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Mixing and intrusion of salt

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4.1 INTRODUCTION

Estuaries are generally classified using two criteria: geological features and characteristics of circulation and mixing. As per the first criterion, the Mandovi and Zuari estuaries are coastal-plain estuaries because they are located on the alluvial coastal plain between the Sahyadris and the Arabian Sea (see the schematic in figure 1.2). Geological evidence from the continental shelf off Goa suggests that between 18,000 years BP (before present) when the last ice age occurred, and 7,000 years BP, the local sea level rose by approximately 110m and has been at the present level since (Nair *et al.* 1979; Rao *et al.* 2003). As the sea level rose, the sea invaded low-lying coastal river valleys and formed the present day estuaries of Mandovi and Zuari. In this chapter, we examine classification of these estuaries from the point of view of their circulation and mixing as inferred primarily from data on salinity. We begin the next section by examining the time series of vertical profiles of salinity collected at one location in the Mandovi.

4.2 TIME SERIES OF VERTICAL STRATIFICATION

On 1 February 1997, starting at about 1000 hours IST, observations on vertical distribution of salinity and temperature were made once every half hour for 25 hours

in the main channel of the Mandovi at Old Goa (see Map A for location). At this time of the year, runoff in the Mandovi and its tributaries is negligible, and the flow is dominated by tides. It was spring tide during this field observation, as can be seen from figure 4.1, and this gave the expected water-level variation at Old Goa owing to the tide. To carry out the day-long time-series observations, a fishing trawler was stationed in the middle of the channel and vertical profiles of temperature and salinity were collected using a SeaBird portable CTD profiler (Seacat).

The data were used to construct the contour plot in figure 4.2(a), which shows variation of salinity as a function of depth and time. The location of the upper water surface in the figure was determined with the help of a tide pole that was located at the jetty close to where the trawler was stationed. The most important feature seen in the data was that vertical stratification due to salinity depended on the phase of the tide. During flow or ebb, when the water level rose or fell rapidly – and, by inference, the tidal current was strong – vertical stratification remained negligible and the water column was well-mixed. As the water level that rose or fell due to the rising or falling tide slowed, and the tidal current weakened, stratification built up. It continued to build up as the tide turned. The stratification was eroded as the rise or fall of the tide picked up. Vertical variation in temperature during the

