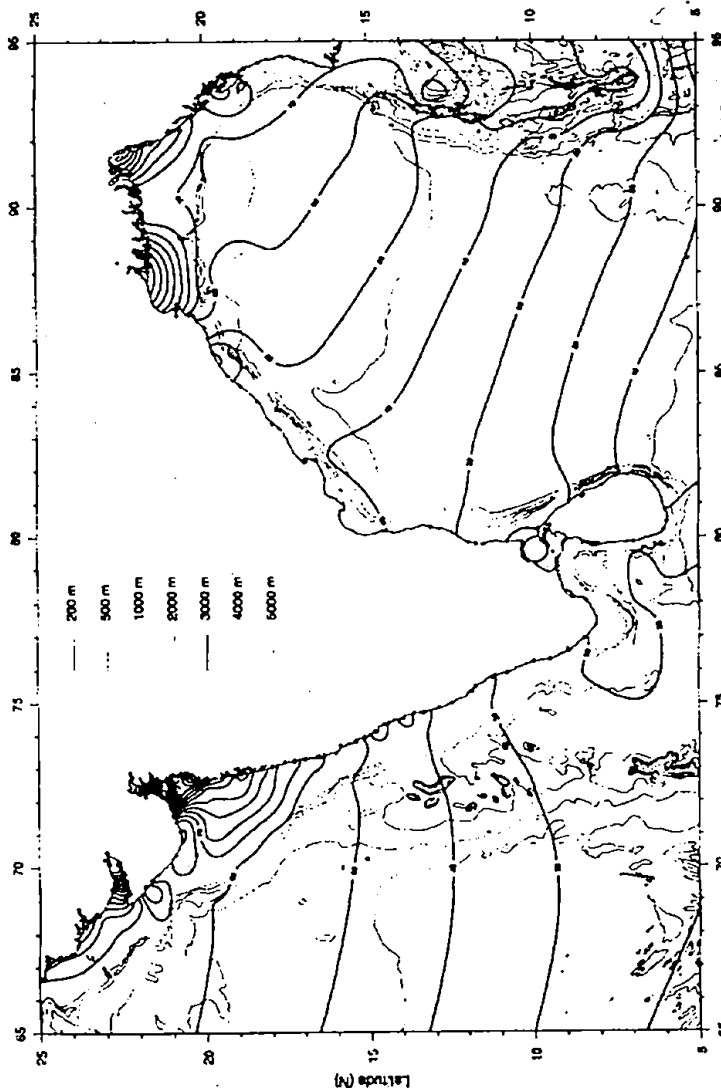
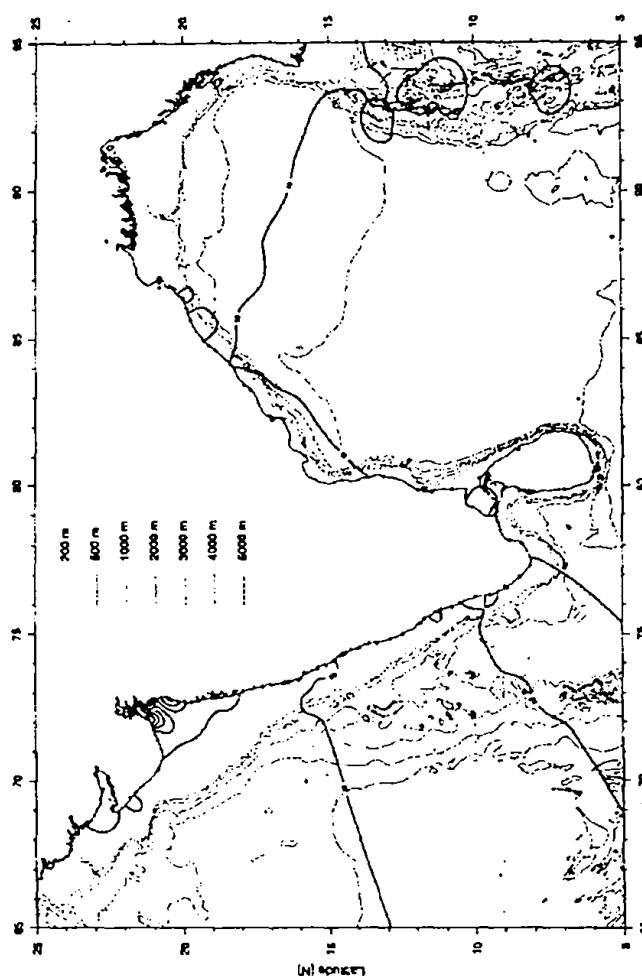


Figure 6. (a)  $M_2$  Principal Lunar



6(b)  $K_1$  (Principal Lunar/Solar)

Figure 6. Amplitude (cm) of major tidal constituents in the Indian coastal areas: (a)  $M_2$  (principal lunar); (b)  $K_1$  (principal lunar/solar). The figure has been drawn using tidal harmonic constants from coastal and island stations (marked with +) and constants given by a global tidal model<sup>18</sup> in the open sea regime. Also shown are contours of equal depth.

