

Chapter 1

Introduction

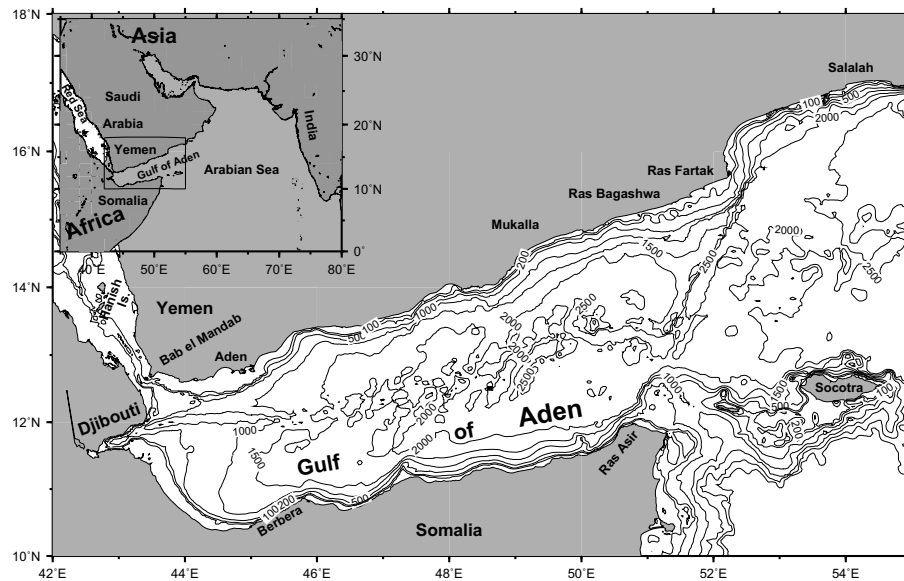
The Gulf of Aden presents a unique ecosystem that deserves scientific attention. In addition to its extraordinary biotic richness, the Gulf of Aden also serves as the highway for international trade between east and west. At present, approximately 3 million barrels of oil is being transported daily through the Gulf of Aden. Traditionally, the Gulf of Aden had provided considerable amount of sea food for the inhabitants of the surrounding arid lands. It will continue to do so in future also if the fisheries are developed using modern scientific knowledge and techniques.

The Gulf of Aden is an elongated stretch of water separating the African continent from the Asian continent (Figure 1.1). It is located approximately between the latitudes 10–15° N and longitudes 43–52° E. On its western end it joins the Red Sea, that produces one of the most saline water masses in the world oceans, and in the east it joins with the Arabian Sea (the Indian Ocean). In effect, the Gulf of Aden acts as the passage for the Red Sea water before it enters the Indian Ocean. The physical boundaries of the Gulf of Aden can be fixed approximately at the narrow Strait of Bab el Mandab in the west upto a line connecting Ras Fartak (east of Mukalla, Yemen) in the north and Ras Asir (northern corner of the Somali Peninsula) in the south. The northern and southern boundaries are well constrained with the land masses of Yemen and Djibouti-Somalia respectively.

The Gulf of Aden is a young ocean basin formed by the rifting of Asia (Arabia) from Africa (Somalia) [Girdler et al., 1980]. It has a well-defined continental margin, small oceanic basin, and an active mid-ocean ridge (Sheba Ridge) in the center characterized by a rift valley and fracture zones [Matthews et al., 1967; Bosworth et al., 2005]. The only other modern continental margin at a similar stage in its development is the Gulf of California [Cochran, 1981]. The Gulf of Aden is approximately 900 km in length and varies in width from 26 km at Bab el Mandab to about 320 km at Ras Asir. It is deepest in the middle ~ 2000 – 2500 m and shallowest (< 1000 m) in the west (west of 45° E). The average depth of Gulf of Aden is ~ 1800 m. In general, the depth increases from west to east. Some studies consider the eastern end of the Gulf of Aden as the north-south line connecting Socotra Island in the south and Ras Fartak along the Yemen coast. The southeastern part of the Al-Surat mountain range (of about 1800 m height) surrounds the Gulf of Aden on the northern side while the Karkaar mountains of approximately the same height surround the coastal plain on the south. The major ports on the coasts of the Gulf of Aden include Aden, Djibouti and Berbera.

