Salinity distribution in the Arabian Sea

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In the Arabian Sea surface salinity ($S_s$) is more than 35 PSU throughout the year, except in the southeastern regions. Increase of $S_s$ in the central Arabian Sea during the summer monsoon season was mainly due to evaporation and vertical mixing of surface waters with subsurface high saline waters. Increased evaporation in the northern Arabian Sea due to low air humidity causes high surface salinity (>36 PSU) throughout the year. The subsurface maximum in the upper 200m corresponds to the Arabian Sea Watermass which lies on the 23.5 kg.m$^{-3}$ sigma-t surface. Large difference between surface and subsurface salinity maxima (>0.2 PSU during winter and summer monsoon) suggests the significance of surface dilution in the eastern Arabian Sea. Another feature in the vertical salinity structure is the transient multiple subsurface maxima separated by pockets of low saline water.

In the Arabian Sea, studying the spatial and temporal variability of the thermohaline structure has been the objective of only a few research investigations. In comparison to thermal structure, information on salinity distribution is extremely sparse in this region. However, most of these studies are confined to a specific season or specific oceanic region in the Arabian Sea$^{1-7}$. In this paper an attempt is made to bring out certain aspects of the salinity distribution in the Arabian Sea. Also, the influence of summer monsoon on the vertical salinity structure at certain locations is discussed.

Materials and Methods

Data utilised for this study are obtained from the National Oceanographic Data Centre (NODC), Washington; the Indian National Oceanographic Data Centre (INODC), Goa; the First Global GARP Expedition (FGGE); the Oceanavax; the Indo-Polish expedition and ships of opportunity. The domain of study extends from the equator to 25°N, 40°E to 80°E, and it excludes the marginal seas, the Red Sea and the Persian Gulf. After the quality control$, approximately 14,000 salinity profiles were available for the analysis. These profiles were utilised to compute the monthly mean profiles of salinity for each 2° × 2° grids.

Hydrographic data collected at certain locations in the Arabian Sea during premonsoon (May) and summer monsoon (August) seasons are utilised to bring out the changes in the vertical salinity structure. The areas selected are off the Somalia coast (50°E, 5°N; labelled as SOM in Fig. 3), off the Arabia coast (59°E, 20°N; ARA), northern Arabian Sea (65°E, 20°N; KAR), off the southwest coast of India (76°E, 8°N; SWC), equatorial Arabian Sea (65°E, 0°; CEQ) and central Arabian Sea (65°E, 10°N; CEN) which respond typically to the different oceanographic and atmospheric features.

Results and Discussion

Monthly distribution of surface salinity

The distribution of surface salinity ($S_0$) presented in Fig. 1 shows values exceeding 36 PSU north of 15°N and decreases southward in all directions with varying magnitude. Here, the increased evaporation due to low air humidity$^9$ results in higher $S_0$ during the winter and summer monsoon season. The surface waters are more saline along the western boundary of the Arabian Sea than along the eastern boundary. In the southeastern Arabian Sea (east of 70°E and south of 10°N), which are in contact with Bay of Bengal, salinity is less than 34.5 PSU during the winter and summer monsoon seasons. During
the northeast monsoon season, i.e. during winter, the low saline Bay of Bengal water joins the northward flowing Equatorial Indian Ocean water and flows as a northward surface current along the west coast of India. This current cause considerable reduction in the surface salinity along the southwest coast of India (35 PSU in October to 34 PSU in January) during winter. The maximum northward extension of this low saline water is about 12°N in January but can be traced up to 17°N in February-March. It starts to retreat from March onwards, which coincides with the reversal in the upper layer circulation.

With the onset and progress of summer monsoon winds, $S_o$ reduces considerably off the southwest coast of India (>35 PSU in May to <33.5 PSU in August) and it increases away from the shore. The monthly distribution of rainfall and river discharge (Periyar and Muvatupuzha rivers) off Cochin (Fig.2) showed drastic increase in their rate between May and August. A lag of one month is noticed between the peak values in precipitation (750 mm in June) and river discharge (600 m$^3$·s$^{-1}$ in July). The excessive rainfall and river discharge during the summer monsoon season caused considerable reduction in the surface salinity along the west coast of India (south of 15°N). On the western boundary of the Arabian Sea, low saline waters carried by the south equatorial current turn towards north forming a boundary current. Off Somalia, this low saline water mixes with the high saline water brought to the surface by upwelling. The admixture of these two watermasses slightly increased the $S_o$ in this

