

# Chapter 6

## Summary and conclusion

In this thesis we have described the hydrographic structure and the water masses in the Gulf of Aden using the available hydrographic data after applying quality control procedures. Also the circulation in the Gulf of Aden was described at the surface and deeper layers on a monthly basis using different data sets. It has been shown that the currents in the Gulf of Aden are not so simple as thought earlier; they are complicated by the presence of eddies embedded in them. The eddies influenced the flows during all months. The analysis suggests that the eddies entering the gulf from the Arabian Sea owe their existence to more than one mechanism.

The hydrographic structure and the water masses in the Gulf of Aden are presented in Chapter 3. The vertical hydrographic structure of the Gulf of Aden shows four layers, a surface layer, an intermediate low saline layer, a high saline RSW and a bottom layer. The surface layer showed strong seasonal variations in its characteristics. The SST was about 24–25 °C during winter (November–February). It increased to reach a maximum (31 °C) in May. During summer (June–August) the SST decreased along the northern side due to upwelling. The upwelling along the northern side during summer started in the eastern side during June and extended towards the west during July–August. In September, the SST started to rise again to  $\sim 30$  °C. Similarly, the mixed layer depth decreased from  $\sim$

80 m during winter to  $\sim 20$  m during summer. The seasonal variation was less in the intermediate low saline layer. It was cooler and more saline during summer as compared to that in winter.

Four water masses were identified using the newly compiled hydrographic data set. Among them, the origin of RSW is well known. The origin of the other three water masses, the GASW, GAIW and GABW were investigated in Chapter 3. As mentioned above, the seasonal as well as the monthly variabilities were highest for the GASW. Though the core density is  $\sim 1024.10 \text{ kg m}^{-3}$ , the lower limit of density varied from  $1023.50 \text{ kg m}^{-3}$  in winter to  $1022.20 \text{ kg m}^{-3}$  in summer due to the increase in temperature. The salinity of the core increases towards the west (Figures 3.5 and 3.6). The  $\theta$ -S- $\sigma_\theta$  structure of this water mass (core  $\theta$ -S  $26.0^\circ\text{C} - 36.0$  psu and  $\sigma_\theta$  24.1) is similar to the salinity maximum D of Rochford [1964] and ASHSW described in Shenoi et al. [1993]. As seen in the net surface flows shown in Figure 4.4 the flows during winter are towards the west over most the gulf with cyclonic and anticyclonic eddies embedded in it. This flow structure establishes in October and continues till April, mostly dominated by geostrophy (Figure 4.4). Hence, during winter, a sizable amount of ASHSW from the east enters the Gulf of Aden. Similarly, during the summer monsoon, the flows are eastward all over the gulf with a sizable amount of surface water from the Red Sea entering the gulf from the west (Figure 4.4f, g, h and i). In addition, during both seasons, some water forms locally due to precipitation and evaporation. Hence, it is possible that during winter, the GASW forms as a mixture of locally formed water and ASHSW, while during summer it is a mixture of locally formed water and Red Sea Surface Water.

In the intermediate layers (200–300 m), the GAIW appears as a minimum in the  $\theta$ -S diagram at  $\sigma_\theta$  level 26.5. The salinity of this layer increases westward due to mixing with the high saline RSW. GAIW occupies  $\sim 9\%$  of the total volume of Gulf of Aden, which is shallower during summer. As shown in Figure 4.5 the GAIW enters the gulf from the east along the northern side during winter and late summer (August–September), whereas dur-

