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Tides and sea-level variability

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2.1 INTRODUCTION

Tides are a consequence of the gravitational pull of the Moon and the Sun exerted on the waters of the ocean as the three-body system consisting of the Earth, Moon, and Sun moves in a stable configuration under the influence of the gravitational pull of one another. Tides at any location on the Earth's surface consist of a superposition of oscillations with well-known periods. The periods depend on characteristics of the motion of the Sun–Earth–Moon system. The study of tides since the last few hundred years has carefully documented the most important of these periods. In the jargon of tidal analysis, a period corresponds to a tidal constituent. There are now well-established procedures to determine the characteristics of a tidal constituent at a location, if a sufficiently long time series of sea level is available. A month-long time series is sufficient to determine the characteristics of about 30 important tidal constituents at a location. Usually, information on half a dozen of the most prominent (largest amplitude) constituents will suffice to understand the important characteristics of the tide at the location.

While studying tides in an estuary, it is generally assumed that the tide at the mouth of the estuary is a consequence of global-scale tidal dynamics to which the contribution of the estuary is negligible. Given the tide at the mouth as a boundary condition, the characteristics of the tide within the estuary, as forced at the boundary, are then studied. We follow the same approach in this chapter. Section 2.2

describes tides using a three-year record at Mormugao located at the mouth of the Zuari estuary (Map A). In 1993, tide-pole measurements were carried out at 15 locations in the Mandovi and Zuari estuaries for three days. The inferences derived from an analysis of these data were that the amplitude of the tide, i.e., the range of water-level variation due to all tidal constituents, remains virtually unchanged in the channels. The tide propagates from mouth to head with an average speed of about 6 ms^{-1} (Shetye *et al.* 1995). However, the time-series of the data collected during this field experiment, being only three days long, did not permit determination of the characteristics of individual tidal constituents. During March–April 2003, tide-pole measurements similar to those during 1993 were carried out at 13 locations by recording the water level once every fifteen minutes. The new time series, being at least 30 days long, allowed the tidal analysis to determine 36 tidal constituents. The inferences reported by Sundar and Shetye (2005) differed from those reported in Shetye *et al.* (1995). The new study, owing to a superior dataset, was able to determine the characteristics of all the important tidal constituents in the two estuaries. In section 2.3 we summarize the results of Sundar and Shetye and then go on to examine the reasons underlying the observed features (sections 2.4 and 2.5). The high runoff in the Mandovi and Zuari estuaries changes the mean sea level in the two estuaries particularly at the upstream end; in section 2.6, the nature of this change is described using the data collected in 1993.

2.2 TIDES AT THE MOUTH

The Survey of India maintains a tide gauge at Mormugao (Map A), an important port. Typical variation of water level during a month as recorded by this gauge is shown in figure 2.1. Shetye *et al.* (1995) used hourly values of sea level recorded by this gauge during 5 June 1990 to 30 November 1993 to determine tidal characteristics. Harmonic analysis of the record gave amplitudes and phases of 69 tidal constituents with periods between 6 months and 3 hours. Of these, the seven diurnal and semi-diurnal constituents listed in table 2.1 had amplitudes in excess of 5 cm. The amplitude and phase of each tidal constituent gets modified as the tide propagates into the estuarine channels.

2.3 DATA OF MARCH–APRIL 2003 AND ANALYSIS

The 13 locations where tide pole measurements were carried out during March–April 2003 are shown in Map B. The 15-minute data collected at these locations were analyzed to determine the tidal amplitude and phase difference of 28 major constituents and 8 related constituents. Of the 13 stations where the observations were carried out, six were located in the Mandovi main channel, five in the Zuari

