Indian Journal of Marine Sciences
Vol. 15, December 1986, pp. 234-240

# Circulation & Watermass Structure in the Central Arabian Sea during December 1982

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*Received* 17 *June* 1985; *revised received* 18 *August* 1986

After the cessation of the SW monsoon over Arabian Sea, the North Equatorial Current sets strongly and the low saline waters from the Bay of Bengal and the equatorial Indian Ocean penetrate into the Arabian Sea. This results in strong horizontal salinity gradients in the upper layers due to the mixing of the Persian Gulf, Bay of Bengal and Arabian Sea High Salinity Waters. The low salinity water is found to originate in the Andaman Sea and its thermohaline index has been derived as T = 18.6°C and S = $34.5 \times 10^{-3}$ and can be traced on the 300 cl/t isanosteric surface. The mixing patterns in the central Arabian Sea have been studied by constructing the triangles of mixing. It is found that, the vertical mixing is dominant along the core of the Persian Gulf Watermass.

It is well known that surface circulation in the entire tropical Indian Ocean responds to the reversing monsoonal wind systems. During the SW monsoon season, the north equatorial current is replaced by the monsoon current flowing eastward. The seasonal somali current sets in, and an anticyclonic flow encompasses the entire Arabian Sea. The flow is known to penetrate to depths up to 1000 m. The salinity distribution has been discussed by several workers[1-5]. Premchand[2] has studied the watermass characteristics of Persian Gulf and Red Sea Waters as they flow out from their respective source regions and has examined the processes that lead to their transformations. He has sought to explain the maxima and the minima in the salinity distribution as a consequence of penetration of different watermasses into an idealized watermass structure, a straight line T-S structure connected by the thermohaline indices of the Tropospheric Equatorial Watermass (T = 25°C; S = $35.3 \times 10^{-3}$) and the Bottom Watermass (T = 0.6°C; S = $34.7 \times 10^{-3}$) originating from the Antarctic Ocean. These studies have indicated that the basic structural features are invariant in the deeper layers. Because of the response to the varying wind systems, the upper layer structure is largely time dependent and therefore, complex. In this paper, the oceanographic parameters along 2 zonal sections, lat. 15° and 19°N, during Dec. 1982 and along a transect joining these 2 zonal sections are presented and the features of the watermass structure along the sections discussed. The percentage composition[6] of the Persian Gulf Watermass has also been derived and presented.

## Materials and Methods

*R V Gaveshani* occupied 2 zonal sections on 15° and 19°N during 17-30 Dec 1982. In addition, stations were occupied along the transect joining the western portions of these 2 zonal sections (Fig. 1). Station curves were plotted for each station. Vertical distributions of temperature, salinity (practical salinity scale of 1978 has been used[7]), thermosteric anomaly and the density flux function[8] were constructed. Geostrophic currents relative to 1000 db level were derived.

## Results

*Distribution along* 15°*N*— The sea surface temperature (Fig. 2a) decreases from 28.9°C near the Indian coast to 26.3°C in the western region. The mixed layer thickness varies from 30 to 90 m. The bottom of the thermocline may be identified by the depth of 14°C isotherm. The thermal structure further shows relatively weak gradients around 600 m. The surface salinity (Fig. 2b) increases towards west from the Indian coast. A salinity maximum can be seen in the zonal belt between 65° and 70°E. The maximum salinity exceeds