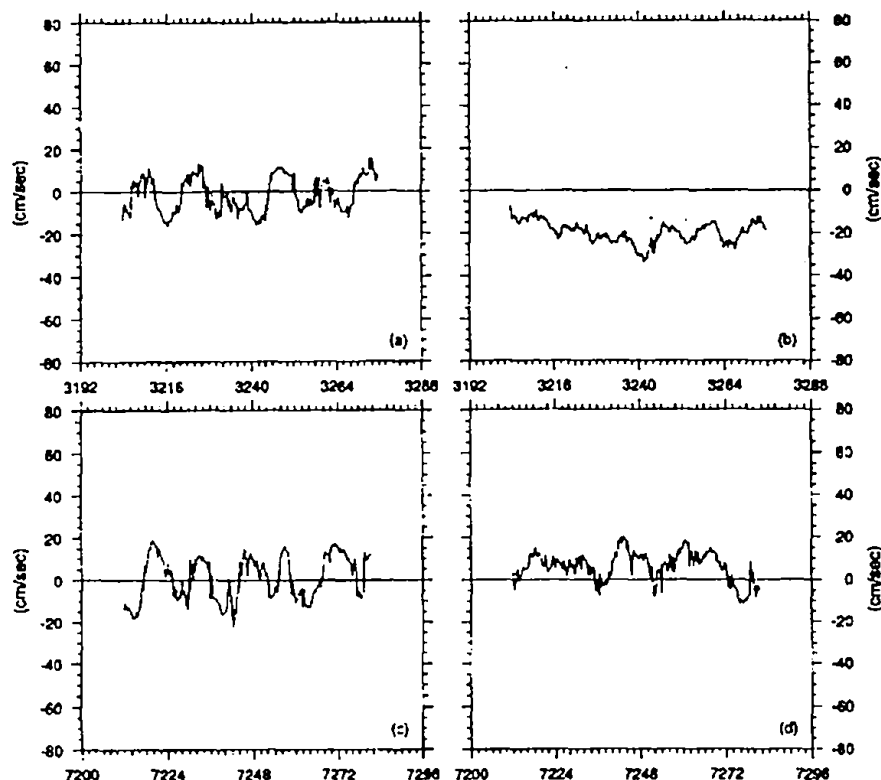
Tides on the wide shelf at the northern boundary of the east coast of India are not as high as those found in Kutch or in Khambhat. However, this area, often called the Head Bay, has another peculiarity. A large amount of freshwater brought by the Ganga and the Brahmaputra flows along this coast. What are the implications of this flow to the physical oceanography of the region? We know that most of this river discharge occurs during the southwest monsoon, and that subsequently it mixes with the ambient waters and spreads along the coastline as a low-salinity plume. What controls its movement? There is no observational data-base adequate to study the dynamics of low-salinity plumes along the coast. They may be having significant impact on the ecology of the region.

Many of the direct current measurements that have been made on the Indian shelf are for short periods, most of them being only a few days long.

These currents have generally been recorded to get an idea of the velocity field at a site where an industrial project is planned. Here we examine observations from two such locations. The first is at  $73.725^{\circ}\text{E}$  and  $15.483^{\circ}\text{N}$  on the shelf off Goa. Shown in Figs. 7(a) and (b) are along-shore and cross-shore components of velocity measured during 13-17 May 1988, at the depth of 10 m. The total depth here is about 12 m, i.e. the currents were measured only a couple of meters above the bottom. Notice that the amplitude of cross-shore component (Fig. 7(a)) is weaker than that of the along-shore component (Fig. 7(b)). Using sea-level record from a nearby location, it can be shown that the cross-shore component is almost entirely due to tidal motion: the flow is towards (away from) the coast when the tide moves in (out). On the other hand, conspicuous in the along-shore component is a flow with a time-scale that is much longer than the dominant tidal periods. One possibility is the presence of the seasonal southward current that tends to form during May. Or, may be this three-day data record reflects the presence of low-frequency oscillations, with periods of the order of few weeks, similar to those seen in daily sea level in Fig. 5? We cannot choose between these possibilities unless we have a longer record. Figs. 7(c) and (d) show cross-shore and along-shore components at approximately the same location but during 27-31 October 1988. The total depth at the location was 16 m and the current meter was at 15 m. The cross-shore component again oscillated about a mean value of about zero, and can be shown to be exclusively of tidal origin. The along-shore component, in contrast to the observations in May, is close to zero. This suggests that may be this component too is primarily tidal. The seasonal along-shore current in the area is weak during October, and it is possible that this is reflected in the figure.