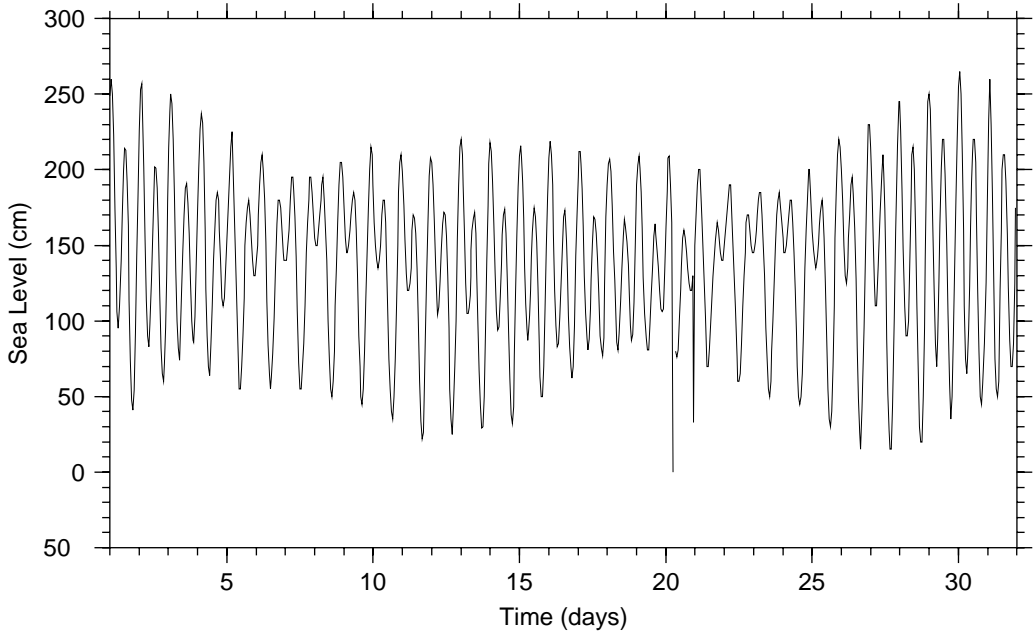


Figure 2.1 Variation in water level recorded by the Survey of India tide gauge at Mormugao during January 1975.

Table 2.1 Diurnal and semi-diurnal tidal constituents at Mormugao with amplitude greater than 5 cm.

Symbol of the constituent	Description	Period (h)	Amplitude (cm)
O ₁	Principal lunar	25.82	16.17
P ₁	Principal solar	24.07	9.32
K ₁	Combined diurnal	23.93	31.98
N ₂	Larger elliptical lunar	12.66	13.30
M ₂	Principal lunar	12.42	55.65
S ₂	Principal solar	12.00	20.23
K ₂	Combined declinational	11.97	5.41

main channel, and two in the Cumbarjua Canal (Map B). The quality-controlled data at these 13 locations are shown in figure 2.2. One feature seen in both estuaries is that the amplitude of water-level oscillation decreases drastically at the upstream end. As will be seen later, this is due to an increase in the elevation of the two stations. Ignoring these stations for the time being, we examine the variation of amplitude and phase lag in the two estuarine channels.

Of the 36 constituents whose amplitudes and phases were determined, six constituents — M₂, S₂, N₂, K₁, O₁, and P₁ — had an amplitude larger than 10 cm at the