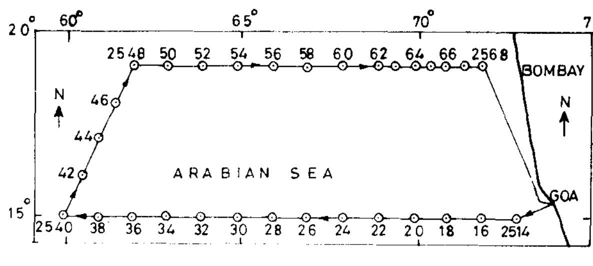


Fig. 1 — Station locations

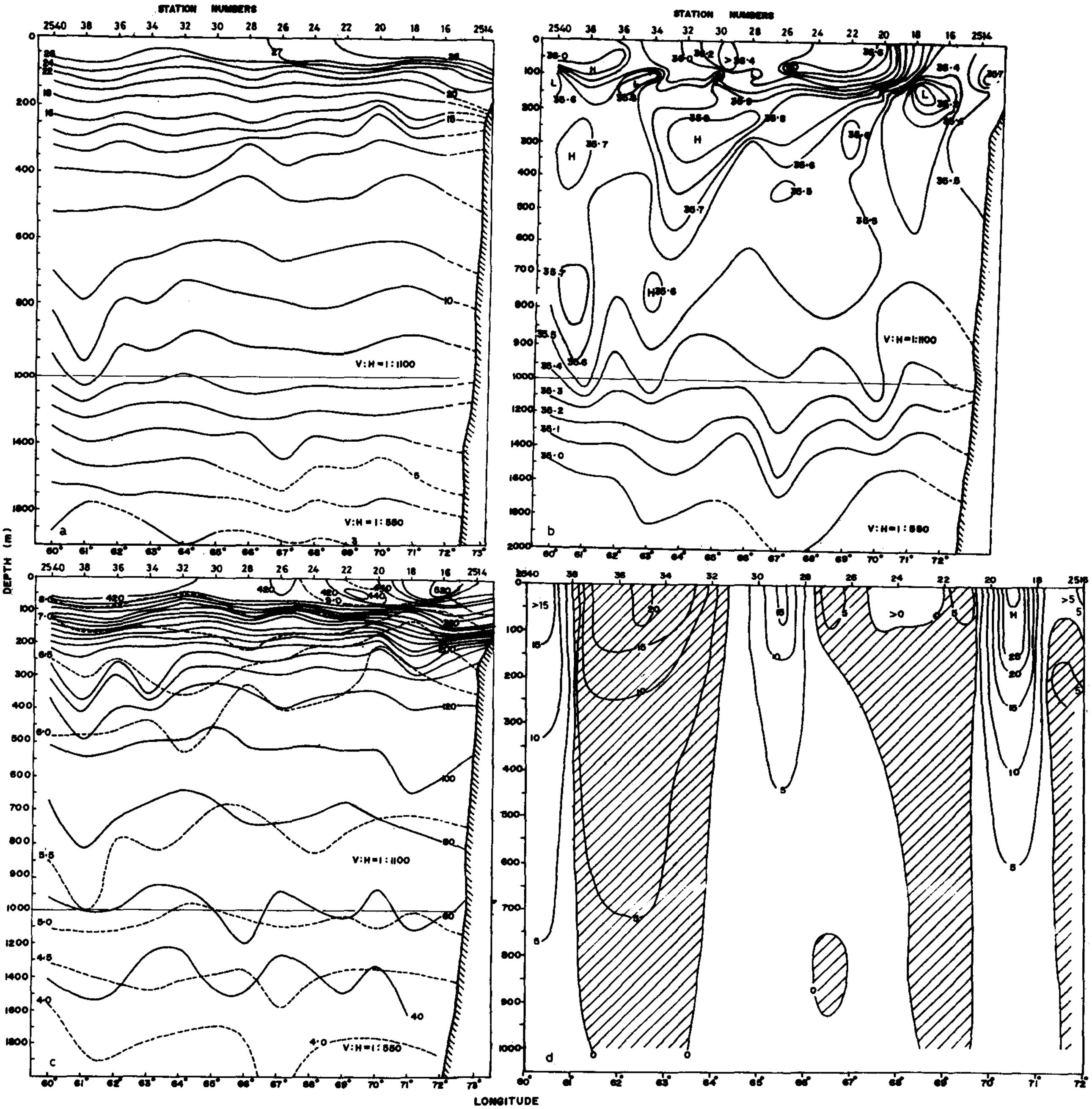



Fig. 2 — Vertical (a) thermal structure, (b) salinity structure, (c) thermosteric anomaly distribution and density flux function, and (d) geostrophic current structure along 15°N

$36.60 \times 10^{-3}$. The distribution of salinity is quite complex in the upper 800 m. A salinity minimum ($35.2 \times 10^{-3}$) could be seen around st 2518 at a depth of about 100 m. Centered around st 2530, in the depth range of 200-300 m, a zone of salinity maximum with salinities exceeding $35.9 \times 10^{-3}$ is seen. Further west along the section, a nearly isohaline layer extends from 100-800 m where the salinities vary between 35.6 and $35.7 \times 10^{-3}$ with identifiable maxima around 300-400 m and 700-800 m. Fig.2c shows the distribution of thermosteric anomaly along with the density flux function (shown in dotted lines) along the section. The low salinity around st 2518 coincides with 300-320 cl/t isanosteric surfaces whereas the high salinity zone in the central regions is located between 120 and 180 cl/t isanosteric surfaces. The figure further shows intense mixing in the regions of salinity maximum. In general, vertical mixing is indicated at all depths all along the section. Surface salinity maximum coincides with 400 cl/t isanosteric surface. A peculiarity of this figure is that the isolines of density flux function run parallel to isohalines where intense vertical mixing is