The second location we examine is near the shelf-edge off Sacramento on the east coast (see Fig. 1 for location). Figs. 8(a) and (b) show, respectively, along-shore and cross-shore component at 25 m during 2 February-4 March 1982. The depth at this location is 200 m. As in case of the currents off Goa, here too we find that the cross-shore component is weaker than the along-shore component, but the cross-shore component has less well defined signatures of semi-diurnal and diurnal tides than those off Goa. This difference could arise because the current meter off Sacramento was located close to the shelf-edge whereas that off Goa was close to the coastline. The along-shore component in Fig. 8(b) has a mean current that moves towards the north. This could be the manifestation of the EICC that is known to be northward at this time. Figs. 8(c) and (d) show along-shore and cross-shore components at approximately the same location, but the period of observation is 26 October-1 November 1981. The current was measured at a depth of 17 m, the total depth at the location being 200 m. Again the diurnal and semi-diurnal oscillations are less apparent than what they were off Goa. Unlike Fig. 8(b) that showed a northward

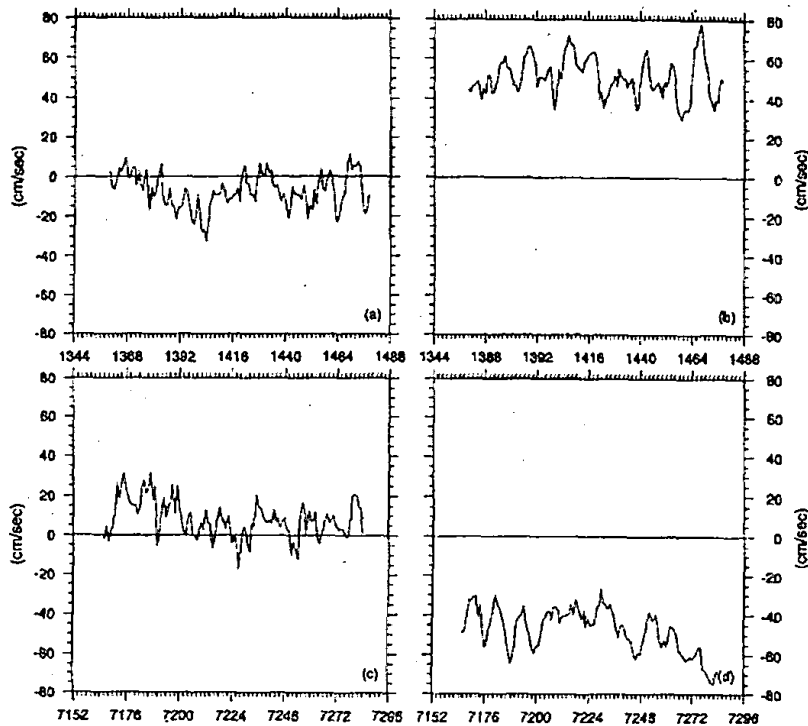
mean current, the mean current in Fig. 8(d) is southward. The EICC is known to flow southward during October. Hence, we may be seeing here the signatures of this current.



**Figure 7.** Currents measured on the shelf off Goa at  $15.483^{\circ}\text{N}$ ,  $73.725^{\circ}\text{E}$ . (a) Cross-shore component (cm/s) during 13-17 May 1988. Positive values imply flow towards the coast. The abscissa gives time in hours, with 3192h representing 0000h on 13 May. (b) same as (a) but for along-shore component. Positive values imply flow northward along the coast. (c) Cross-shore component (cm/s) during 27-31 October 1988. Positive values imply flow towards the coast. The abscissa gives time in hours, with 7200h representing 0000h on 27 October. (d) same as (c) but for along-shore component. Positive values imply flow northward along the coast.

