Thermohaline Structure & Watermasses in the Northern Arabian Sea during February-April

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Temperature and salinity distribution in the northern Arabian Sea during February-April 1974 was studied with the help of vertical sections parallel and perpendicular to the coast. In regions occupied during February, deep mixed layer and in regions occupied during March-April, shallow seasonal thermocline were present. Thickness of the main thermocline was about 75 m near the mouth of the Gulf of Oman and increased towards the northwest coast of India. Together with the formation of seasonal thermocline, the surface layers exhibited complex salinity structure. Persian Gulf water was generally present at about 300 m depth, while Arabian Sea high salinity water was noticed around 60 m depth in the eastern part of the study region. East of 63°E, the Persian Gulf water was not observed as a tongue but was present in various pockets. It is inferred that the chief now of Persian Gulf water is not along the west coast of India.

Though considerable information is available on the Indian Ocean as a whole, not much has been reported about the Arabian Sea north of 20°N. Ramam et al.1 have studied the watermasses of this region during different seasons. Rochford2 has discussed the flow paths of various watermasses of northern Indian Ocean. Other works of interest in this area are of Wyrtki3, Wooster et al.4 and Colborn5. The present study is based on the data collected on board INS Darshak during February-April 1974.

Methods

During OCEANOVEX expedition (1974) continuous profiles of temperature and salinity against depth were obtained, using Plessey 9060 STD (salinity, temperature, depth) recorder, from northern Arabian Sea (Fig. 1). Areas A and A1 were covered in February. Sts 71 and 72 (area A) were occupied in April to study the seasonal variation in properties. Area B was covered in March-April. Temperature and salinity values were noted from STD records at every 10 m up to 100 m, every 50 m between 100 and 500 m and every 100 m below 500 m. Maximum sampling depth was 2000 m which is the range of the instrument. Digitised data were reconciled with the nansen cast data. Coarse spacing was used to avoid effects caused by short lived micro variations. Hence, the results presented are only the gross features, with better resolution as compared to the conventional nansen cast data.

Vertical sections parallel and perpendicular to the coast were prepared (Fig. 1). Isotherms were drawn at an interval of 0.5°C up to 500 m and 1°C further below, while isohalines were drawn at 0.1‰ interval. Isohalines of 0.05‰ were introduced wherever found necessary.

Results and Discussion

Sections parallel to the coast—The upper region of areas A and B showed differences in temperature and salinity which were due to the increased summer heating in area B. Below 100 m, the effect of surface heating was not very significant (Figs 2a, 3a and 4a). Even the wind induced circulation in the Arabian Sea did not penetrate below surface layers (~150 m)6. Düing7 showed that the vertical extension of monsoonal effects was <200 m in the present region of study. Hence, it is expected that in February-April the effect due to variation in wind may also be confined to thin surface layer. The stations were, therefore, joined in spite of the observational time lag. In the middle of the section where areas A and B were joined, the isolines were drawn by broken lines up to 100 m in order to avoid the abrupt ending of isolines. These are not to be mistaken as real features.

The depth of the mixed layer was chosen as the depth where temperature dropped by 1°C from surface temperature. The lower limit of the thermocline was selected as the depth where the temperature gradient fell below 0.025°C/m.

Section I (Fig. 2)—Surface temperature varied between 22.3 and 26.7°C in area A (Fig. 2a). There was a steady increase in surface temperature towards north from st 41 to st 69 (24.6 to 26.7°C) which was due to the progressive increase in the summer heating. Mixed layer was generally deep in area A (about 125 m). The deep mixed layer observed was due to the effect of winter convection and is characteristic of this region5. At sts 28 and 29 exceptionally deep mixed layer (200 m) was observed. The thermocline at these stations was sharp. In area B, seasonal thermocline was observed close to the surface with a gradient of about 0.15°C/m.
Banse reported the presence of strong seasonal thermocline in the northeastern Arabian Sea in late April and early May between 30 and 50 m. Colborn indicated a weak summer thermocline in northeastern Arabian Sea and a strong summer thermocline in the northwestern Arabian Sea. The thickness of the main thermocline was about 75 m at st 2 and increased towards the Indian coast to about 175 m. Gradient in the main thermocline was about 0.05°C/m. St 5 showed an inversion at about 300 m while st 12 had 2 inversions, one at about 150 m and another at about 350 m. Numerous domes and troughs were present in the subsurface layers which could, perhaps, be indicative of horizontal shears due to possible existence of eddies.