ing June and July the flow at 300 m is eastward similar to that at the surface (Figure 4.5f and g). Our analysis shows that PGW cannot be the source of GAIW (Figure 3.12a). Hence, it is likely that the GAIW enters the gulf either from south through the Somali region or from the east. Three sources have been identified for the low salinity water through the Somali basin in the western Arabian Sea. First, the low salinity water brought into the Somali basin by the northern branch of the South Equatorial Current (SEC). The second possibility is the low salinity Subtropical Subsurface Water (SSW), which originates at the Subtropical Convergence in the southern hemisphere near  $40^{\circ}$  S. Warren et al. [1966] and Wyrski [1971] showed that this water penetrates as far as  $10^{\circ}$  N off East Africa and is partially responsible for the low salinity in the intermediate layer of the northern Somali basin. The third possibility is the Antarctic Intermediate Water (AIW), which forms at the Antarctic Convergence Zone at around  $40\text{--}50^{\circ}$  S, sinks and flows towards the north. Our analysis shows that it is possible that both SSW and AIW contribute to the existence of the salinity minimum in the Gulf of Aden at intermediate levels. The Socotra passage seems to be the main connection between Gulf of Aden and the Somali Basin. The passage also acts as the pathway for the southward migration of RSW.

RSW originated from the Red Sea occupies  $\sim 35\%$  of the total volume of the Gulf of Aden. On an average, this water mass occupies about 700 m (400–1100 m) thick layer of water column in the gulf, with its core at about 600–800 m (Figure 3.1). The salinity of this water mass decreases towards the east.

The GABW identified in the  $\sigma_{\theta}$  range 27.5 to 27.8 occupies about 38% of the total volume of Gulf of Aden. Since there is no production of bottom water in the Arabian Sea basin it is necessary to transport the bottom water from elsewhere. The AIW could be one of the sources for this water mass. The water of southern origin that enters the Gulf of Aden from the south, through the Somali basin, ultimately mixes with the high saline RSW to produce the GABW with salinity more than 34.80 psu. The mixing of warm RSW with cooler water from the south leaves a wide range of potential temperature

(2–11 °C). The percentage compositions, estimated based on the mixing theory of water masses (Figure 3.10), suggest the presence of ~ 10–20% RSW in the GABW. The bottom water in the western most Gulf of Aden could be the RSW itself.

In Chapter 4, three major data sets have been used to describe the monthly evolution of currents in the Gulf of Aden. The ship drift data showed the seasonality in the circulation (Figure 4.1) similar to other data sets, but cannot be used to bring out the mesoscale eddies embedded in the flows. Similarly, the Ekman drift estimated from winds (Figure 4.2) did not show the presence of eddies in the gulf or adjoining seas. Ekman drifts were towards the west during the winter monsoon (November–March) and towards the east during the summer monsoon (June–August). The Ekman flow in the month of September appeared to be an exception to the summer monsoon flow pattern; the flow inside the gulf was abysmally weak (Figure 4.2i). Similar was the case in May, the transition period between winter and summer monsoons. The Ekman drifts in April as well as in October, the other two transition months, were westward similar to the winter flows. Thus, due to the Ekman drifts, two well defined flow patterns form in the Gulf of Aden; (i) a westward flowing winter pattern and (ii) an eastward flowing summer pattern. The winter pattern started in October and continued till April, whereas the summer pattern existed only for a short duration of 3 months (June–August). In addition to the generation of well defined flow patterns, the Ekman drift does not seem to contribute to the generation of eddies in the gulf.

The analysis of geostrophic currents, however, clearly showed the embedded eddies in the flows (Figure 4.3). Several eddies were seen in the geostrophic currents during all months and they were consistent in the geostrophic currents derived from altimeter SLA. As seen in the net surface flows shown in Figure 4.4, the eddies dominated the circulation in the Gulf of Aden over the mean flow. The eddies seen at the surface extended to deeper layers, often to 1000 m or more.

The net flows at the surface were westward during October–April and were maximum

during November to February. This westward flow would transport water from the Gulf of Aden into the Red Sea. Similarly the eastward flow in the western end of the gulf during the summer monsoon (June–August) (Figure 4.4g and h) is a continuation of the outward flow from the Red Sea in the surface layer. The westward geostrophic currents in the western end of the gulf at 300 and 600 m layers in August–September (Figure 4.5h, i) are consistent with the intrusion of Gulf of Aden water into the Red Sea in the intermediate layers. Earlier reports had also shown that the summer regime in the Bab el Mandab Strait is dominated by the massive intrusion of cold ( $19\text{ }^{\circ}\text{C}$ ), low salinity (36.0–36.5 psu) water from the Gulf of Aden [Murray and Johns, 1997; Al Saafani and Shenoi, 2004].

