CHAPTER 3

Salient Features of Hydrography
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3.1 Upper-Ocean Circulation

Along with the reversal of winds the near-surface water circulation also reverses completely every six months. Aside from directly affecting the surface flow changes in monsoon winds also give rise to coastal and equatorial Kelvin waves and equatorial Rossby waves that have both annual and sub-annual periods (McCreary et al., 1993). Due to the tropical location of the entire North Indian basin and its relatively small size (as compared to the North Pacific and the North Atlantic) these waves propagate rapidly through the region strongly influencing circulation in areas far away from their origin. This complicates the dynamics of surface waters as the circulation at any site is forced by local as well as remote (large, basin-scale) processes, and therefore it cannot be studied in isolation.

Major surface currents in the Arabian Sea during the two monsoon seasons are schematically depicted in Fig. 3.1. All major currents north of the $10^\circ S$ undergo seasonal reversal. During the SWM, surface circulation in the Arabian Sea is generally clockwise. The most energetic flow during this season occurs off the East African coast where the East Africa Coastal Current (EACC) feed the Somali Current, which is one of the strongest western boundary currents in the world having a volume transport of 60 Sv ($1 \text{Sv}=10^6 \text{m}^3 \text{s}^{-1}$), which is of the same magnitude as the Gulf Stream. This flow is distinguished by the existence of several quasi-stationary anticyclonic
Fig. 3.1. Schematic diagram of surface currents in the Arabian Sea during the two monsoons (a) NE Monsoon and (b) SW Monsoon.

(EACC - East African Coast Current; SECC - South Equatorial Counter current; SC - Somali Current; WICC - West Indian Coast Current; NMC - Northeast Monsoon Current; LH - Lakshadweep High; SG - Southern Gyre; GW - Great Whirl; SE - Socotra Eddy; RHJ - Ras-al-Hadd Jet; LL - Laccadive Low; SMC - Southwest Monsoon Current).

(Adopted from Schott and McCreary, 2001)
eddies of which the Southern Gyre (SG) and the Great Whirl (GW) are most notable. These eddies cause offshore deflection of most of the water flowing northward around 4° and 10°N, inducing upwelling at these latitudes (Schott and McCreary, 2001). As compared to 4°N, upwelling at 10°N is more pronounced and longer lasting. The water upwelling here spreads far and wide, to the south by the GW and along the axis of the Somali Jet. Further north, strong SWM winds also force intense upwelling along the coasts of Yemen and Oman, but surprisingly the near-surface currents here do not exhibit an organized pattern and seasonality expected from the wind stress except near the coast. Instead, the flow is dominated by meso-scale eddies which also facilitate rapid offshore advection of the cold upwelled water as filaments and plumes that extend up to 1,000 kilometers from the coast (Flagg and Kim, 1998). The resultant coastal upwelling is demonstrated here by the presence of wedge-shaped features [discernible in satellite imageries of sea surface temperature (SST)] along the left (shoreward) shoulders of the SG and GW (Fig 3.2).

In addition to coastal upwelling caused by the strong southwesterly winds, upwelling is also expected to occur offshore during the SWM. This is because strong gradients in wind speed across the Findlater jet leads to Ekman pumping to the left of this jet (Bauer et al., 1991). Although the turbulence caused by strong winds should tend to deepen the mixed layer, the net effect is of entrainment of nutrients into the euphotic zone supplementing the nutrient supply through the offshore advection of upwelled water from the coastal upwelling zones (Smith, 2001).
Fig. 3.2. Monthly climatologies of remotely-sensed surface chlorophyll a (a-c) and SST (d-f) for February (a,d), May (b,e) and August (c,f). Source (Jerry Wiggert, University of Maryland and Bob Evans, RSMAS, University of Miami)
Along the west coast of India, the region of the present study, circulation is much less energetic and relatively poorly organized during the SWM. The West India Coastal Current (WICC) flows toward the equator. The southward flow begins in March, becomes strongest by July, and collapses by October (Cutler and Swallow, 1984; Shetye and Shenoi, 1988). It is ~150 km wide and transports 4 Sv in the south and 0.5 Sv in the north (Shetye, 1998).

The southward flowing WICC is expected to bring the thermocline up along the Indian coast. The region does, in fact, experience upwelling, but with characteristics and effects quite different from the western Arabian Sea. The process begins in May along the Malabar Coast (southwestern India) and the west coast of Sri Lanka, and gradually propagates northward. Local winds along these coasts are upwelling-favourable, and so the process is not only more intense here as evident by lower sea surface temperatures (Wyrtki, 1971), it also has a farther offshore reach (beyond the continental shelf) (Shetye et al., 1990). The latter is also due to the existence of the Laccadive Low, a cyclonic eddy, which is an integral part of the SWM circulation (Fig. 3.1). Elsewhere (along the central west coast of India) thermocline shoals up to the coast.