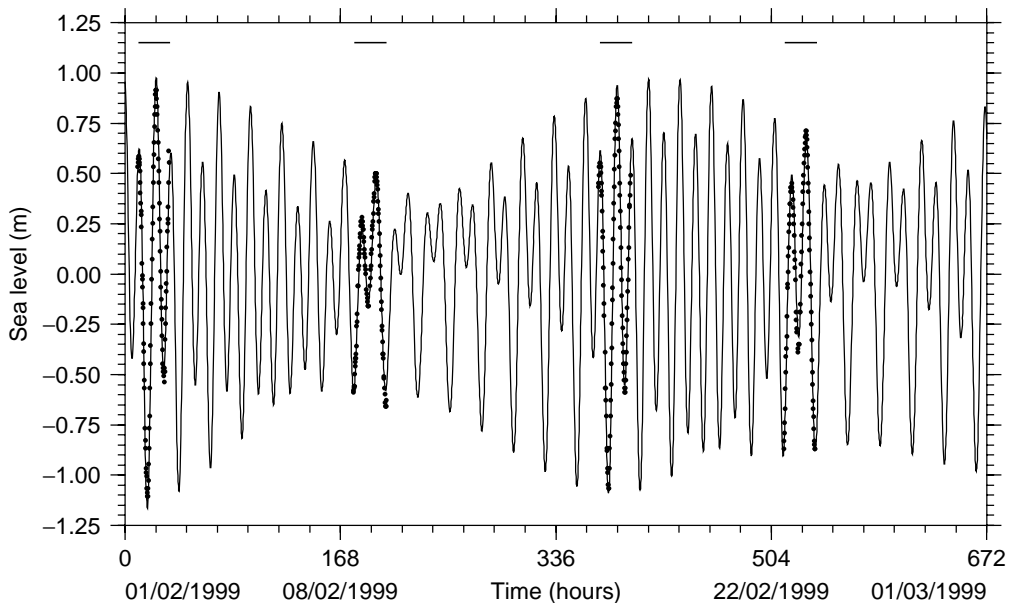


Figure 4.1 Expected water level at Old Goa during February 1999. The symbols (circles) show the measured water level at Old Goa; these tide-pole observations were made on the days when profiles of temperature and salinity were collected. The water level measured at Old Goa is super-imposed on the tide predicted at Mormugao (solid line) after shifting the latter (in time) to make it coincide with the water level at Old Goa; the tide at Old Goa lags the tide at Mormugao by about 40 minutes. The four horizontal lines show the time when vertical profiles of salinity and temperature were collected at Old Goa.