Processes on the shelf, rate of vertical mixing for example, are very strongly influenced by local winds, i.e., winds that arise due to small scale processes such as sea breeze. A large fraction of the coastline of India is believed to come under the influence of sea breeze.<sup>19-22</sup> Yet, in the oceanographic literature in the country there is virtually no mention of the implications of these winds to the oceanography of the region. Fig. 9 shows 10-minute averages of winds measured from the roof of the National Institute of Oceanography, Goa, which is located close to the coast. As seen in Fig. 9, the diurnal cycle in winds due to land/sea-breeze circulation is the most dominant feature of the winds. Observations from June 1996 to May

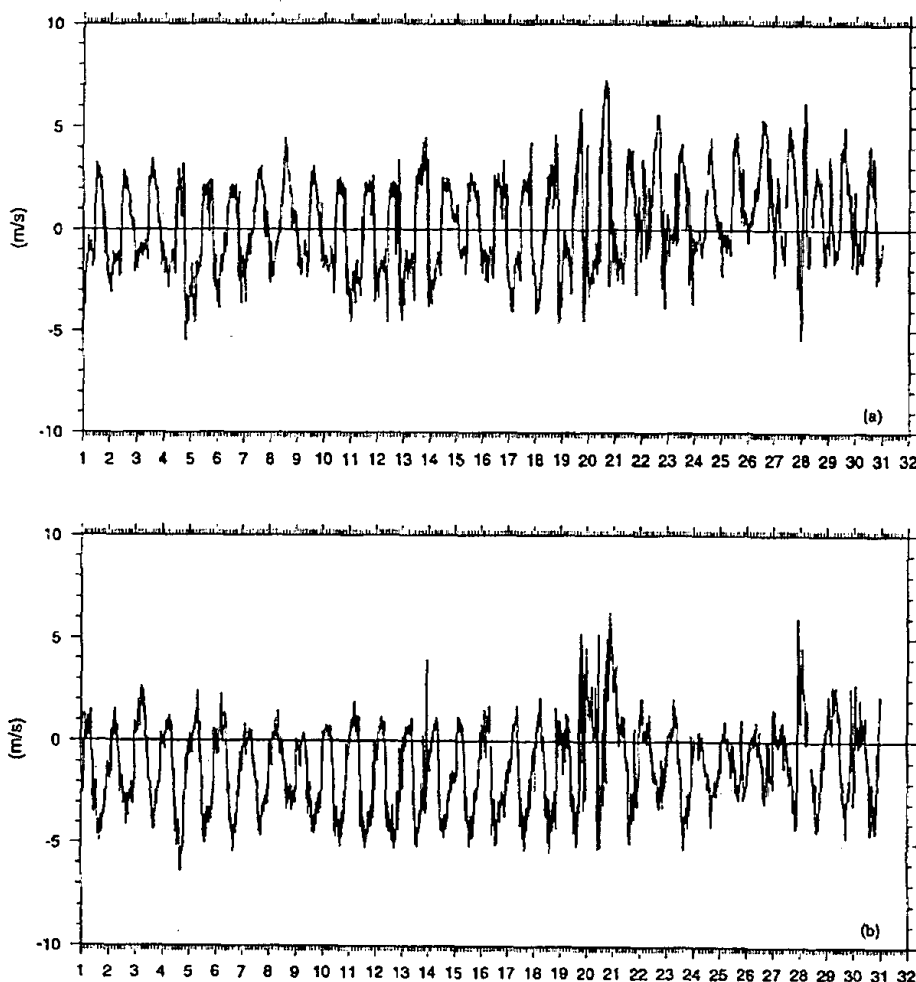
1997 show that this circulation was prominent throughout the year, except during the 2-3 months when the southwest monsoon was active (Fig. 10). What are the implications of these winds to the diurnal variability of wind-wave spectrum on the Indian shelf? What role do these winds play in inducing vertical mixing over the shallow areas close to the coast? Do they induce a diurnal cycle in circulation? To address these questions we need to know the pattern of winds on the shelf. How far from the coast does the land/sea-breeze extend? What is its structure on the shelf? We do not know.



**Figure 8.** *Currents measured on the shelf off Sacramento on the east coast of India (see Fig. 1) at approximately 16.323°N, 82.287°E. (a) Cross-shore component (cm/s) during 26 February - 4 March 1982. Positive values imply flow away from the coast. The abscissa gives time in hours, with 1344 h representing 0000 h on February 26. (b) same as (a) but for along-shore component. Positive values imply flow northward along the coast. (c) Cross-shore component (cm/s) during 26 October - 1 November 1981. Positive values imply flow away from the coast. The abscissa gives time in hours, with 7152h representing 0000h on 26 October. (d) Same as (c) but for along-shore component. Positive values imply flow northward along the coast.*

The reader would have noticed that the discussion in this section has been speculative and more questions have been raised than answered. This reflects the poor state of understanding of the shelf dynamics. Unlike the large-scale coastal currents that we can now put in perspective using a well developed theoretical framework, our understanding of the shelf circulation

is rudimentary. This must change, not merely for the sake of knowledge, but because this knowledge could lead to applications related to protection of the environment. For example, the Gulf of Kutch today is undergoing a major change because of rapid expansion of industrial activity on its banks. Many of the new industrial complexes are based on petrochemicals. Yet, our knowledge of the physical oceanography of the region is at best meagre. This knowledge is necessary to build effective mathematical models that are needed in decision-making in environmental management. Such models could provide clues on areas most vulnerable to oil-spills, or insights on sediment transport that has implications for submarine pipelines.