We presented the analysis of interannual variability of sea level as a proxy to the variability of geostrophic currents at the surface. The annual and high-frequency signals dominate the sea level variability in the Gulf of Aden (Figure 4.6 and 4.7). The SLA variability in the gulf at interannual frequency is minimum and insignificant at 99% confidence level. It is significant at 95% confidence level only over small patches inside the gulf (Figure 4.7). Since the variability in the SLA is related to the geostrophic currents at the surface, it is clear that the interannual variability in the surface geostrophic currents inside the gulf are also insignificant. The geostrophic currents have dominated the net surface flows as seen in Figure 4.4 in the Gulf of Aden. Based on this argument, we conclude that the interannual variabilities in the circulation in the Gulf of Aden are insignificant.

The analysis of circulation in the Gulf of Aden presented here confirmed the earlier descriptions of the seasonality of surface currents and also provided new insights. First and foremost is that the currents in the Gulf of Aden are not so simple as thought earlier; they are complicated by the presence of eddies embedded in them. Secondly, the eddies influenced the flows in all months. Thirdly, the eddies are found only in geostrophic currents and not in Ekman drifts induced by winds and fourthly, the eddies act over the entire water column extending from the surface down to at least 1000 m.

The characteristics of eddies are described in detail in Chapter 5. The possible rea-

sons for the formation of eddies in the vicinity of the gulf and their westward movement were also investigated. Westward moving eddies were evident in the Gulf of Aden during November–May (Figures 5.1– 5.3) and our analysis showed them to be associated with the westward propagating Rossby waves. The westward propagating Rossby waves radiated from the Indian west coast, as well as the Rossby waves generated in the interior of the Arabian Sea ( $52\text{--}60^\circ$  E), contribute to the cyclonic and anticyclonic eddies in the vicinity of the Gulf of Aden. The low–frequency signal (mainly annual signal) showed a discontinuity in the longitudinal band between  $52^\circ$  E and  $60^\circ$  E; its intensity and spatial extent demonstrated considerable interannual variability. The uplifting of the thermocline, local wind stress, and the presence of Socotra Gyre in the vicinity, all contributed to this discontinuity in the annual signal. The westward propagating high–frequency Rossby waves generated locally (west of  $60^\circ$  E) are also a source for westward propagating mesoscale eddies in the Gulf of Aden. They move into the gulf from the east, either directly or through the Socotra Passage. They survive and move westward within the gulf inspite of the frictional effect of the boundaries of the gulf.

The analysis suggested that the eddies entering the gulf from the Arabian Sea owe their existence to more than one mechanism. Local Ekman pumping was important during the summer monsoon (June–September). In May and during the latter half of the summer monsoon (late July to September) and the fall inter–monsoon (October), the dominant mechanism was the generation of eddies by the instabilities in the Somali Current and the large eddies associated with it (Great Whirl and Socotra eddy) ([Fratantoni et al., 2006; Simmons et al., 1988]). During the winter monsoon (November–April), the dominant mechanism involved the westward propagating Rossby waves generated either in the Arabian Sea by Ekman pumping or along the west coast of India by poleward propagating Kelvin waves. Thus, the westward propagating Rossby waves from the Arabian Sea were more important for the circulation in the gulf over half the year.