1.1 Weather and climate

The Gulf of Aden and the adjoining north Indian Ocean come under the influence of seasonally reversing monsoon winds, a feature unique to the north Indian Ocean region. The monsoon winds over the north Indian Ocean, in general, reverse twice a year, blowing generally from the southwest during summer monsoon (June-September) and from the northeast during winter monsoon (November-February). March-May and October are the months of transition between the two monsoons. This temporal reversal of the winds arise due to the changes in atmospheric pressure patterns associated with the differential heating and cooling of the Asian land mass, especially the Indian sub-continent, with respect to the neighboring ocean. Earlier authors have followed different criteria in combining

Figure 1.1 Map of the Gulf of Aden and parts of the western Arabian Sea.

the months to represent the seasons. Anonymous [1982] stated that the Gulf of Aden experiences two distinct monsoon seasons, the southwest monsoon during the months of May to September and a northeast monsoon during the months of October to April. The months of April–May, and September–October are transitional months. Piechura and Sobaih [1986] considered the months of July–August as the period of southwest monsoon. However, they point out that sometimes the southwest monsoon starts in the west in June and in the east in May. They considered that the northeast monsoon was restricted to the months of November–February. Other months were considered as periods of weak variable winds. To study the seasonal variation of dissolved oxygen Al Sayed and Kolli [1992] described four seasons in the Gulf of Aden. Northeast monsoon during December–February, premonsoon during March–May, southwest monsoon during June–September and postmonsoon during October–November. Sobaih [1986] also made use of the same seasons while describing the data collected from the coastal stations of Yemen.

The description of wind patterns, over the Gulf of Aden, available in the literature also

do not suggest a uniform definition for the seasons. Hence, to avoid the arbitrariness in defining the prevailing seasons over the Gulf of Aden, it is necessary to propose a uniform definition based on the prevailing winds. In the present study, the pattern of climatological winds from satellite derived (QuikSCAT) data are used to categorise the months under different seasons. Figure 1.2 shows the climatological monthly mean winds over the Gulf of Aden and northwestern Arabian Sea. Over the Gulf of Aden, the southwesterly winds set in June, heralding the arrival of summer monsoon. They strengthen further during July and August ($\sim 8 \text{ m s}^{-1}$ west of 51°E). In September, the winds are weak ($< 2 \text{ m s}^{-1}$) and blow from different directions inside the gulf. While over the northwestern Arabian Sea, the summer monsoon sets in May and persists till September. The easterly/northeasterly winds start inside the gulf in October ($\sim 4 \text{ m s}^{-1}$) and persists till April. In the northwestern Arabian Sea, the winter monsoon appears in November rather than in October and continues till March. In May, the magnitude of the winds weakens considerably to less than 2 m s^{-1} though the direction remains more or less the same (easterly) except in the eastern gulf (east of 50°E) where they blow from south. The summer monsoon appears to last only for 3 months (June–August) over the gulf as against the 5 months duration (May–September) in the western Arabian Sea. Similarly, the east/northeasterly winds prevail over the Gulf of Aden for 7 months (October–April) compared to the 5 months duration (November–March) over the western Arabian Sea. In essence, the Gulf of Aden experiences a shorter summer monsoon (June–August) and a longer winter monsoon (October–April). Since the Gulf of Aden and northwestern Arabian Sea are strongly linked with each other in their circulation and dynamics, it is proposed to consider the months of June–September as summer monsoon months and the months of November–March as winter monsoon months. The months of April–May and October will be considered as the months of transition or inter-seasonal months (Table 1.1). The pattern is similar in the wind climatology provided in Comprehensive Ocean-Atmosphere Data Set (COADS) [Woodruff et al., 1993].

Occasionally, a tropical cyclone originating in the north Arabian Sea reaches the entrance to the Gulf of Aden. The greatest chance of encountering a cyclone in the gulf is in November [Anonymous, 1982]. In addition, three extreme weather conditions also occur in the Gulf of Aden. These are locally known as (i) *Belat*, a strong sand storm, during the winter monsoon in mid-December (it generally persists for one to three days), (ii) *Khamsin* hot dry north wind that blows across the Gulf of Aden during the summer monsoon that occurs for three to four times a year lasting for 3–4 hours, and (iii) *Shamal*, also occurring during the summer monsoon, blows mostly from the north for a few successive days [Anonymous, 1993].