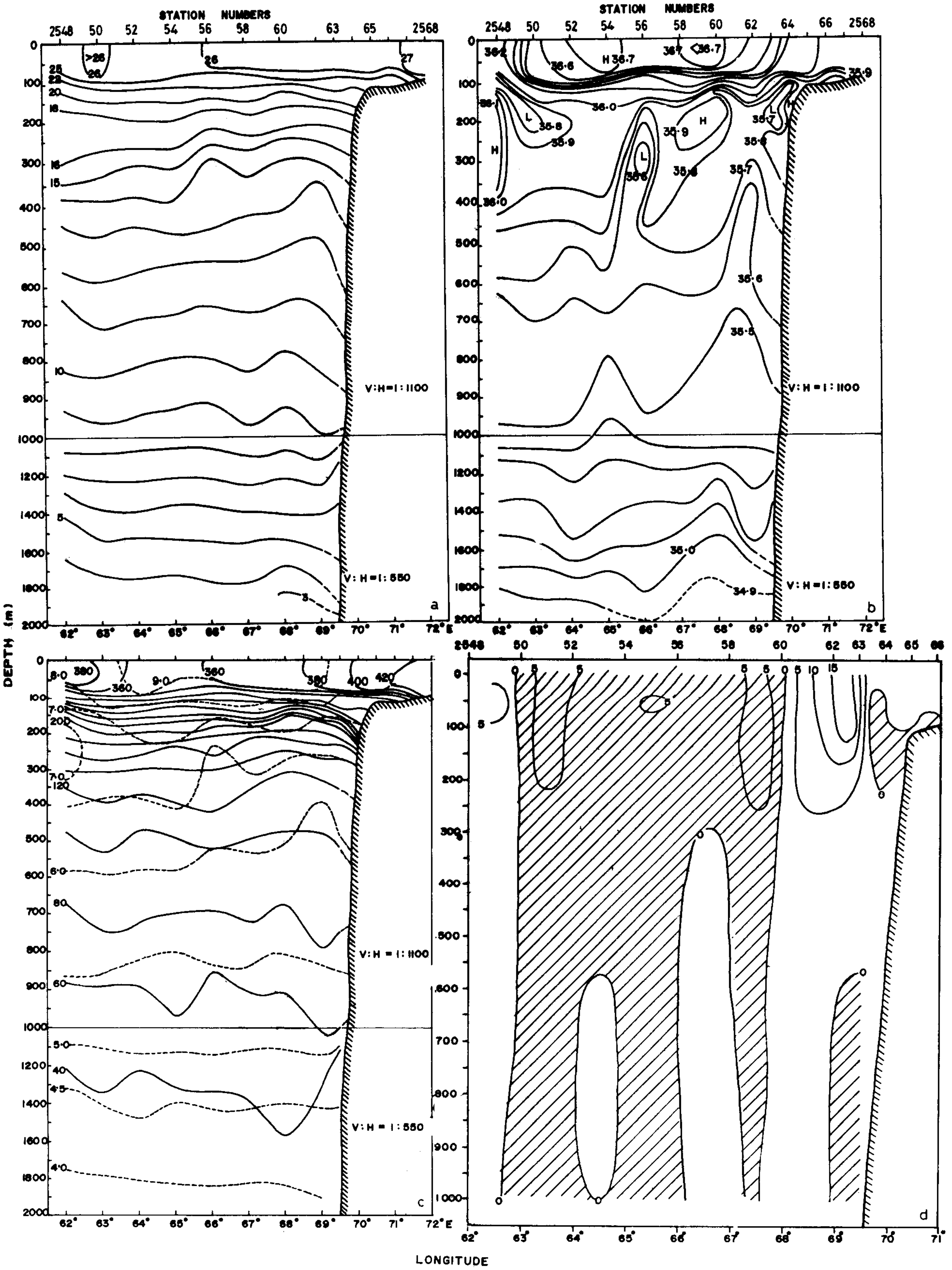



Fig. 3 — Vertical (a) thermal structure, (b) salinity structure, (c) thermosteric anomaly distribution and density flux function and (d) geostrophic current structure along 19°N