Figure 6.1 shows the schematic diagrams summarizing the hydrographic structure and

circulation during winter (January) and summer (July). During January (Figure 6.1a) the distribution of the salinity at the surface is uniform ( $\sim 36.0$  psu) over most of the gulf except for a few patches of higher or lower salinity ( $\sim 0.1$  psu). The surface current during January is towards the west with a cyclonic eddy between  $46$  to  $48^\circ$  E and an anticyclonic eddy to the east of it along the southern coast of the gulf. The vertical distribution of salinity during this month (Figure 6.1a, bottom panel) shows the four-layer structure in the Gulf of Aden. The GASW occupies the top 100 m of the water column that flows towards the west. The GAIW occupies the layer between 100–500 m in the eastern part of the section and 100–400 m in the west. This layer flows westward along the northern side of the gulf. The salinity of this layer increases towards the west due to the mixing with the high salinity RSW. The RSW layer is seen clearly in this section occupying about 700 m thick layer of the water column, between 400–1100 m, with the salinity decreasing towards the east. The eastward flow of this layer is seen along the southern part of the gulf (Figure 6.1a, bottom panel). GABW is seen below the RSW layer.

During July (Figure 6.1b), the surface salinity along the western and the southern sides of the gulf is  $> 36.2$  psu. Along the northern side of the gulf, lower salinity is seen indicative of upwelling. The flow is eastward over the gulf with an anticyclonic eddy at the center between  $46$  and  $48^\circ$  E. The four-layer structure seen during January is also seen during this month from the vertical sections (Figure 6.1b, bottom panel) with the GASW occupying only  $\sim < 50$  m along the southern part and  $\sim 20$  m along the northern part of the gulf. This layer flows eastward during this month. The GAIW occupies from 100–400 m; the flow is eastward in this layer also. The RSW show high salinity in the western part of the gulf. The salinity of this layer decreases towards the east as it flows out from the gulf. The anticyclonic eddy seen at the surface extends to the deeper layers, where the isopycnal lines deepen at that location.

In conclusion, this study provides a synthesis of various data sets and describes the structure of hydrography and circulation in the Gulf of Aden diligently. Though we have

attempted to explain the dynamics of the processes within the frame-work of available data, numerical models that can simulate the observations are required to explain the dynamics of unexplained processes.



**Figure 6.1** (a) Schematic diagram of the salinity distribution based on the new climatology during winter (January). The top panel represents the horizontal distribution. The vertical sections shown in the lower panel are along the lines AB and BC shown in the upper panel. The vertical (lower panel) distribution of salinity (psu) clearly shows the four-layer structure of the water masses. The flows at surface and at the deeper layer are also shown. The isopycnal lines separating the water masses are also show in the vertical sections.