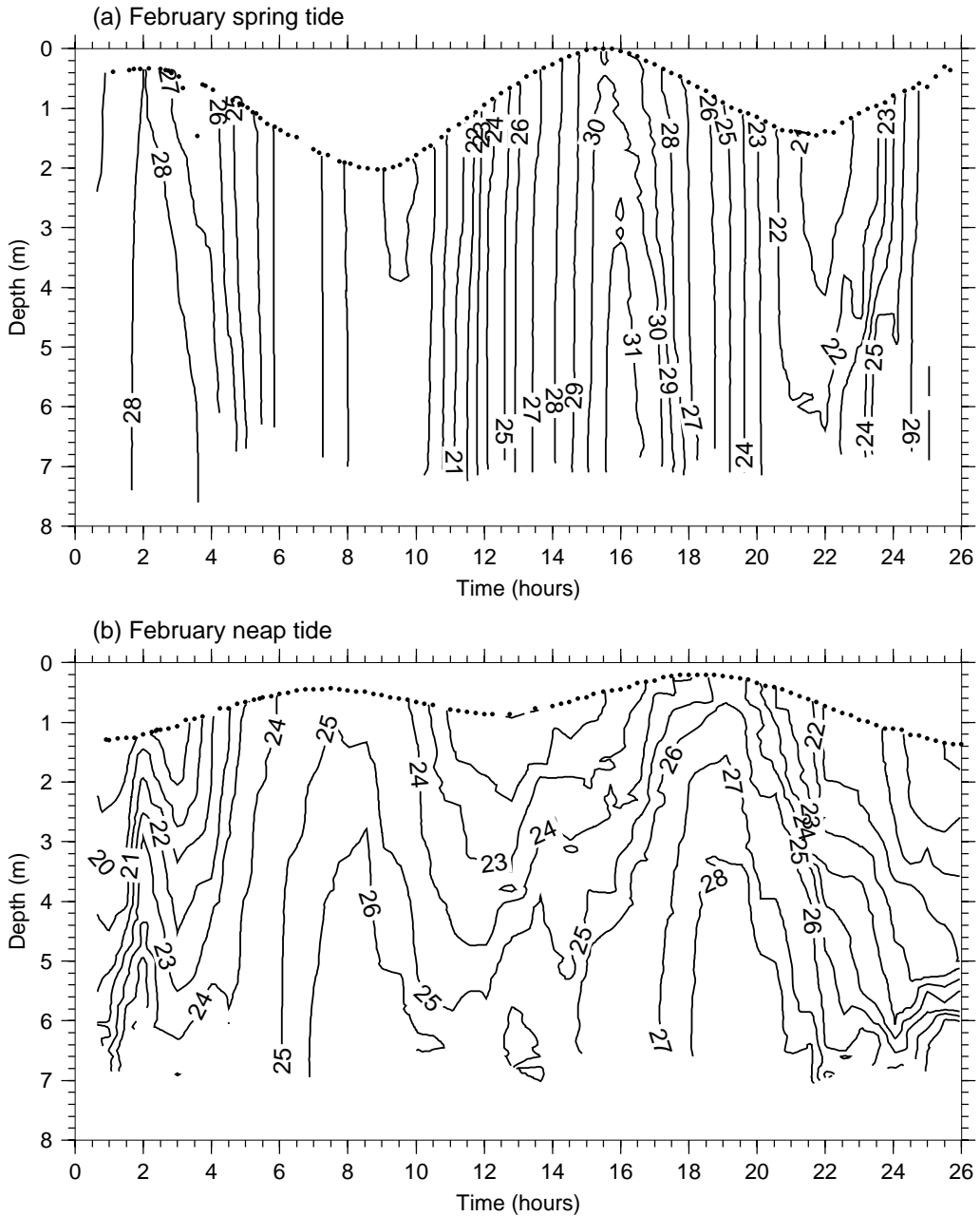


Figure 4.2 Contour plot showing vertical structure of salinity (psu) in the Mandovi at Old Goa (marked by OL in Map B). A profile was collected once every half an hour. The tide was measured using a tide pole attached to a nearby jetty. (a) Observations during spring tide (1–2 February 1999); the horizontal axis gives time in hours starting from 1000 hours on 1 February. (b) Observations during neap tide (8–9 February 1999); the horizontal axis gives time in hours starting from 1000 hours on 8 February.

observations was negligible. The maximum and minimum temperature observed anywhere in the water column during the field observation were 27.1°C and 25.9°C. Hence, as expected, it is the salinity field that provided density stratification.

Time-series observations of vertical structures were repeated on three other occasions, 8–9 February, 16–17 February, and 22–23 February 1999, at the same location. While the tidal range during the observations on 1–2 February was 2.02 m, it was 1.16 m, 1.94 m, and 1.58 m respectively during the three successive field observations that followed (see figure 4.1). The observed characteristics of vertical stratification on 16–17 February and on 22–23 February were similar to the variation on 1–2 February. On 8–9 February, i.e., during the neap tide, they were different (figure 4.2b). Salinity stratification was much better developed on this day: starting from about nine hours from the start of the observations till 18 hours from the start, the water column remained well stratified. During these nine hours, the water level changed by less than 70 cm. In contrast, water level changed by as much as 2 m in 6 hours during the spring-tide observations shown in figure 4.2(a). Faster the rate of change of water level, and hence, by inference, larger the tidal current, greater is the erosion of stratification. When the variation in water level is slow and currents are weak, the scope for build-up of stratification is greater.

Of the four time series, three were similar to that in figure 4.2(a), showing a water column that is well-mixed all the time, except when the tide turns. Strong stratification, such as that seen in figure 4.2(b), builds up only during neaps. During springs, the maximum difference in the water column was about 4 psu, but such high values were rare, and most of the time the difference was less than 2 psu. During neaps, the maximum difference was much higher, and it was not uncommon to see variations of 6 psu in salinity.

4.3 SECTION OF SALINITY ALONG THE MANDOVI ESTUARY

On 28 December 1999, at 1245 hours, a fishing trawler started from approximately 35 km from the mouth of the main channel of the Mandovi and moved towards the mouth near Aguada. The trawler reached the mouth at 1540 hours. The nature of the tide during this journey can be appreciated from the tidal variation shown in figure 4.3. En route, the trawler halted at 10 locations to collect data on vertical profiles of salinity and temperature. These profiles allow us to construct a section of salinity along the Mandovi estuary. The section is shown in figure 4.4(a). A similar section that was made on 27 October 1997, two days after occurrence of neap tide, is shown in figure 4.4(b). Spring tide occurred on 17–18 October and 3 November. These two sections do not represent an instantaneous situation in the estuary. Nonetheless, they are useful to get an estuary-wide representation of the stratification.