At very shallow depths (often within 10 m of the surface), the upwelled water is generally prevented from reaching the surface by a warmer, fresher-water lens formed from intense precipitation in the coastal zone. Thus, both temperature and salinity effects combine to result in a very pronounced near-surface density gradient that impedes vertical mixing.

Hydrographic conditions described above are clearly seen in vertical sections of properties off Goa presented in Figs. 3.3a-e. This section was
repeated on a number of occasions, in different months and years however, data for only five sets of sampling (SS 141, SK 103, SS 136, SK 140 and SS 128) are used here. Upsloping of isotherms close to the coast was observed on all cruises conducted from June to October-November, providing evidence for upwelling, and the temperature structure just off the continental shelf/slope was indicative of the existence of the undercurrent (upward sloping at the top of this feature and downward tilt close to its bottom; Shetye et al., 1990). The undercurrent is more conspicuous in salinity and oxygen sections (salinity < 35.4; O$_2$ > 10 µM; e.g., Figs. 3.3b and 3.3c). Although believed to be associated with the SWM circulation, its signatures were often still discernible during other seasons. In fact, as inferred from the tracer distributions, the most intense undercurrent was observed to occur on a cruise undertaken in December 1998 (salinity at its core being < 35.1 – Fig. 3.3d). However, the shallow thermocline near the coast implied that the flow on this occasion was still directed toward the equator; and so, while these conditions were atypical, they provide a measure of the interannual variability. The undercurrent becomes progressively less distinct from the south to the north (Shetye et al., 1990), but still observable at least as far as off Mumbai.

As stated above upwelling along the west coast of India gradually shifts northward. That is, it begins and also ends earlier in the south than in the north. Along the northwest coast of India shallow mixed layers last well into the NEM (up to November-December; Banse, 1968). This implies that upwelling along the Indian west coast cannot be forced by local winds alone. An upwelling of Kelvin wave can explain the northward propagation of low sea levels. Consistent with the observations model simulations suggest that
Fig. 3.3. Distribution of temperature (°C), salinity and oxygen (μM) along the cross shelf section off Goa.
remote forcing from the Bay of Bengal plays a major role in driving the WICC and associated upwelling (McCreary et al., 1993).

During the NEM surface circulation in the Arabian Sea is generally counterclockwise (Fig. 3.1). In the western Arabian Sea surface flow (directed southward) is much less vigorous as compared to the SWM, and the upwelling ceases to occur by October. Along the west coast of India, on the other hand, the circulation is best developed during this season in spite of weak winds. In fact, the WICC, which now flows northward, is the most prominent surface current in the entire Arabian Sea during this period. Flowing anomalously into the wind this current is estimated to carry almost twice as much water (~10 Sv) as its southward flowing variant during the SWM (Shetye et al., 1991). As it moves northward it gradually narrows from 400 km at 10°N to 100 km at around 22°N, forming a narrow jet with a transport of 7 Sv (Shetye et al., 1991). The broadening of the WICC off the southwest coast of India is in part due to the presence of an anticyclonic eddy – the Laccadive High – located just north of the islands it is named after Laccadive islands (Bruce et al., 1994), and in part due to the dissipation of energy from this current as it moves northward through the westward radiating Rossby waves. It is obvious that the WICC during the NEM cannot be but remotely forced. It originates as a result of bifurcation of the basin-scale westward-flowing NEM Current in the region southwest of the island of Sri Lanka (Schott and McCreary, 2001). The warm, low-salinity waters of the WICC exert a major control on biogeochemical cycling in the eastern Arabian Sea during the NEM. Outside the region affected by the WICC, the surface waters are cooled to 24-26°C by the northeasterly continental winds leading to
deep mixed layers (MLDs) (Figs. 3.3d and 3.3e) and entrainment of water from the thermocline, a process prevented by strong thermohaline stratification in the WICC.

### 3.2 Water Masses

For any given region, characteristics of a water mass are expressed with the help of the potential temperature-salinity ($\theta$ - $S$) diagram (Sverdrup et al., 1942). The major water masses in the Arabian Sea along with their respective density ($\sigma_\theta$) levels have been identified by Wyrtki (1971) based on physico-chemical properties.

The Arabian Sea is a region of negative water balance where evaporation exceeds precipitation by as much as 150 cm yr$^{-1}$ off the Arabian coast (this difference decreases to $\sim$-20 along the southwest Indian coast (Venkateswaran, 1956). This results in high surface-salinites. Winter cooling of surface waters in the north leads to the formation of a shallow high-salinity water – the Arabian Sea High Salinity Water (ASHSW) – identified by a salinity maximum at $\sigma_\theta = 25$ surface (Rochford, 1964). This maximum can be readily identified in the $\theta$-$S$ diagrams shown in Figs. 3.4 – 3.6.