indicated. The deeper salinity maximum along the western portions of the section appears on 80 cl/t isanosteric surface. Fig.2d shows the geostrophic flow across the section relative to 1000 db surface. East of 70°E, northerly flow prevails close to the Indian coasts with a weak subsurface southerly flow. The salinity minimum observed near the Indian coast appears in the shear zone around st 2518. West of this northerly flow, a weak southerly flow prevails and further west of 66°E the flows alternate. The salinity maximum centered around st 2530 and in the far west between 300 and 800 m is located in the shear zones.

*Distribution along* 19° *N*– The sea surface temperature varies from 26° to 27°C with higher values towards the Indian coast (Fig.3a). On an average, the sea surface temperature is 1°C lower than that in the southern section. The mixed layer is well developed compared to that in the southern section. The vertical temperature gradients in the thermocline are relatively weak. The surface salinity (Fig.3b) exceeds $36.7 \times 10^{-3}$ in the central regions and decreases towards west and east. The salinity distribution shows similar features as in the southern section. Conspicuous are the low salinity pockets in the depth range of 100-250 m with salinity less than $35.7 \times 10^{-3}$, a zone of high salinity between 200 and 300 m in the central regions and a salinity maximum exceeding $36.1 \times 10^{-3}$ between 150 and 400 m in the extreme west. The thermosteric anomaly along this section indicates that the higher surface salinities are associated with 360-380 cl/t isanosteric surfaces and the low salinity pocket with 320 cl/t isanosteric surface. The subsurface high salinities are embedded between 140 and 200 cl/t isanosteric surfaces. The superimposition of the density flux function on the isolines of thermosteric anomaly indicates vertical mixing in the western portions of the section. The basic feature of geostrophic circulation (Fig.3d) is the dominance of southerly flow in the central regions of the section. Both along the eastern and western regions northward flow prevails. As in the earlier section the high and low salinities are located in the current shear zones.

*Distribution along transect*– The surface water (Fig.4a) in the northern region is cooler. The vertical temperature gradients are strong between 75 and 150 m and below this depth they are weak. The bottom of the thermocline may be identified with the depth of 14°C isotherm. Horizontal temperature gradients are stronger between 100 and 150 m. The trend of the isotherms indicates considerable dynamic structure in