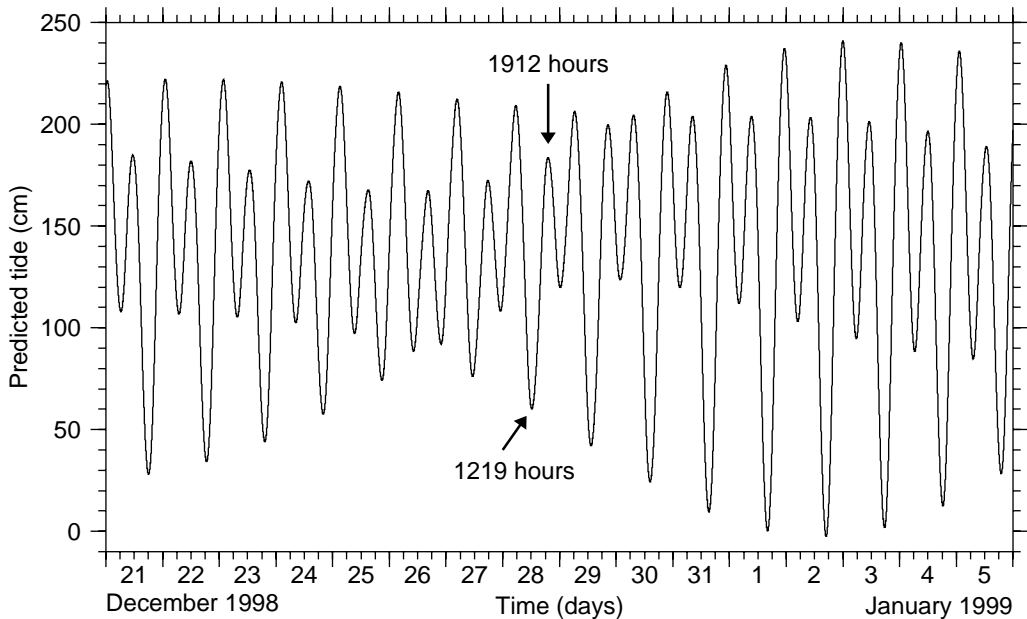


Figure 4.3 Predicted sea level at Mormugao during 21 December 1998 to 5 January 1999.

4.4 SALT INTRUSION IN MANDOVI AND ZUARI ESTUARIES

Sections such as the ones shown in figure 4.4 are not easily available in the Mandovi and Zuari estuaries. It is known, however, that during the dry season, salinity keeps increasing in the two estuaries, indicating intrusion of salt. Intrusion of salt in the Zuari during the dry season and its flushing during the wet season was first documented by Qasim and Sengupta (1981). Shetye and Murty (1987) modelled this annual cycle of salinity in the Zuari using a tidally-averaged advection and diffusion model. In the model, the estuary was flushed of salt during the wet season by freshwater entering the estuary at the upstream end. During the dry season, salt intruded upstream owing to horizontal diffusion.

The data on vertical stratification that we have discussed so far, namely, the four time series at Old Goa and two salinity sections, suggest a behaviour that is typical of partially-mixed estuaries. Similar behaviour can be seen, for example, in the observations reported by Miranda *et al.* (1998), who studied the Bertiooga Channel, Sao Paulo, Brazil. Extensive observations reported by Townbridge *et al.* (1999) and by Geyer *et al.* (2000) for the Hudson estuary also reveal similar behaviour. A hallmark of this behaviour is the difference (often called asymmetry) in stratification and in circulation that arises between springs and neaps, and within a tidal cycle. The observations in the Mandovi offer an example of the former. It is known that they are a consequence of two mechanisms: baroclinic gravity-current formation and tidal streaming (see Stacey *et al.* 2001, for an overview).