**Figure 9.** Winds measured on the rooftop of the main building of the National Institute of Oceanography, Goa, during April 1997. (a) Ten-minute average of eastward component (m/s) of wind. The abscissa is the date. (b) Same as (a) but northward component.

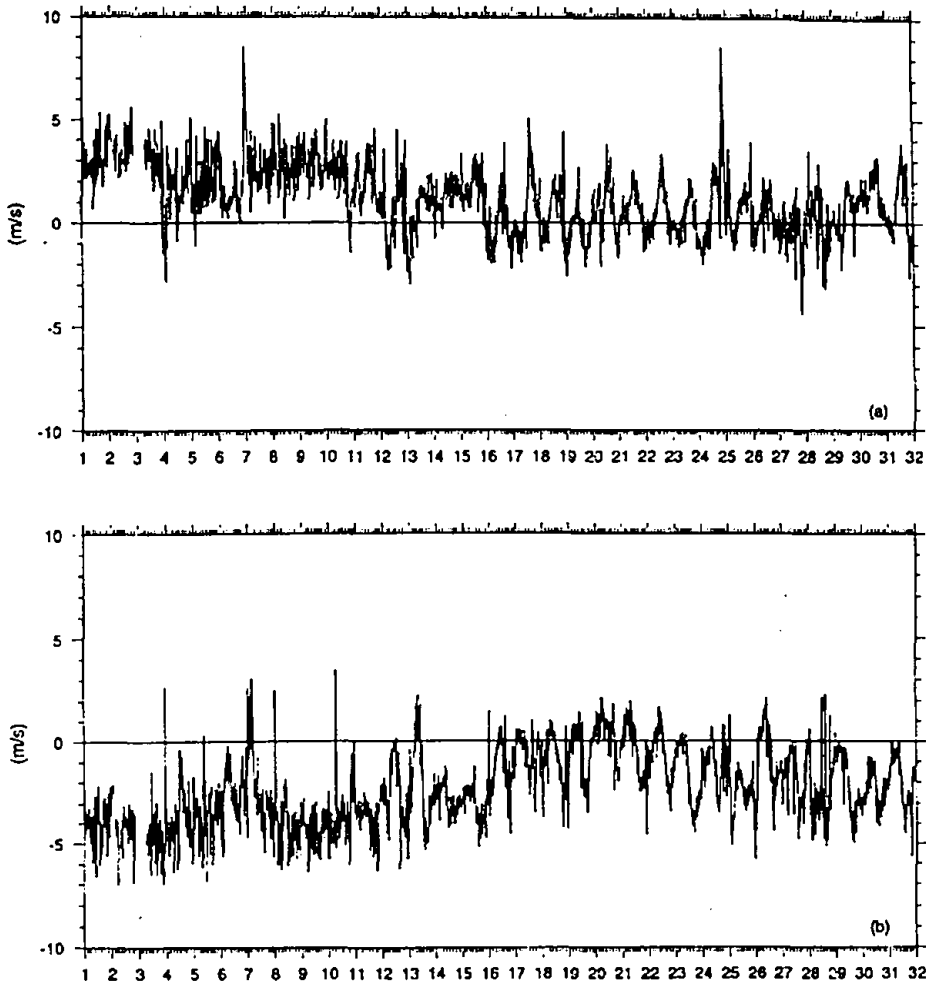


Figure 10. Same as Fig. 9 but during August 1996.

There is reason for optimism that the state of our knowledge of the shelf will change in the near future. Progress made in understanding the large-scale currents was a necessary first step to understand the shelf circulation. In the two cases we examined, one off Goa and the other off Sacramento, the large-scale currents do seem to have significant impact on the shelf circulation. Hence, development of a framework to understand the large-scale currents is relevant for studying the shelf. This progress needs to be sustained. The four areas where attention needs to be focused are the role of large-scale currents in driving the shelf circulation, tidal dynamics, local winds on the shelf and their implications, and movement of freshwater plumes. It is encouraging to note that efforts are now underway to expand programmes to study the shelf. India has recently acquired two coastal research vessels that would be helpful in studying the shelf. A programme for monitoring the coastal regime using moored buoys has also begun. The tide-gauge network along the coast of India is being upgraded. It is expected that the next decade will produce a much improved data base on shelf processes, and analysis of these data should provide useful insights.