Highest surface salinity was observed at st 2 off Gulf of Oman (36.6%/o) and decreased eastwards to about 36.3%/o (Fig. 2b). It is interesting to note that at st 28 and 29 deep isohaline layer was present in association with the deepened mixed layer. Such features might occur in the presence of anticyclonic eddy causing convergence and consequent sinking. In area B, the surface layers showed a complex salinity structure exhibiting, in general, a shallow salinity minimum. Here, an increase in salinity was observed between 50 and 100 m. Halocline was noticed all along the section coinciding with the upper part of the main thermocline. A subsurface salinity minimum was, generally, centred around 200 m. Salinity maximum present at about 300 m was of the Persian Gulf water and appeared to spread as a tongue up to st 21 beyond which it appeared as several pockets towards the Indian coast.

The salinity maximum at 300 m was generally accompanied by either a small temperature inversion or a thin isothermal layer as observed in the STD records (available with the authors). This feature was, however, more conspicuous at sts 5 and 12 where large temperature inversions were associated with the salinity maxima. The large inversion observed at st 5 was bifurcated by some mechanism as it reached st 12, creating 2 blobs centred around 150 and 350 m. Varma and Rao attributed this to the breaking of internal waves. Another interesting feature was that at st 48 the salinity maximum was observed at 200 m. This vertical shift might perhaps be due to the prominent uneven bottom topography in the neighbourhood. Below 500 m both temperature and salinity decreased monotonically.
Temperature and salinity distribution in section II (Fig. 1) was somewhat similar to that of section I. Hence it is not presented. However, unlike section I no large temperature inversion was observed.

Section III (Fig. 3)—A large temperature inversion was observed at st 10 centred around 300 m. The seasonal shallow thermocline was present in area B and the thickening of main thermocline towards the Indian coast was observed. Maximum surface salinity was observed in the middle of the section (st 65). Mixed layer did not show any deepening in the middle of the section as in the sections I and II. This might be because the possible anticyclonic eddy of sections I and II did not extend to this section. Subsurface salinity minima and maxima were observed and the tongue like extension of Persian Gulf water reached up to st 26.
Fig. 3—Vertical distribution of temperature (a) and salinity (b) along section III
The halocline, in general, followed the shape of the main thermocline. At st 10, corresponding to the temperature inversion, a large increase in salinity was observed.

Section IV (Fig. 4)—Temperature and salinity distribution was generally similar to that of section III (Fig. 4a). The marked feature was the shallowing of the main thermocline at st 32. Maximum surface salinity of about 36.6°/oo was observed at the middle of the section (st 66; Fig. 4b). It is interesting to note that at st 32 the salinity maximum of Persian Gulf water which generally occurred at about 300 m was drawn up to about 200 m. Due to this, Persian Gulf water did not appear as a tongue as observed in the western part of other sections. The high saline water that was drawn upwards, along with the marked shallowing of thermocline might be due to the presence of a cyclonic eddy around this region, probably generated by the sharp rise in the bottom topography. Such topographic features can generate cyclonic eddies.

Two sections (V and VI) perpendicular to the coast are given in Figs. 5 and 6 respectively to bring out some of the features more clearly. The exceptionally deep mixed layer at the northern end and the shallow one at the southern end of section V (Fig. 5) might be due to the presence of the eddies of opposing directions at the either end of the section. It appears from the upward trend of isolines seen in deeper waters also that these eddies were not confined to surface layers. Sastry and D’Souza while studying the circulation in Arabian Sea during southwest monsoon have observed whirls which extended to deep layers. The early stages of the development of the seasonal thermocline was seen in section VI (Fig. 6). This shallow thermocline was more developed at the shoreward end of the section.