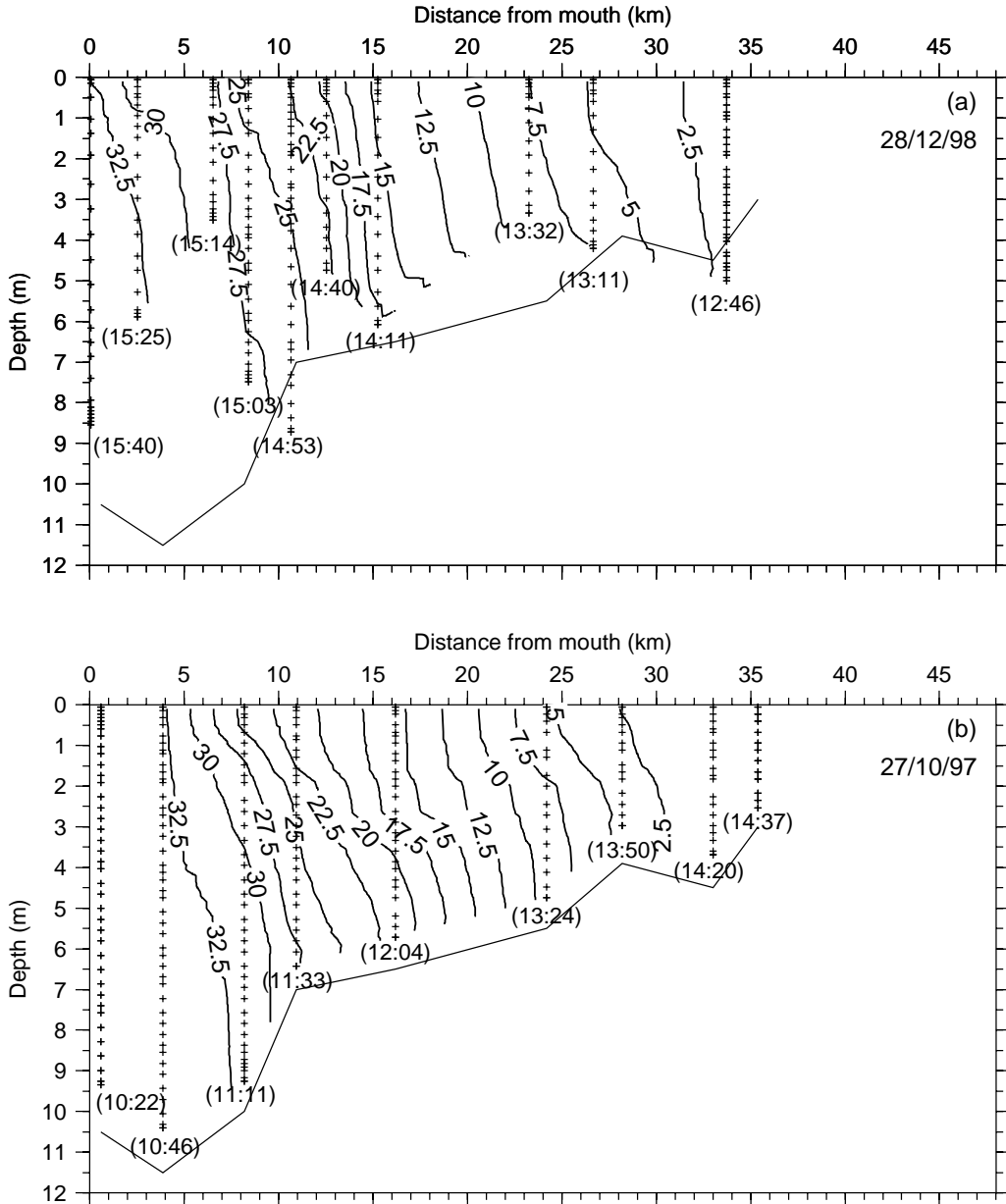


Figure 4.4 Section of salinity along the length of Mandovi estuary. The horizontal axis gives distance (km) from the mouth; the vertical axis gives depth in m. In a profile, the depths at which salinity was measured are shown by crosses. The time of collection of profile is shown in hours at the bottom of the profile location. **(a)** Section based on 10 sections collected during 1245–1540 hours on 28 December 1998; the boat from which the profiles were collected moved towards the mouth. **(b)** Section based on nine sections collected during 1022–1437 hours on 27 October 1997; the boat moved from the mouth towards the head.