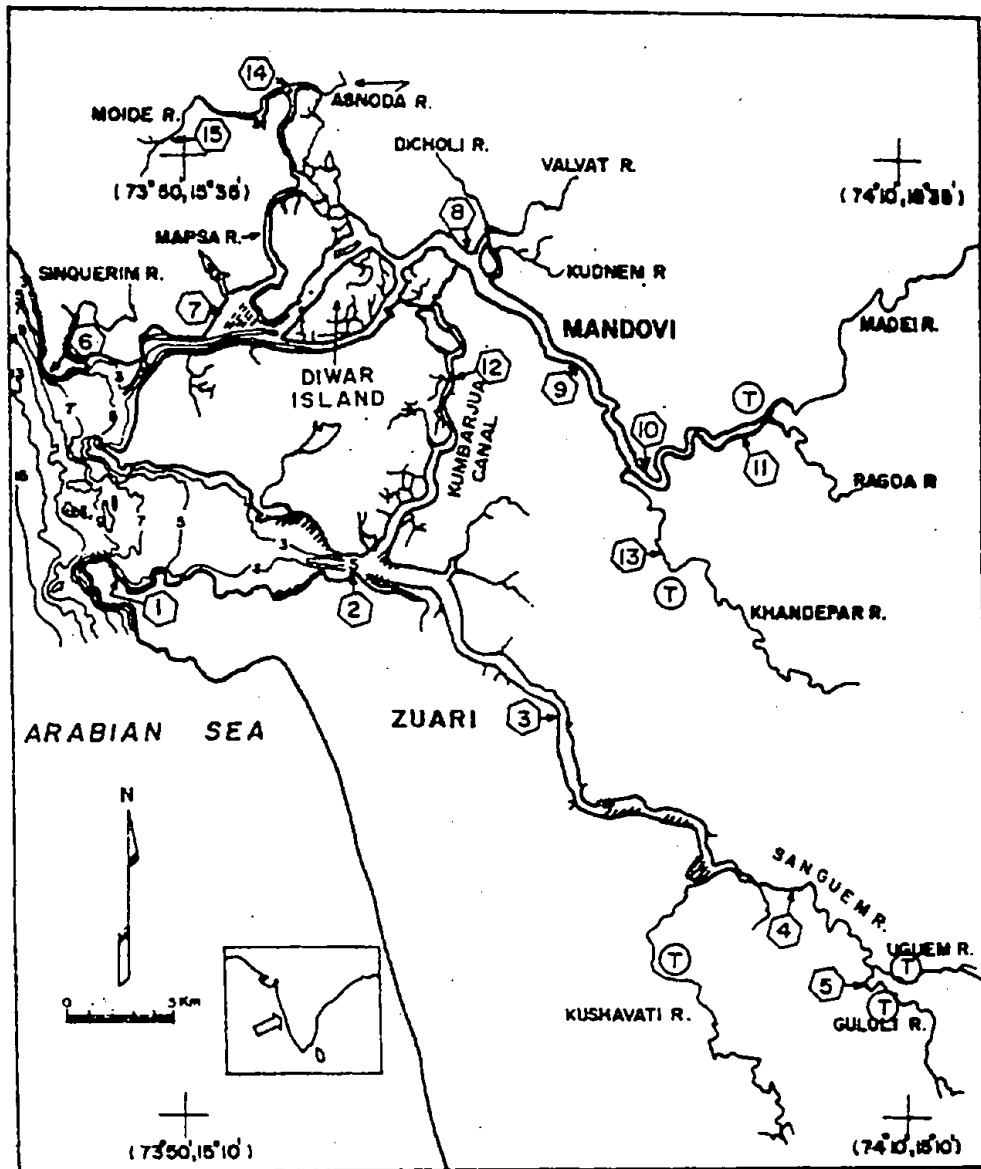
### 3. ESTUARINE CIRCULATION

There are possibly a couple of hundred estuaries of varying sizes located along the coast of India. They form a regime of great concern because they are under high stress. Traditionally they have been favourite locations for human settlement. Many major cities (Mumbai is an example) are located on the banks of the estuarine channels, and domestic sewage and industrial effluents are often discharged into them. With rapid increase in population and in industrial activity there has been a similar increase in the material dumped into the channels, exposing the ecology of these systems to considerable stress. In addition, freshwater influx into these systems has decreased because it has been diverted for agricultural, domestic and industrial use. It is therefore expected that the estuaries along the coast are in a state of rapid change. Unless we learn to manage these systems, the asset that they have proven to be in the past will turn into a liability.