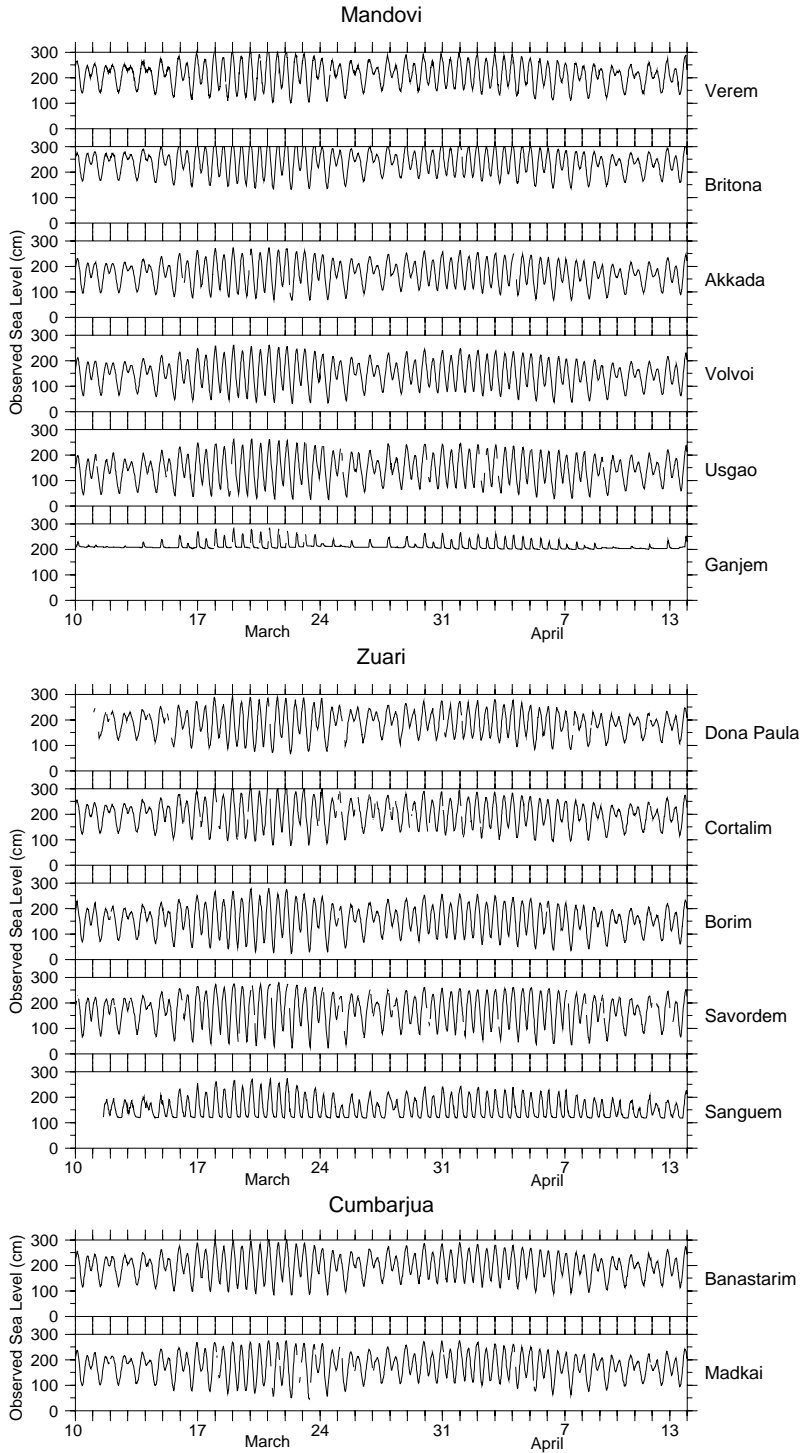


Figure 2.2 Observed sea level (cm) during the period of observation. The horizontal axis gives date and month. (After Sundar and Shetye 2005.)