Watermasses—An attempt was made to identify various watermasses observed. The upper 500 m was characterised by the presence of salinity maxima and minima. The most prominent among these was the maximum, generally, centred around 300 m. The highest salinity was encountered near the mouth of the Gulf of Oman (Figs 2b, 3b and 4b). This was the Persian Gulf water (PGW). Salinity in the core of PGW dissipated as it spreads which could be seen from the variation in salinity between 36.65°/oo near the mouth of Gulf of Oman and about 35.75°/oo off Kathiawar (Figs 2b, 3b and 4b). It maintained a steric level between 140 and 160 cl/t (Fig. 7). Even though PGW was present at almost all stations, its spreading was not gradual. The distribution of the core values of PGW (Fig. 8) indicated that it might be spreading as a tongue towards south in the region west of 63°E. The vertical sections (Figs 2b, 3b and 4b) also showed that PGW did not spread as a tongue towards east beyond 63°E. Sts 28, 38, 47, 48 and 49 and the stations occupied off Bombay (sts 73-78) did not show the presence of PGW. These findings suggest that the chief flow path of PGW is not along the west coast of India which is not in agreement with the findings of Wyrtki, but is more or less in agreement with Rochford who showed the main flow path of PGW through the western Arabian Sea towards south. However, Wyrtki also speculated...
a flow of PGW to Somali basin during northeast monsoon.

The large temperature inversions and salinity maxima of PGW encountered at sts 5, 10 and 12 (Figs 7a, b and c) near the mouth of the Gulf of Oman were not observed at the neighbouring sts 6 and 11 (Figs 7a and c). Temperature inversions associated with salinity maxima in the mouth of Gulf of Oman were observed by Wyrtki3 (pp 439-440) also. This anomalous feature could be due to the sudden spilling of PGW into the deeper waters in the Gulf of Oman after passing through the shallow Hormuz strait.

Ramam et al.1 described a salinity maximum observed at 40 m (about 315 cl/t) near the mouth of Gulf of Oman as PGW. Present data in the same area during February did not show any salinity maximum centred around that depth; moreover PGW was observed further below at about 300 m. However, present observations in this area in late April (st 72, Fig. 7d) showed besides the PGW centred around 300 m, a salinity maximum at about 50 m. This shallow salinity maximum might be due to summer heating as explained elsewhere. Again, the salinity maximum which Ramam et al.1 described as Red Sea water could be PGW. It is noteworthy that Red Sea water (about 100 cl/t) generally found at depths >500 m in the Arabian Sea was not traced in this region. This is in agreement with the findings of others2,9.

A salinity maximum was observed below the surface layers centred around 50 m (between 310 and 350 cl/t) in regions off Bhuj and Kathiawar and at about 60 m (between 330 and 460 cl/t) off Bombay. This was the Arabian Sea high salinity water formed by the excess evaporation9. The steric levels of this watermass agreed with those reported earlier2,3.

In area B, a shallow salinity minimum between 10 and 30 m was observed in association with the seasonal thermocline. In the western part of area B where the seasonal thermocline was very sharp, another shallow salinity maximum was observed around 60 m depth (Fig. 2b, 3b and 4b). Although the depth of occurrence of this maximum was almost the same as that of Arabian Sea high salinity water, it was heavier (280 cl/t). Hence, the occurrence of this maximum might be due to the persistence of the high saline surface water which sank during winter due to convection. This was further ascertained by comparing T-S relationships for 2 adjacent sts 22 and 72 occupied in February and April respectively (Fig. 7d). Similarity of the characteristics of the salinity maximum of st 72 at about 50 m to the surface waters of st 22 indicated that the subsurface salinity maximum of st 72 could be the remnants of winter surface water sunk due to convection. Banse8 also indicated such a feature off Karachi during premonsoon.

Rochford2 described a watermass (Watermass 'C')
as originating in the northern Arabian Sea. In the present study such a watermass could not be identified. However, a marginal increase in salinity was observed at sts 9 and 17 around 100 m and at sts 27 and 28 around 150 m. Other investigators\(^3\,^9\) had also not reported the watermass 'C'.

It is interesting to note that watermasses identified in the present study did not spread as a core but were traceable in numerous pockets. This feature was attributed to the possible presence of eddies in this region.

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**References**