The scientific issues associated with management of these estuaries are: (a) nature of circulation and mixing; (b) movement of freshwater through the estuary and its implications to the estuarine ecology; and (c) biochemistry of the estuaries and its implications to water-quality. It is only when we get an handle on these issues that we will be able to define what can be done or what must not be done with regard to maintaining the health of these systems. However, information on only a handful is available in the literature. One such estuary is the Mandovi-Zuari.<sup>23-25</sup> The estuary has two main channels, the Mandovi and the Zuari, that open on to the shelf off Goa (Fig. 11). Each is generally considered to be typical of the estuarine channels found along the western coast of India, and has the following characteristics: (a) its width and cross-sectional area drops rapidly in upstream direction; (b) the channel is shallow, its depth is of the order of 10 m at the mouth, and only about 2 m at a distance of about 50 km; and (c) tidal amplitude in the channel remains unchanged over a large stretch of the channel; and then drops rapidly near the head where freshwater influx is significant, as seen in Fig. 12. (d) available information on vertical profiles of salinity suggests that the channels are vertically well-mixed.

During the last few years there has been considerable improvement in our ability to simulate currents and amplitude of tides in these shallow estuaries.<sup>25 & 26</sup> This must now be followed up with empirical studies that provide quantitative estimates of rate of mixing in the estuaries. Understanding the distribution of salinity in the systems is a good way to begin. As of now the data-base on this aspect, however, is rather poor. It is only recently, after portable Conductivity-Temperature-Depth profilers became available, that reliable information on vertical salinity structure has become available. Closely linked to distribution of salinity in an estuary is its freshwater budget. How much freshwater enters the estuary? How much of it is from the main rivers that join the estuary, how much as small streams,

and how much as sub-surface flow from ground water table? We do not have answers to such questions on a single estuary in the country.



**Figure 11.** The Mandovi-Zuari estuarine network. The depth contours are with respect to mean sea level. To avoid clutter they are shown only near the mouths of main channels of Mandovi and Zuari. 'T' in a circle shows the location up to which tidal influence is felt in the rivers Kushavati, Uguem, Guloli, Khandepar and Mandovi. The 15 locations where sea level variation is shown in Fig. 12 are indicated with a number inside a hexagon. The correspondence between the numbers and the locations is as follows 1. Marmagoa, 2. Cortalim, 3. Loutulim, 4. Sanvordem, 5. Sanguem, 6. Aguada, 7. Penha de Franca, 8. Sarmanas, 9. Volvoi, 10. Sonarbaag, 11. Ganjem, 12. Banastarim, 13. Khandepar, 14. Sirsai, 15. Mapsa.