When tidal flow is weak, during neaps or when the tide turns, the baroclinic pressure gradient associated with the salinity gradient from mouth to head dominates over the tidal barotropic pressure gradient. This leads to the formation of a gravity (i.e., baroclinic) current that moves saline water upstream near the bottom of the estuarine channel. Fresher water near the surface moves downstream. As a result, stratification builds up. It decays once the tidal current picks up and enough turbulence is generated by the interaction of the current with the channel bottom. Associated with the intermittent stratification is intermittent vertical shear. Gravity-current formation enhances shear during ebb and reduces it during flood. The strength and duration of the intermittent episodes of stratification and shear formation and decay at a location in the estuary depend on many details that are related to the generation of turbulence at the location. The second mechanism that leads to an asymmetry in stratification and in shear is tidal straining (Simpson *et al.* 1990). In estuaries that have an along-channel salinity gradient and have a vertical shear in the water column, the shear causes fresher water to flow over more saline water during ebb. This enhances stratification, stabilizes the water column, suppresses turbulence, and the shear gets enhanced. During flood, the opposite happens: stratification is reduced, turbulence is enhanced, and shear is reduced. The asymmetry leads to residual circulation and net transport of salt into the estuary, observational evidence for which has been given by Jay and Smith (1990) and Jay and Musiak (1994, 1996).

Salt flux into a narrow (in which variations in the cross-channel direction can be ignored) estuary owing to advection depends on the vertical integral of the product of along-channel velocity and salinity. The two tidal asymmetries allow the magnitude of the integral to differ between flood and ebb, or between neap and spring, thus permitting net salt flux into an estuary.

During 1993, water level and salinity were measured in the Mandovi and Zuari estuaries at 15 locations (see Map C) for three days each during two different months, April and August. The April observations were carried out for 72 hours starting 0000 hours on 7 April. The August observations were also carried out for 72 hours starting 0000 hours on 19 August. During these observations, salinity was measured by collecting a water sample from the surface from the bank of the estuary once every hour. The April observations provided data on salinity during the second-last month of the dry season from October to May. The August observations provided data on conditions during the second half of the four months of the wet season from June to September. Figure 4.5 summarizes the data on salinity for the Mandovi estuary. The lower panel in the figure permits appreciation of the salt intrusion into the estuary during the dry season. Figure 4.6 does the same for the Zuari.