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**Fig. 1**—Monthly distribution of surface salinity

**Fig. 2**—Monthly distribution of river discharge and precipitation off Cochin.
region. Off the Arabian coast, the low saline water brought to the surface by the processes of upwelling causes dilution (>36 PSU in May to <35.5 PSU in July). $S_o$ increased in the central Arabian Sea (<35.5 PSU in April) to values over 36.5 PSU in July) due to increased evaporation and the vertical mixing of the surface waters with subsurface high saline waters. This high saline water with salinity greater than 36 PSU extend as a tongue towards the southeastern region in association with the prevailing flow pattern.

**Salinity variability with the progress of summer monsoon**

In the Arabian Sea, the vertical and horizontal salinity structure exhibits large scale modification on an annual cycle. One of the characteristic features of the vertical salinity structure is the presence of a subsurface salinity maximum in the upper 200m throughout the season (Fig.3), except at ARA and KAR. The temperature and salinity ranges of this maximum correspond to a sigma-t of 23.5 kg.m$^{-3}$ has been called the Arabian Sea Watermass (ASW). At KAR and ARA, this subsurface maximum is not seen because they are in the regions where ASW is formed (>36.5 PSU) at the surface resulting a decrease of salinity with depth. However, at ARA, the intrusion of a high saline watermass i.e. Persian Gulf Watermass, below 125m results in the formation of subsurface salinity minimum around 125m. The ASW which has its origin in the north/northeastern Arabian Sea occupies its own levels depending on its density as it traverse away from the source region. This watermass is noticed at 100m at CEN and 75m at SWC and CEQ with the respective core salinities 36.1 PSU, 35.5 PSU and 35.3 PSU.

With the commencement of the summer monsoon, salinity in the surface layers increased at CEN (0.7 PSU), SOM (0.4 PSU) and KAR (0.2 PSU) and this increase is evident up to 80m at CEN, 50m at KAR and 80m at SOM. At CEN and KAR, the increased evaporation causes the increase in $S_o$. At CEN, in addition, vertical mixing of surface waters with subsurface high saline waters also contribute to the increase in salinity. At ARA, SWC and CEQ the water column up to 200m exhibits considerable reduction in the salinity. In the surface layers, maximum reduction is noticed at SWC (±1.8 PSU) and is confined to the upper 15m. Here, the reduction in $S_o$ is mainly due to increased precipitation and river discharge (Fig.2). During the summer monsoon season, the surface flow is southward while it is northward at the subsurface levels. This northward flowing undercurrent brings low saline waters of equatorial origin towards north and in turn reduce the subsurface salinity. The process of upwelling which causes upward movement of this low saline waters towards surface levels also reduces the salinity in this zone. Another impact of upwelling on the vertical salinity structure is the shoaling of the subsurface salinity maximum from a depth of 75m to 15m by August. The water column between the southward surface currents and northward subsurface currents are characterised by intense turbulence mixing. This intense mixing in turn destroy the well defined subsurface maxima and reduced its core salinity by 0.6 PSU (35.5 to 34.9 PSU). At ARA the entire water column undergoes drastic reduction in salinity (±1PSU in the surface layer and ±0.3 PSU at 125m). At CEQ not much conspicuous change is noticed in $S_o$ between the two.
periods. However, the subsurface maxima noticed around 50 m during premonsoon becomes less evident and its salinity continuously decreased with depth.

Hitherto all the studies have highlighted the presence of a single subsurface maxima in the upper 100 m salinity field. However, analysis of the salinity data collected from the eastern Arabian Sea during premonsoon period reveals the occurrence of transient multiple cores (2 to 3 cores) in the halocline separated by pockets of low saline waters (Fig. 4). Vertical separation between these cores varies from 10 to 15 m and its salinity progressively decreases with increasing core depth. The temperature and salinity of these cores corresponds to the ASW (23.5 kg.m\(^{-3}\) ). Of these cores, the topmost one (15 m thickness) is the most pronounced. It is interesting to note that in association with these cores, either inversions (\(\approx 0.2^\circ C\)) or step like structures (5 to 10 m thickness) are noticed in the temperature field. Harceesh Kumar et al.\(^{14}\) attributed the occurrence of multiple cores to the transient period between the reversal of flow from southerly to northerly at this level. Once the flow at this level (50 m) stabilised in the northerly direction, multiple cores disappeared leaving an organised single core. However, spatial variability of this multiple core is yet to be established.