The subsurface (mesopelagic) water-mass structure in the Arabian Sea is affected to a very large extent by outflows from the two marginal seas – the Persian Gulf and the Red Sea – that are connected to the Arabian Sea through the Gulf of Oman and the Gulf of Aden, respectively. The Red Sea is a deep (>2000 m) silled basin (sill depth at the Strait of Bab-el-Mandeb ~100 m); the Persian Gulf is a shallow embayment without a sill at its entrance (the Hormuz Strait) having a maximum depth of 67 m. Both water bodies are
located in very arid regions resulting in surface salinities in excess of 40. The extremely high surface salinities together with cooling in the northern parts of these land-enclosed basins give rise to high-density water masses that spill over their entrances into the gulfs linking them with the Arabian Sea, sink to appropriate depths corresponding to the density achieved after some at their entrance points, and spread horizontally over considerable areas (Rochford, 1964; Wyrtki, 1971; Dietrich, 1973). The outflows are compensated by near-surface flows of lower salinity water into the marginal seas (Grasshoff, 1969, 1975; Morcos, 1970; Hartman et al., 1971). The core layers in the Arabian Sea are characterized by salinity maxima that have been assigned nominal \( \sigma_t \) values of 26.6 for the Persian Gulf Water (PGW) and 27.1 for the Red Sea Water (RSW) by Wyrtki (1971). The approximate depths of these density surfaces in the Arabian Sea are 250 m and 500 m, respectively.

The composition of water masses in the area of present study can be deduced from the potential temperature – salinity (\( \theta - S \)) plots. Selected stations along three sections were chosen for this purpose just off the continental margins – the first is off Ponnani in the south (Fig. 3.4), the second is off Goa in the centre (Fig. 3.5), and the third is off Mumbai in the north (Fig. 3.6). \( \theta - S \) diagrams in the first region exhibit relatively small variations at \( \sigma_t > 25 \), but large changes at shallow depths (Fig. 3.4). A single broad salinity maximum in the deeper layer evidently corresponds to RSW below which the \( \theta - S \) relationship is almost linear indicating binary mixing between the Arabian Sea High-Salinity Intermediate Water (cf. Wyrtki, 1973) and the North Indian Ocean Deep Water. Another salinity maximum is found just below the surface mixed layer generally within the \( \sigma_t \) range of 23-24. Salinity values at this
Fig. 3.4. Potential temperature ($\theta$) - salinity (S) diagrams for stations off Ponnani.
Fig. 3.5. Potential temperature ($\theta$) - salinity (S) diagrams for stations off Goa.
Fig. 3.6. Potential temperature ($\theta$) - salinity ($S$) diagrams for stations off Mumba
maximum approached or exceeded 36 indicating that the water at this depth was of the northern origin. Above this feature salinities decreased rapidly due to the freshening of surface layer. As most of the observations were made during the SWM, this decrease in salinity was apparently brought about by monsoonal precipitation and land runoff. However, a similar freshening of surface layer should be expected to occur during the NEM as well because of the northward advection of low-salinity waters of the WICC. The salinity maximum corresponding to PGW is not seen at this location. Instead the two maxima mentioned above are separated by a broad salinity minimum. This implies northward flow, presumably in the undercurrent.

The RSW is more prominently seen in the θ-S diagrams off Goa (Fig. 3.5). Above this maximum, the θ-S characteristics are a lot more variable than in the south. At about 26.5 σθ surface, for example, one usually observes a salinity minimum that can at times be replaced by the salinity maximum of the PGW. When this happens, the salinity minimum is shifted to shallower depths, but it is always present, and as discussed above it probably corresponds to the poleward undercurrent, arguably the major source of low salinity waters in the eastern Arabian Sea. It may be pointed out that temporal changes in circulation at the depth of the undercurrent can make the low-salinity water move up and down the coast; during this process sometimes entraining other water masses, especially PGW, leading to complex thermohaline structure. It may also be noted that the lowest salinities at the minimum were recorded on two cruises (SK140 and 149d) undertaken in early December. As stated earlier, the SK140 observations are probably atypical. However, if the poleward undercurrent is active only during the SWM it is expected to have
maximum impact on tracer distribution in late summer/autumn and these
effects should persist for some time even after the surface flow has reversed.
The shallow salinity maximum corresponding to ASHWW shows even wider
changes, with the maximal and minimal salinity values differing by as much as
1. In general the water is saltier and denser than in the south.

The influence of the RSW is negligible in the north (Fig. 3.6). This is
consistent with previous observations. Ramesh Babu et al. (1980), for
example, found this watermass to be absent north of about 17°N latitude. On
the other hand the PGW acquires greater importance in the north as one gets
closer to its source. Sometimes the maximum is broken into several maxima
because of entrainment of lower-salinity waters (e.g., from the undercurrent).
Consequently, the salinity values at a $\sigma_\theta$ value of 26 vary from 35.2 to 36. The
shallow salinity maximum corresponding to ASHWW occurs at higher density
surface here than in the south.