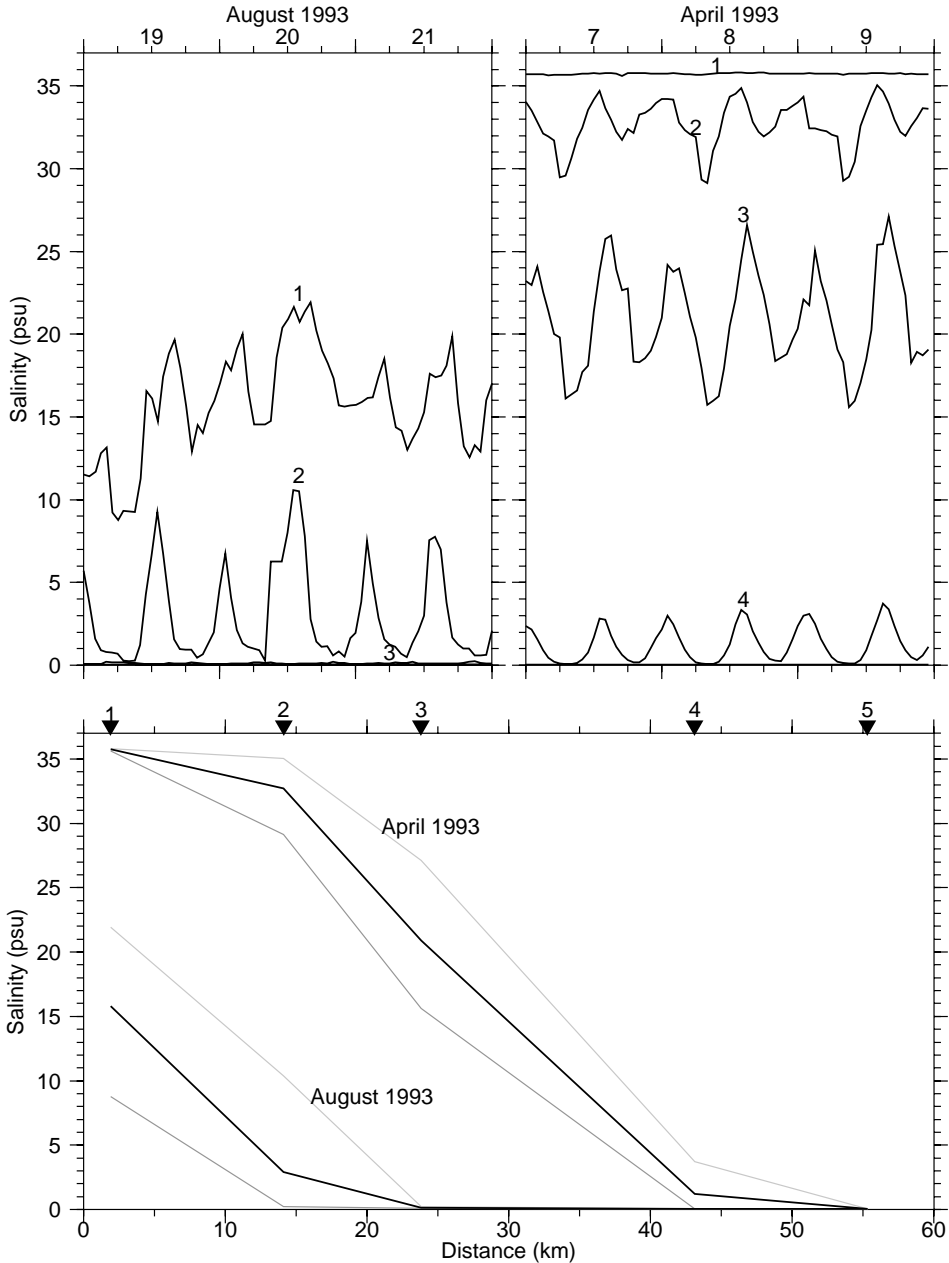


Figure 4.5 **Top left:** Salinity (psu) observed during 19–21 August 1993 (spring tide) in the Zuari at the 5 locations, numbered 1–5, shown in Map C. The salinity corresponding to each location is identified in the figure with the same number as in Map C. The horizontal axis shown at the top of the figure gives the time of observation during the three days of observation. **Top right:** Same as top left except during 7–9 April 1993. **Bottom:** The two dark lines show the mean salinity (psu) during the three days of observations as a function of distance (km) along the length of the channel during April and August. Arrowheads at the top show the locations where observations were carried out. The grey bands above and below the dark line give the range of salinity (psu) during the observations.