Precipitation in the region is sparse, hence no study has been conducted on the rainfall over the Gulf of Aden. The data available from the raingauge stations in Yemen (Aden and Mukalla) indicates that most of the precipitation occurs during the winter monsoon. However, at Salalah, a station to the east of the gulf along the southern coast of Oman, most of the rainfall occurs during the summer monsoon [Anonymous, 1993]. The rainfall information for the years 2001, 2002 and 2003 at Aden and Mukalla are shown in Table 1.2. The annual rainfall varies drastically from year to year, as do the rainy months during the three years. The annual rainfall was maximum during 2002 (~85 mm) at Mukalla and at Aden (~58 mm). Most of the rain in 2002 was during April at Mukalla (~63 mm) and Aden (~42 mm); rest of the rain was received during December–March. In contrast to 2002, the annual rainfall during 2001 was < 15 mm both at Aden and Mukalla. Similarly the rainfall in 2003 was also low at Aden (< 30 mm) and Mukalla (< 4 mm).

Table 1.1 The four seasons over the Gulf of Aden based on the patterns in winds

<i>Season</i>	<i>Period</i>
Summer (southwest) monsoon	June–September
Fall inter-season	October
Winter (northeast) monsoon	November–March
Spring inter-season	April–May

Figure 1.2 Monthly climatology of surface winds over the Gulf of Aden derived from QuikSCAT data.