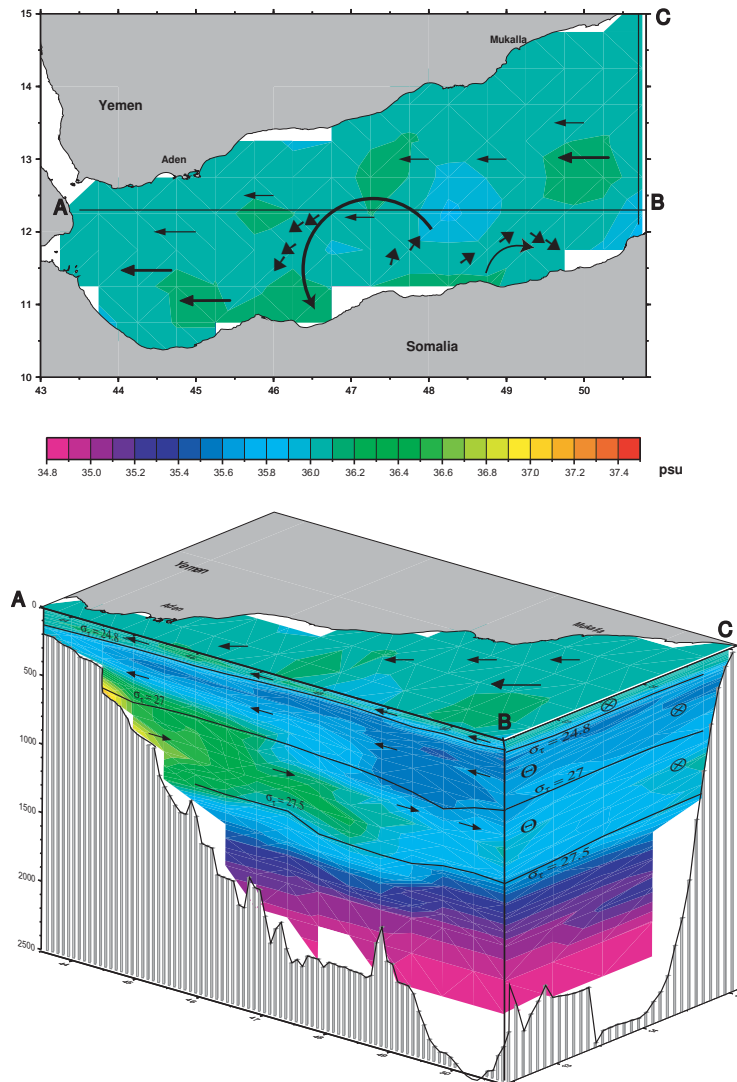
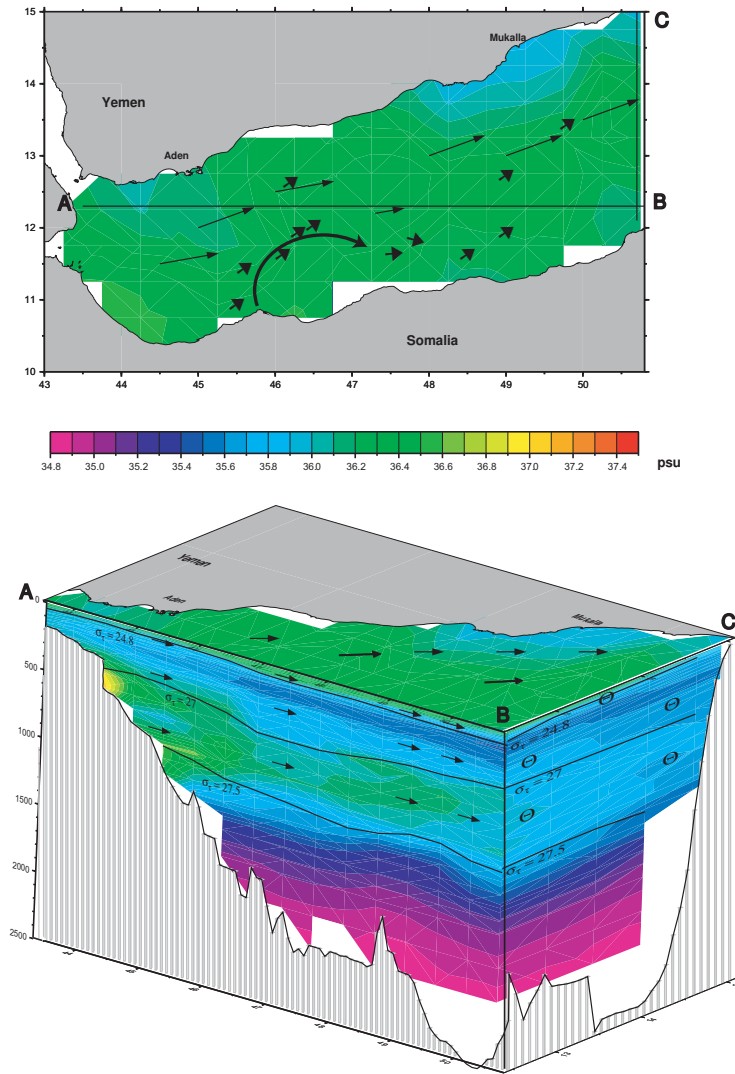


Figure 6.1 (b) Same as for 6.1a for summer (July).



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