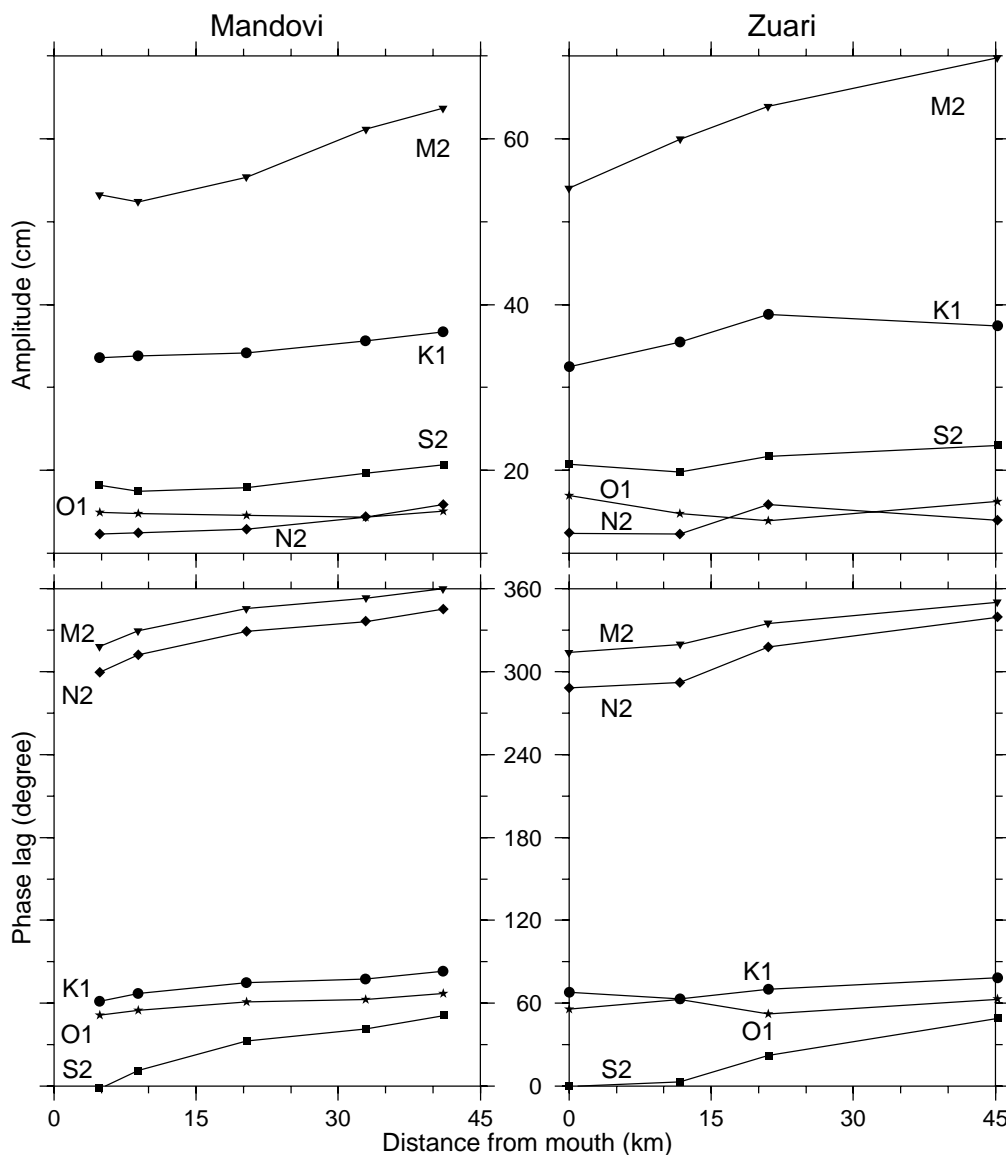


Figure 2.3 Variation in amplitude (cm) and phase lag in degrees (referenced to IST) of M_2 , S_2 , N_2 , K_1 , and O_1 in the main channels of the Mandovi and Zuari estuaries. (After Sundar and Shetye 2005.)

mouth of the two estuaries. Figure 2.3 shows how the amplitudes of five of these constituents (M_2 , S_2 , N_2 , K_1 , and O_1) changed from mouth to head. Shetye *et al.* (1995), using three days of data, had inferred that tidal amplitude remains virtually unchanged in the two estuarine channels. From studies based on the month-long data reported in Sundar and Shetye (2005), we find that behaviour of the amplitude in a channel depends on the constituent. The amplitude of the semi-diurnal

constituents increased by about 20% in the Mandovi from mouth to head and by about 30% in the Zuari; the increase in diurnal constituents was about 10% in the Mandovi and 15% in the Zuari. Phase lag of both semi-diurnal and diurnal tides increased from mouth to head in both estuaries, and the increase was more for the semi-diurnal than for the diurnal.

2.4 TIDAL DYNAMICS

It is known that in shallow estuarine channels that converge (cross-sectional area decreases from mouth to head), three factors determine tidal propagation. The first is the rate of decrease in channel cross-sectional area from mouth to head. More rapid the decrease, greater is the tendency of the amplitude to grow. This is a consequence of geometry: more confined the available cross-sectional area, greater is the increase in amplitude. Another factor is friction. Greater the friction, greater the decay of the tide as it propagates. Frictional dissipation usually varies among tidal constituents because the nonlinear effects that lead to transfer of energy from one constituent to another depend on the constituent. Numerical models of estuarine tidal circulation are usually successful in accurate simulation of tidal amplitude (see chapter 3). While such models are useful in applications, simpler, preferably analytical, models are useful to gain a perspective of the dynamics underlying tidal propagation.