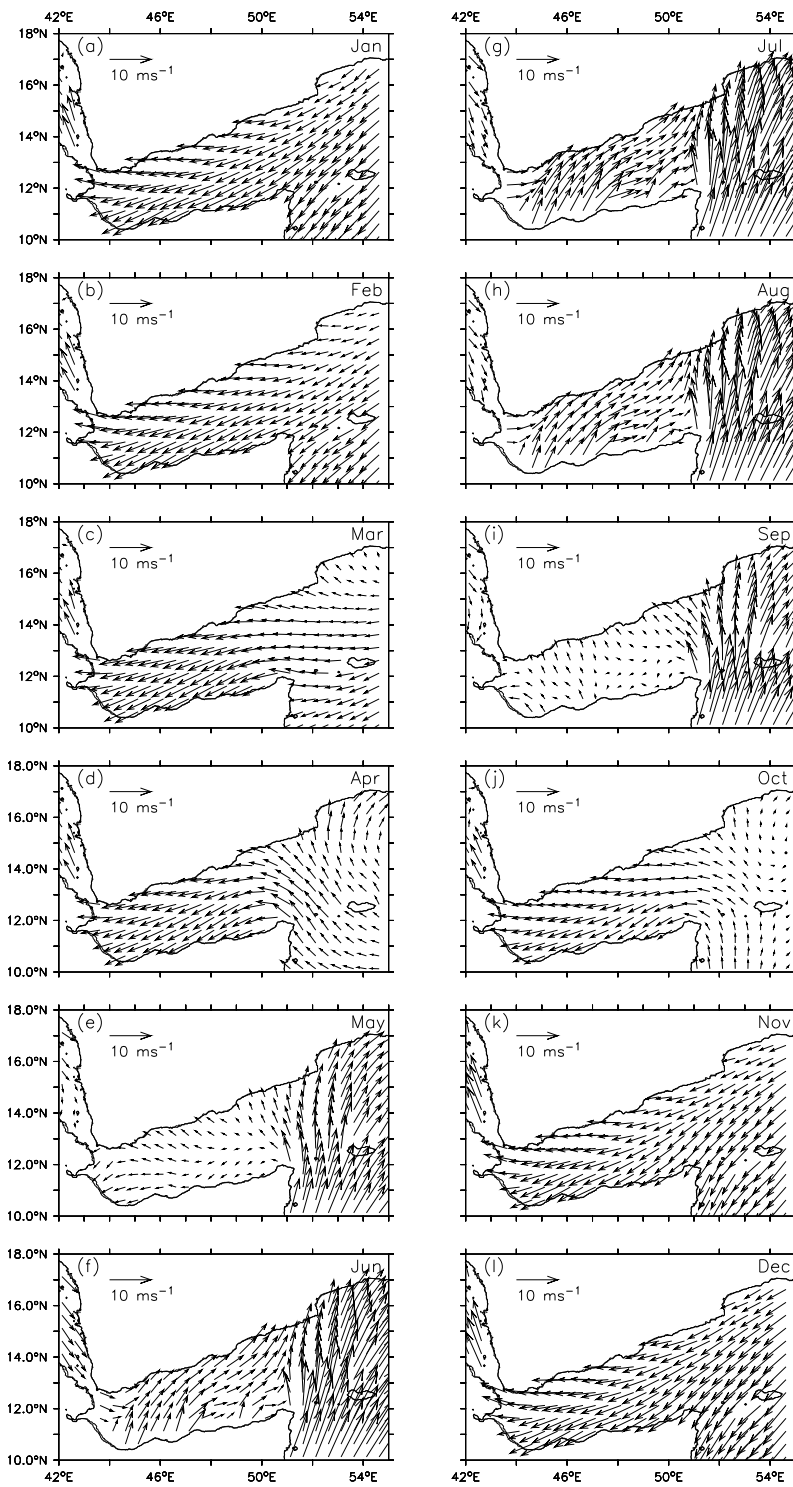


Table 1.2 Monthly mean rainfall (mm) at Aden and Mukalla (stations located on the northern coast of the Gulf of Aden) for the years 2001, 2002 and 2003. Data source - Civil Aviation & Meteorology Authority of Yemen.

Month	Aden			Mukalla		
	2001	2002	2003	2001	2002	2003
January	3.1	1.1	0.0	0.0	1.0	0.0
February	0.0	2.0	0.0	0.0	4.1	1.0
March	0.0	9.5	0.0	0.0	7.8	0.0
April	0.0	42.4	5.2	0.0	63.0	0.0
May	4.5	0.0	0.0	0.0	0.0	0.0
June	0.0	0.0	0.0	0.0	0.0	0.0
July	0.0	0.0	0.0	0.0	0.2	1.2
August	6.3	0.0	11.0	0.0	0.1	0.0
September	0.0	0.0	0.0	4.2	0.0	0.0
October	0.0	0.0	0.0	0.0	0.0	0.0
November	0.0	0.0	0.0	0.0	0.0	0.2
December	0.0	2.1	13.7	8.3	9.0	1.1
Annual	13.9	57.1	29.9	12.5	85.2	3.5

1.2 Hydrography and water masses

After the conclusion of the International Indian Ocean Expedition (IIOE) a few Soviet research vessels and Food and Agriculture Organization (FAO), through Norway fisheries research, collected hydrographic data from this region. Most of the data was collected for fishery research and not for the study of physical oceanography of the Gulf of Aden. Details of one such survey conducted by the Marine Science Research and Resource Center (MSRRC) of Yemen for the northern Gulf of Aden is available in Stirn et al. [1985], Piechura and Sobaih [1986] and Nasser [1992]. Subsequent investigations carried out in this area concentrated mostly on the study of the exchange of water between the Red Sea and the Gulf of Aden [Maillard and Soliman, 1986; Murray and Johns, 1997; Siddall et al., 2002; Aiki et al., 2006] and on the spreading of Red Sea water in the Gulf of Aden [Fedorov and Meshchanov, 1988; Bower et al., 2000, 2002; Ozgokman et al., 2003; Peters and Johns, 2005; Peters et al., 2005]. Beal et al. [2000] dealt with the spreading of the Red Sea Water out of the Gulf of Aden.

The extensive exchange of water between the Red Sea, the Gulf of Aden and the Arabian Sea, the strong evaporation and the monsoonal winds that blow over the region, all assist in the formation of complex vertical structures in the water column of the Gulf of Aden [Khimitsa, 1968; Stirn et al., 1985]. The earlier studies that used the available hydrographic data to describe the water masses in the Gulf of Aden include Rochford [1964], Khimitsa [1968], Piechura and Sobaih [1986], Nasser [1992], Maiyza and Mohamed [1993], Mohamed et al. [1996] and Mohammed [1997]. Since Chapter 3 is exclusively dedicated to deal with the water masses in the Gulf of Aden, the summary of the findings of these studies will be presented there.