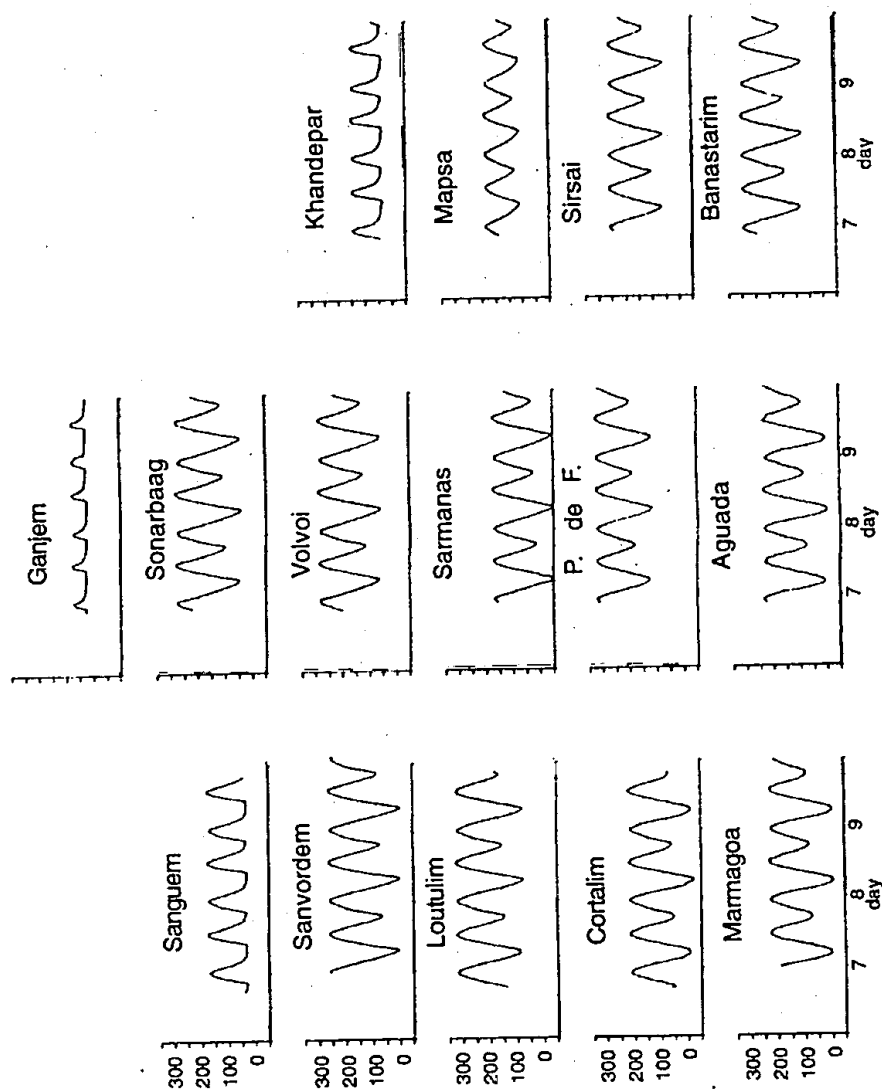


Figure 12. Sea level variation (cm) during 7-9 April 1993 at the 15 location shown in Fig. 11. The horizontal axis gives the date.

Once the questions regarding circulation and mixing are answered, it would be possible to simulate realistically the salinity field in an estuary. The next step then would be to develop capability to predict concentration of non-conservative chemical species (dissolved oxygen, biological oxygen demand, etc.) that determine the water-quality of the estuary. This ability is needed to examine possible scenarios that would result under different conditions of river water influx, and of sewage and industrial effluents entering the estuarine channels. Examination of these scenarios is critical to develop strategies for managing the estuaries.

In summary, there are many outstanding issues that need to be addressed to understand how the Indian estuaries work. By studying them we could also contribute to the understanding of tropical estuaries of the world about which little is known. It is very likely that in the near future there will be increasing pressures on the Indian physical oceanographer to address these issues and to answer them quantitatively. Many of these issues, such as prediction of water-quality, are multidisciplinary, and the physical oceanographer has a constructive role to play. This opportunity must not be lost.

#### **4. WHAT NEEDS TO BE DONE: CONCERNS AND OPPORTUNITIES**

From the last three sections we find that progress has been made during the last few years in understanding the large-scale currents in the waters around India. However, the area closer to the coastline needs further attention. This area offers many outstanding research issues. More importantly, the knowledge gained by addressing these issues offers potential for application in pressing environmental and engineering problems. We list here some of these:

- Effect of intra-seasonal variability of winds on large-scale coastal circulation
- Contribution of the large-scale circulation to the shelf circulation
- Tidal circulation on the shelf
- Local winds (sea-breeze, for example) on the shelf and their implications to circulation and mixing
- Dynamics of low salinity plumes along the coast
- Modelling of freshwater budget, salinity distribution, and water quality in Indian estuaries

The importance of the knowledge concerning shelf and estuarine regimes to address environmental concerns has been realized in the country during the last decade. It is this realization that has led to improvements in infrastructure such as availability of coastal research vessels, deployment of moored buoys, improvement in the tide-gauge network, and availability of satellite-based sensors. This ability to monitor the coastal area is expected

to form the backbone of an ocean information service and subsequently an ocean forecasting service planned by the Department of Ocean Development, New Delhi. The research issues raised above are critical for success of these services. Hence, we have an optimistic scenario: worthwhile research goals, availability of infrastructure, and possibility of translating research outputs into applications and services.

In spite of this optimism, there is a major concern. The long-term effectiveness of any research and development system is critically dependent on its quality of manpower. To sustain a system that delivers useful products on coastal physical environment will require manpower that is well versed in modern techniques of both observations and theory in the field of physical oceanography and marine meteorology. Do we have sufficiently qualified manpower? More importantly, do we have educational infrastructure to create it? It is a matter of serious concern that we do not have in the country today a single facility which offers the post-graduate student a Master's or Doctoral programme with opportunity to get first hand experience in both observations and theory. In other words, the budding researcher has no opportunity to get a well-rounded education.

If we go ahead with establishment of new ocean-related services without addressing this concern, it will compromise the long-term efficiency and effectiveness of the services. A better approach would be to address simultaneously the twin issues of manpower generation and of development of new services. Such an approach should involve: (1) Attracting to the new services, with the promise of a career, talented graduates in the physical and mathematical sciences; (2) Offering these graduates Master's/Doctoral level study programmes at an educational facility set up by pooling together intellectual resources and infrastructure in the country. If we pursue such a twin approach, we would have taken a much desirable integrated approach to development of manpower and its effective use.

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