Many authors have examined the characteristics of tidal propagation under the influence of the two factors mentioned above, geometry and friction. Friedrichs and Aubrey (1994) examined propagation of a tidal constituent in a converging channel as a unidirectional progressive wave. In this model, amplification due to geometric effect is cancelled by friction to allow the tide to propagate as a free wave. Nayak and Shetye (2003) looked at the same problem by allowing a reflected wave to form within the estuarine channel. In this case, the characteristics of tidal propagation of a constituent are determined by the combined effect of the incident wave (which is like the progressive wave of Friedrichs and Aubrey, but is allowed to amplify or decay under the combined influence of geometry and friction), and a reflected wave that propagates in the direction opposite to that of the incident wave. Suresh and Shetye (2007) studied the propagation of tides in the Mandovi and Zuari using dynamical relations similar to those in Nayak and Shetye (2003). In these relations, propagation of each tidal constituent into the estuary was modelled as an incident wave of surface height and cross-sectionally averaged velocity forced by the tide at the mouth. In this model, a wave propagates in the channel under the influence of pressure gradient, estuarine geometry, and friction. With the propagation of an incident wave, a reflected wave gets generated in the model. The estuarine geometry (width and depth) was modelled so as to mimic the observed geometry, i.e., the estuary had two parts, a bay and a channel. The former was wider, marginally deeper, and more rapidly converging than the latter. The friction coefficient was tuned to simulate the observed behaviour of the constituent.

Comparison between the observed and predicted values of amplitude and phase for the most significant semi-diurnal and diurnal constituents, M2 and K1, suggests that this simple model captures the essence of tidal dynamics of the estuaries. The wavelength of the incident wave in the model is of the order of a few hundred kilometres, much longer than the length of the estuary. Hence, consistent with observations, it is expected that the water level would rise or fall with little phase difference along the length of the estuary (observed maximal phase difference is ~ 60 degrees in semi-diurnal and ~ 20 degrees in diurnal constituents). The phase speed of the wave depends on a number of model parameters, including depth (deeper the channel, faster the propagation), rate of convergence of the channel, period of the incoming wave, friction, etc., and varies between 5 and 15 ms^{-1} in the Mandovi and 8 and 30 ms^{-1} in the Zuari for the semi-diurnal constituents. Corresponding figures for the diurnal constituents are 6–17 ms^{-1} in the Mandovi and 5–14 ms^{-1} in the Zuari. The phase lag of the tide at a location in the channel is determined by superposition of the incident and reflected waves. The amplitude of the incident wave decreases from mouth to head, whereas that of the reflected wave increases from mouth to head. Model computations showed that at a distance of 30 km from the mouth, the incident wave is nearly 10 times larger than the reflected wave in both estuaries. At a distance of 5 km from the head, the amplitude of the reflected wave is nearly half that of the incident wave in both estuaries. At the head, the two waves cancel each other to satisfy the boundary condition of no net flow (i.e., the dry season condition). The most useful characteristic of a model of this kind is that it provides a useful conceptual framework to understand the observed distribution of amplitude and phase in the estuaries in terms of propagation of two waves.

2.5 DECAY OF TIDAL AMPLITUDE OWING TO INCREASE IN CHANNEL ELEVATION

Having examined the tidal propagation over the coastal plain, we now examine what happens at the upstream ends of the estuarine channels. This part of the channel, being at the foothills of the Sahyadris, has a mean elevation above that of the coastal plain. The drastic drop in tidal amplitude seen at the upstream ends of the two estuarine channels is related to this increase in elevation. We now examine this issue using the explanation given in Sundar and Shetye (2005). Each of the seven panels in figure 2.4 gives a section of the channel topography and water level along a line drawn through the middle of the Mandovi channel. Both the topography and the water level are based on observations: the topography is the same as that described in chapter 1, and the water surface depicted in the figure is based on data collected during the 2003 observations. Two consecutive panels in the figure show how the water level changed over a period of two hours during spring tide. The seven panels together cover 12 hours. The figure helps to visualise how the water level along the channel changes during a tidal cycle, and hence to understand how