Seasonal changes of the surface layer water characteristics described by Piechura and Sobaih [1986]; Nasser [1992]; Maiyza and Mohamed [1993] gives an account of the variability in the surface temperature of Gulf of Aden. Most of the variability in the sea surface temperature (SST) is seasonal. SST is highest (31–32 °C) during end May and

beginning of June. In July–August, it cools down to 29–30 °C, the degree of cooling depends on the strength of the summer monsoon. During the summer monsoon, the SST along the Arabian coast, the region adjacent to the Gulf of Aden, reaches a minimum of 17 °C. The heating of the surface takes place in September soon after the weakening of summer monsoon winds over the gulf and the SST bounces back to ~30 °C within a month. It cools again in October–January, ~ 24–25 °C, in response to the winter monsoonal winds and warms again during February–May in response to the spring warming that dominates the region during this period. The cycle is apparent in the satellite derived SST too. Figure 1.3, shows the annual cycle of SST derived from Tropical Rainfall Measuring Mission/TRMM Microwave Imager (TRMM/TMI) satellite over the Gulf of Aden. It reaches the maximum in May–June, falls in July–August, rises again in September and falls again in October–January before warming steadily in February–May. In essence, the SST over the Gulf of Aden exhibits strong seasonality.

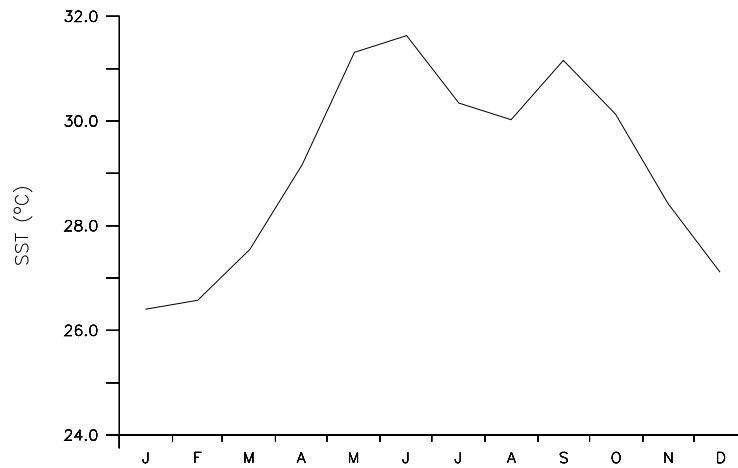
Similar to the changes in SST, the surface mixed layer also shows strong seasonality. In summer, the mixed layer depth (MLD) decreases to less than 20 m and increases to over 100 m in winter. Accordingly, the depth of thermocline also shoals and deepens in summer and winter respectively; about 20–120 m in summer and 150–250 m in winter [Piechura and Sobaih, 1986].

Seasonal changes in the subsurface water, though much smaller than in the surface water, are still distinguishable. The lowest temperature and highest salinity is observed during the summer months and the highest temperature and lowest salinity during the winter months [Piechura and Sobaih, 1986].

1.3 Surface circulation

Very little information is available on the surface circulation in the Gulf of Aden. Most of the information on surface currents come from the ship drift observations [Kolli et al.,

Figure 1.3 Annual cycle of sea surface temperature (°C) over the Gulf of Aden. The SST was derived from Tropical Rainfall Measuring Mission/TRMM Microwave Imager (TRMM/TMI) satellite data for the period from January 1998 to December 2005



1992]. The general understanding of the surface currents in the gulf from the previous studies indicate that the flow during the winter monsoon months (November–February) is from east to west along the northern coast of the gulf and from west to east along the southern coast of the gulf. During the summer monsoon (June–August) and in September the flows are in the opposite direction; westward along the southern coast and eastward along the northern coast. In between these two seasons, the currents are weak and varying. In fact the flow in the Gulf of Aden is not regular suggesting any large scale currents along the coast, but is broken down to various closed circulation cells during the two prominent monsoon periods [Kolli et al., 1992]. Wooster et al. [1967] stated that the winter pattern starts in October with a weak flow of water into the gulf, which is fully developed in November through April. During summer, the direction reverses but with increased strength. An anticyclonic eddy is also seen in the central gulf during July–August (see charts CA1–CA4 in Wooster et al. [1967]). Though this analysis provided a fair picture of surface currents in the Gulf of Aden it used very little data from the southern part of the gulf.