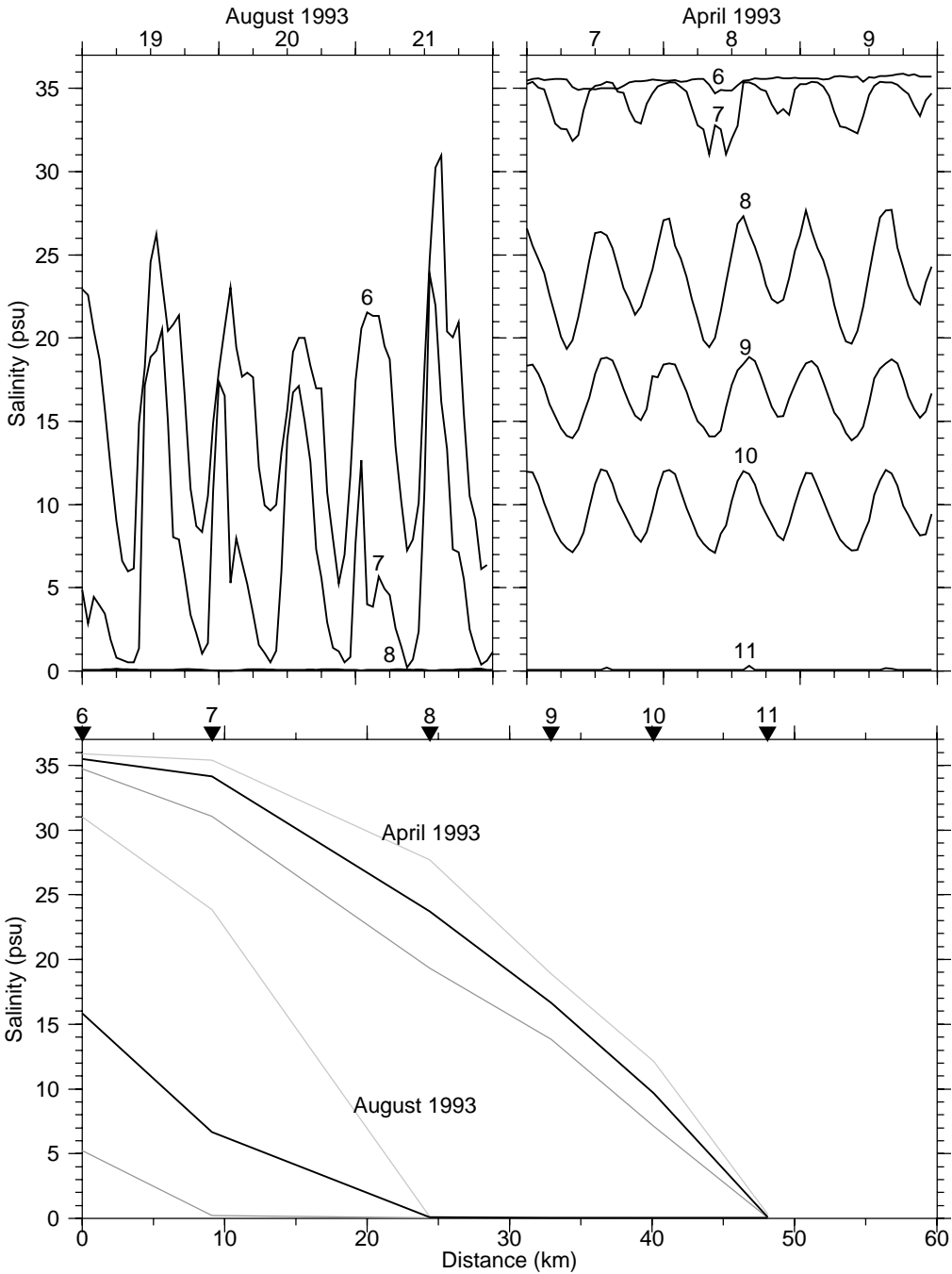


Figure 4.6 Same as figure 4.5, except that the salinity (psu) was observed in the Mandovi at the 6 locations, stations 6–11, shown in Map C. The salinity corresponding to each location is identified in the figure with the same number as in Map C.

4.5 CONCLUDING COMMENTS

The data presented in chapters 1 and 2 and in the present chapter allow us to classify the Mandovi and Zuari estuaries. By virtue of their location and shape of their channels, they are coastal-plain estuaries with convergent channels. By nature of tides, with spring tides in excess of 2 m, they are macrotidal. In view of the pattern of rainfall experienced by the estuaries, they are positive estuaries during the wet season. It appears that as the dry season progresses and freshwater influx decreases, the estuaries do not turn into negative estuaries even at the peak of the dry season. On the basis of data on vertical stratification presented in the present chapter, the Mandovi and Zuari are partially-stratified estuaries.

Finally, Indian estuaries have often been described as “monsoonal”, but the precise meaning of the word has not been stated. The description of runoff in the Mandovi and Zuari estuaries given in chapters 1, and of salinity variation given in the present chapter, helps us to define the term better. At the end of the monsoon, the water in the Mandovi and Zuari is completely changed due to replacement of the pre-monsoon water by freshwater flowing through the estuaries. This replacement is complete because the estuaries are flushed many times over. At the end of the monsoon, the estuarine processes start their eight-month-long dry-season evolution, in which horizontal mixing due to processes common in partially-mixed estuaries leads to mixing of freshwater at the upstream end, i.e., remnants of the water brought in by monsoonal runoff, and the saline water at the sea end. During the four-month wet season, evolution of the estuary is dominated by spurts of freshwater that flush the estuary completely. This contrast between the temporal evolution of Mandovi and Zuari estuaries between the dry season and the wet season justifies their classification as “monsoonal”.

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