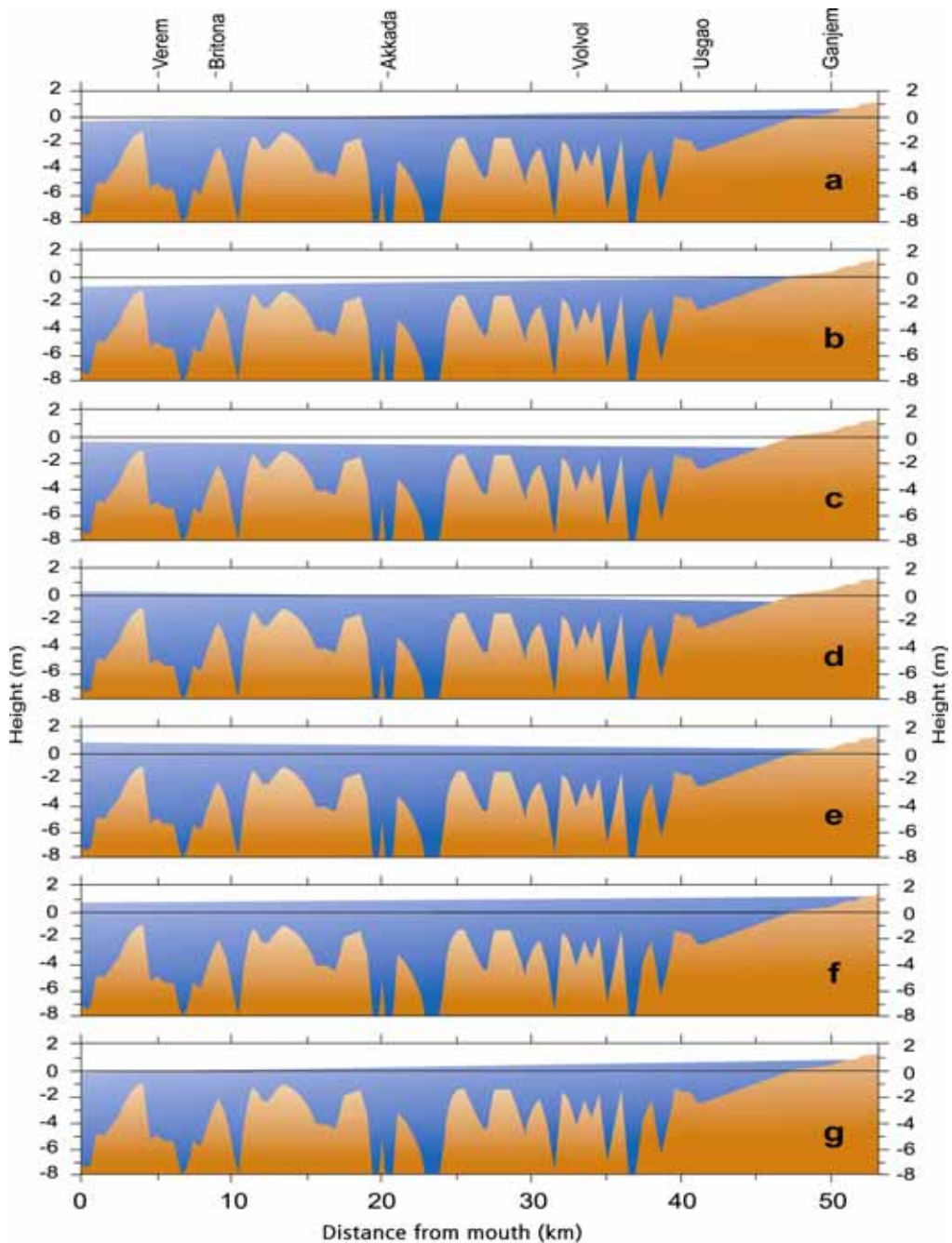


Figure 2.4 Each of the seven panels in this figure gives an instantaneous section of the channel topography and water level along a line drawn through the middle of the Mandovi channel. Two consecutive panels are separated by two hours during spring tide. (After Sundar and Shetye 2005.)

the increase in channel elevation causes the tidal amplitude to drop at the upstream end in an estuarine channel. As seen in figure 2.2, the tidal amplitude drops sharply from Usgao to Ganjem in the Mandovi and from Sanvordem to Sanguem in the Zuari. The tide reaches Ganjem in the Mandovi only when the tide is high enough to overcome the effect of increased channel elevation. The impact of the tide is felt at Ganjem in panels A, E, F, and G of the figure. In the rest of the panels the influence of the tide is not seen at Ganjem. In these cases the water level at Ganjem is determined merely by whatever little runoff exists in the river channel.