The dynamic topography maps prepared by [Wyrтки, 1971] indicate a weak flow during January–February with a northeastward flow along the northeastern part of the Gulf of Aden. During the summer monsoon months, July–August, an anticyclonic cell forms in the center of the gulf and shifts eastward towards the mouth of the gulf during September–October. The dynamic topography maps of Seriy and Khimitsa [1963] indicate two eddies, one cyclonic in the gulf (east of 50° E) and the other, an anticyclonic eddy, to the east of the gulf off Ras Fartak. The geostrophic current derived from the hydrographic data collected by *R. V. F. Nansen* in the upper 500 m [Sandven, 1979] also indicated numerous eddies at different locations.

The recent attempts that described the circulation in the Gulf of Aden or along its segments include Mohammed and Kolli [1992] and Johns et al. [2001]. The details of their findings will be presented in Chapter 4 dedicated exclusively to describe the currents in the Gulf of Aden.

1.4 Upwelling

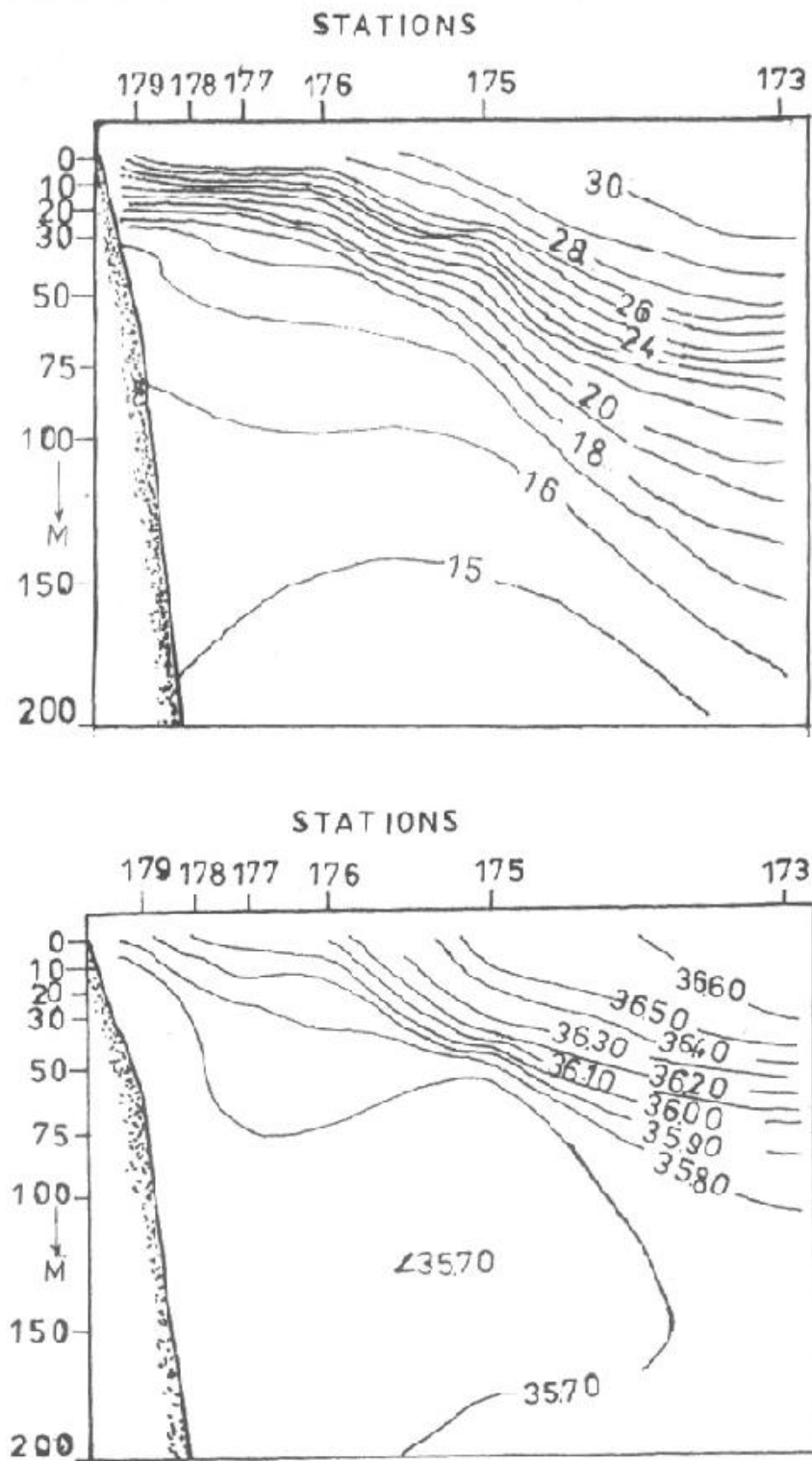
Numerous investigators have reported the occurrence of upwelling along the Gulf of Aden and Arabian coasts [Bruce, 1974; Swallow, 1984; Piechura and Sobaih, 1986; Savidge et al., 1990]. Understanding the process of upwelling is important since the Gulf of Aden has been regarded as one of the most productive areas [Kabanova, 1968; Currie et al., 1973; Krey and Babenard, 1976]. Piechura and Sobaih [1986] showed that the upwelling develops first in the far eastern parts of the Yemeni coastal waters in May and subsequently, progresses further towards the west. Mostly, the upwelling appears in separated patches similar to those appear in the coastal waters elsewhere [Boje and Tomczak, 1978]. Awad and Kolli [1992] studied the upwelling process in the Gulf of Aden by analyzing the hydrographic data collected during 1984–85. They described the distribution of hydrographic properties and estimated the strength of upwelling. The most conspicuous