**Monthly distribution of subsurface salinity maxima.**

From the above discussions it is clear that there is a subsurface salinity maxima in the upper 200 m of the Arabian Sea throughout the year. To understand the seasonal variation of this maxima, its core depth \((D_{\text{max}})\) and core salinity \((S_{\text{max}})\) are presented in Figs. 5 and 6 respectively. In general, \(S_{\text{max}}\) is maximum \((>36.4 \text{ PSU})\) north of 10°N and decreases towards lower latitudes. In addition, \(D_{\text{max}}\) varies from values less than 10 m in the northern region to values over 100 m in the southeastern Arabian Sea. Shallow \(D_{\text{max}}\) (<10 m) and high \(S_{\text{max}}\) (>36.4 PSU) occur in the north / northeastern Arabian Sea especially during the winter and summer monsoon, which are the periods of maximum evaporation\(^9\), suggests that a high saline watermass is formed in this region due to evaporative processes. This high salinity water that formed at the surface and has a temperature and salinity range correspond to a

sigma-t of \(\approx 23.5-24 \text{ kg.m}^{-3}\) has been called the Arabian Sea Watermass\(^1\). During the summer monsoon, this high saline watermass (>36.4 PSU) extends as a tongue from the northeastern Arabian Sea towards the central regions, and is present at a depth of 20 m or less. This watermass descends to deeper levels, particularly south of 10°N, leading to the formation of a subsurface salinity maximum, as it traverses south / southeastward \((S_{\text{max}} < 35.8 \text{ and } D_{\text{max}} > 80 \text{ m east of 70°E})\). These changes suggest that the ASW flow equatorward over the remnants of low saline waters of Bay of Bengal and equatorial region noticed in the surface layers during the winter\(^4\).

The low saline Bay of Bengal / Equatorial Indian Ocean watermass, brought by the prevailing northerly currents, occupies the surface layers of the continental shelf of the southwest coast of India during winter. The northerly currents also produce sinking off the entire west coast of India. As a result, the core of ASW is pushed down to deeper depths (> 60 m) with a lowering of core salinity (<35.8 PSU). With the progress of summer monsoon the core of ASW shoals to depths less than 50 m over the west coast of India and off Somalia coast due to upwelling, and its salinity is even less than that off the west coast of India (35.4 PSU). The reduction in
Fig. 5—Monthly distribution of salinity maxima in the upper 200m.

Fig. 6—Monthly distribution of the depth of salinity maxima.
core salinity is due to the increase in the vertical mixing induced by the southward surface currents and northward undercurrent associated with upwelling carrying low saline waters northward. Off Somalia, the progressive replacement of high saline water by low saline south equatorial water and the associated mixing results in the presence of moderate saline waters (35.2 PSU) by September. Off the Arabian coast also, marked reduction is noticed in the core salinity by the end of southwest monsoon (36.2 PSU in May to 35.8 in August).

To study the difference between $S_0$ and $S_{max}$, the monthly distribution of $\Delta S$ ($\Delta S = S_{max} - S_0$) is presented in Fig. 7. Generally, northern (north of 20°N) and western (west of 65°E) Arabian Sea is characterised by small $\Delta S$ (<0.2 PSU) while it is greater than 1 PSU east of 70°E especially during winter and summer monsoons. During the summer monsoon, $\Delta S$ greater than 0.2 PSU mostly confined to the coastal regions of the west coast of India (east of 70°E) with a strong meridional gradient (1.6 PSU in 5° longitude in August). In contrast to summer monsoon, during winter, the regions where $\Delta S$ is greater than 0.2 PSU spread over larger areas both in the offshore and alongshore direction. Even during this period, meridional gradients are stronger east of 65°E (1.8 PSU in 5° longitude in November). Since $S_{max}$ exhibits less variation compared to $S_0$, higher values of $\Delta S$ in the eastern/southeastern Arabian Sea during the winter and summer monsoon season suggests the importance of dilution in the surface layers. Low values of $\Delta S$ (<0.2 PSU) noticed in rest of the Arabian Sea are mainly due to the increase in surface salinity (Fig. 1) and decrease in the core salinity (Fig. 5).

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**References**