2.6 CHANGE IN MEAN SEA LEVEL BETWEEN WET AND DRY SEASON AND DRY SEASON

During the summer monsoon, when runoff into the estuaries is high, the water-level variation is determined not only by the tide, but also by the variation in runoff. Impact of the runoff is particularly high in the upper reaches of the estuaries. Shetye *et al.* (1995) measured the difference between mean water levels during two three-day long periods. One of these was during the dry season (7–9 April 1993) and the other during the wet season (19–21 August 1993). The difference as measured by them is shown in figure 2.5. At the upstream end of the Mandovi the difference was well over 1.5 m and the tide was no more felt. It is expected that when an active spell of the monsoon occurs, this difference would be much higher. During such spells,

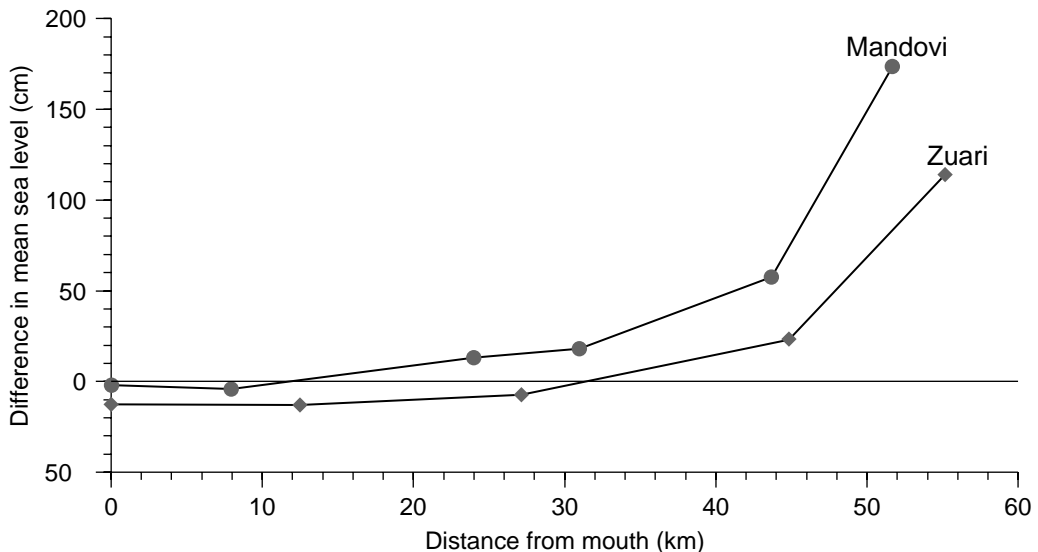


Figure 2.5 Difference (cm) in mean sea level between 19–21 August 1993 (wet season) and 7–9 April 1993 (dry season) as a function of distance from the mouths of the main channels of the Mandovi and Zuari. (After Shetye *et al.* 1995.)

the Mandovi becomes an extension of the rivers like the Mhadei and Khandepar that supply freshwater to it. Marine influence on water-level variability disappears.

The influence of the runoff on water level decreases in the downstream direction as the channel, cross-section widens. As seen in figure 2.5, at the mouth of the Mandovi, the mean water level was marginally lower during the wet season. In the Zuari, the mean water level was lower by about 10 cm. Such a lowering of water level is expected from the dynamics of large-scale currents along the west coast of India. The summer monsoon is the time of an equatorward current along this coast and upwelling occurs (Shetye *et al.* 1990). Coastal upwelling is expected to be accompanied by lowering of sea level.

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