feature is the cooling of near surface layer by more than 8 °C. Figure 1.4 reproduces the figure from Awad and Kolli [1992]. The temperature and salinity sections along 49° E during July extends from the central region of the gulf (station 173) to the northern coast (station 179). The isotherms shallow towards north within a short distance; the isotherm of 20 °C rises from ~ 100 m depth at station 173 to 20 m at station 179 in the north. Similarly the isohalines shallow towards the north. They attributed the upwelling during summer monsoon and downwelling during winter along the northern part of the gulf to the dominant wind over the gulf. However they could not describe the upwelling along the southern coast of the gulf due to insufficient data. Al Sayed and Ghaddaf [1993] attributed the frequent occurrence of fish mortality in the Gulf of Aden during the southwest monsoon to the presence of very cold, low oxygen water near the surface. Morcos and Piechura [1990], using the data in the archives of the British Museum, stated that very strong upwelling takes place along the Yemen coast in the west.

1.5 Sea level

The attempts made to understand the sea level variations in the Gulf of Aden are very limited [Morcos, 1990]. Patzert [1974] presented the sea level changes at Aden and Perim (Myuun) Island and concluded that these changes resulted from the reversal of circulation, which is closely associated with the reversals in the monsoon winds acting on the sea surface. Figure 1.5 shows the monthly climatology of mean sea level at Aden, based on PSMSL data for the periods 1879–1893, 1916–1933 and 1937–1969. The sea level at Aden rises between September and May and falls during June–July to reach the minimum in August. The seasonal oscillations in the mean sea level can arise due to astronomical effects, effects of evaporation, precipitation and river discharge, atmospheric pressure, and steric sea-level effects. The effects of purely astronomical conditions (long-period tides) are not significant; they do not exceed 12 mm at these latitudes [Pattullo et al.,

Figure 1.4 Vertical distribution of temperature and salinity along 49° E during July in the Gulf of Aden. After Awad and Kolli [1992]



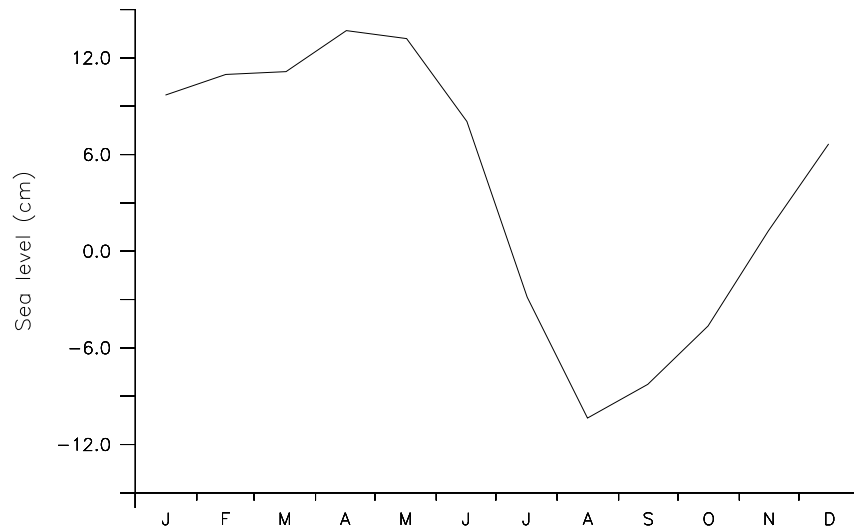
1955]. Because rainfall is very low and no large rivers are discharging into the Gulf of Aden, these two factors can be ignored. Maximum evaporation over the gulf occurs during winter when the sea level is highest [Privett, 1959]. Since the sea level variations are completely out of phase with the variations in evaporation, evaporation also does not appear to control the oscillations of mean sea level.

The isostatic adjustment of the ocean surface to changing atmospheric pressure requires that the sea surface rise (fall) by 1 cm for every 1 mbar decrease (increase) in pressure. Patzert [1974] noted that the atmospheric pressure at mean sea-level is highest during January and lowest during July at Aden with a range of ~ 10 mbar. Corrections to the monthly mean sea-level curves for the pressure variations results in an increase in the range of mean sea level. Thus the observed variations in mean sea level does not appear to be due to the effect of atmospheric pressure change.

Variations of the density within a water column, from which the steric sea level is calculated, depends on the thermohaline variations within the column. It is high when water is warm and/or less saline and low when water is cold and/or more saline. In the upper 300 m of the water column near Aden, the steric variations have the same phase and similar range as the sea level at Aden, though the range of the steric variations is larger by approximately 8 cm [Patzert, 1974]. This variation in density of the upper 300 m of the water column is due to the upwelling of cool, low-salinity water that occurs in the northwestern Gulf of Aden during the southwest monsoon.

1.6 Objectives

From this brief summary of the previous studies it is clear that the information available on the hydrography and circulation of the Gulf of Aden is meagre. For example, the literature is incomplete on the description of the annual cycle of hydrography, the water masses, their origin, the annual cycle of circulation at different depth levels, the meso-

Figure 1.5 Annual cycle of sea level (cm) at Aden.

scale features like eddies that occur in the gulf and their origin. The data sets used by the earlier researchers were either specific to a smaller region within the gulf or were confined to specific timings. With the recent developments in satellite techniques in measuring various oceanographic parameters and due to the advancement in numerical modeling skills, larger reliable data sets are now available for further research in this area.

In this thesis, we have synthesized various data sets, hydrography, satellite derived sea levels, satellite derived winds and some model outputs to describe the circulation and water masses in the Gulf of Aden more precisely than before. The major objective of this study is to describe the seasonal cycle of circulation and hydrography in the Gulf of Aden and to identify the possible mechanisms that control the circulation. Towards this, we have first described the variability in hydrography and water masses in the Gulf of Aden quantitatively on a monthly scale and identified their origins. Next, we have described the mean monthly picture of circulation in the Gulf of Aden using different data sets like hydrography, ship drifts and satellite derived sea levels and last, we have examined the mesoscale features that influence the circulation in the Gulf of Aden and identified their

forcing mechanisms using various data sets and model outputs.

Chapter 2 describes the data sets, specifically, the hydrographic data used in the thesis and the procedures followed for quality control and objective analysis. Chapter 3 is devoted to describe the hydrography and water masses in the Gulf of Aden. In Chapter 4, we describe the circulation in the Gulf of Aden using ship drift, hydrography, satellite altimetry and winds derived from satellite scatterometers. Chapter 5 describes the mesoscale eddies that influence the circulation in the gulf and their origin. Using satellite derived sea levels, we argue that the westward propagating eddies in the gulf are linked to the westward propagating Rossby waves in the Arabian Sea. Chapter 6 summarizes and concludes the thesis.