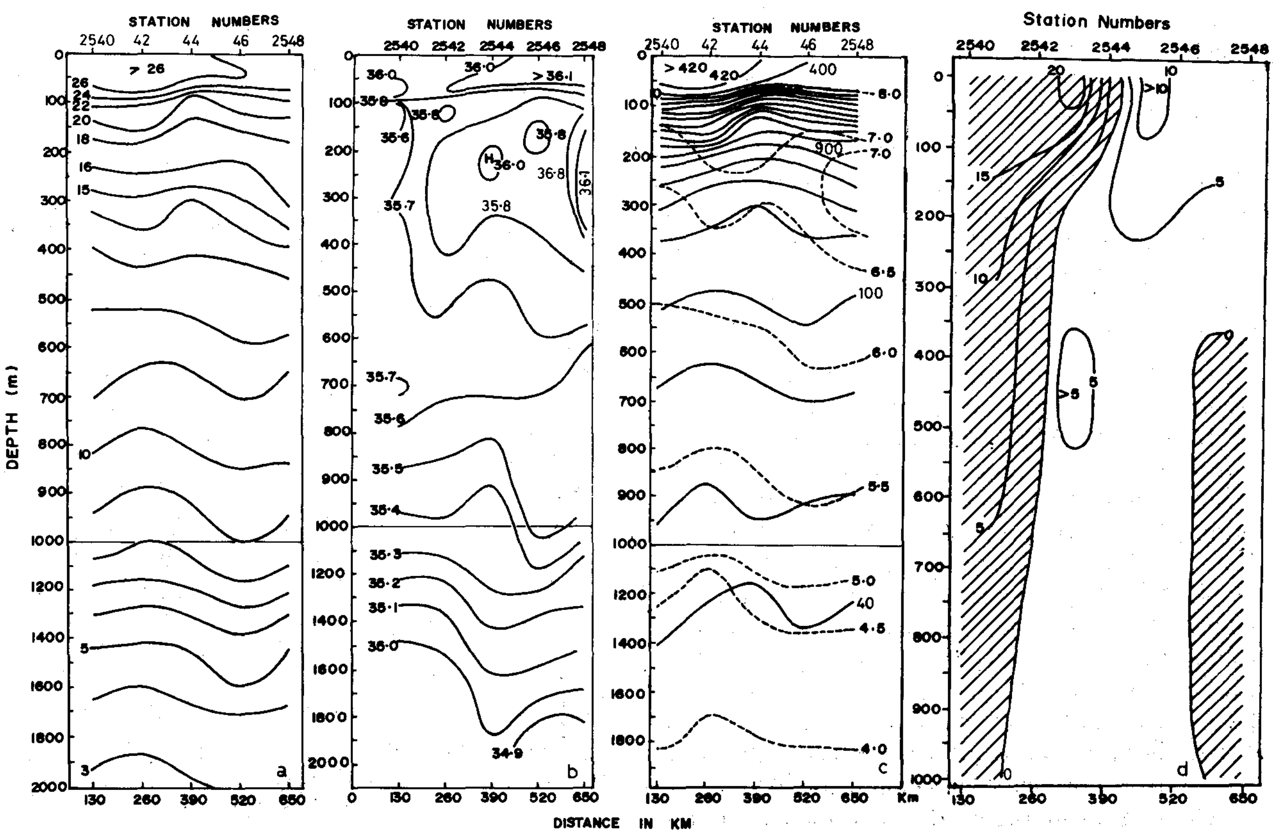



Fig. 4 – Vertical (a) thermal structure (b) salinity structure (c) thermosteric anomaly distribution and density flux function and (d) geostrophic current structure along Transect

the deeper layers. The sea surface salinity (Fig.4b) is higher ($36.1 \times 10^{-3}$) north of st 2544 and south of it, the salinity is less than $36.0 \times 10^{-3}$. A strong halocline is seen around 100 m. In the subsurface layers a zone of salinity maximum ($> 36.1 \times 10^{-3}$) is observed around 250-300 m in the northern regions of the section. Salinity decreases monotonically below 400 m depth. The salinity structure further indicates the formation of isohaline layer in the depth range of 600-1000 m in the north and 300-800 m in the south. The thermosteric anomaly and the density flux function along this section are shown in Fig.4c. In the upper layers there is considerable vertical mixing associated with the core layer of the Persian Gulf Water. The surface salinity exceeding $36.1 \times 10^{-3}$ coincides with 400 and 420 cl/t isanosteric surfaces. Considerable vertical mixing is seen in the upper layers also. The geostrophic circulation relative to 1000 db surface shows (Fig.4d) flows towards southeast in southern region and to the northwest in the northern region of the section.

## Discussion

The surface temperature has bimodal characteristics[9] with maximum temperature exceeding 31.5°C and minimum around 24°C. Thus the thermohaline index of the surface waters varies over a wide range of temperature. The Arabian Sea High Salinity Water which forms over most of the northern Arabian Sea with excessive evaporation over precipitation can have different characteristics depending upon surface meteorological conditions. Moreover the near surface circulation reverses in response to the monsoonal wind systems. During the NE monsoon period the north equatorial current sets-in and penetrates into the Arabian Sea. The low salinity waters observed (Fig.2b) are clearly due to the penetration of fresh water from the equatorial regions.

In order to understand the presence of low salinity watermass the hydrographic data collected in the Bay of Bengal and Andaman Sea during 33 cruise of *R V Vityaz* under IIOE programme were analysed (data available at NIO data centre). In particular, the distribution of salinity on 300 cl/t isanosteric surface (Fig.5) shows fresh water in the Andaman Sea with salinities $< 34.6 \times 10^{-3}$. In the meridional direction, a conspicuous salinity minimum is seen on this surface penetrating westward, south of Sri Lanka. Fig.6 shows the acceleration potential on the 300 cl/t isanosteric surface which shows several cyclonic and anticyclonic flows. The basic feature in the present context is a major flow from northeast Bay to southwest to Sri Lanka which merges with the north equatorial current further south. Comparing the salinity and flow pattern (along 90°E), the higher salinities south of salinity

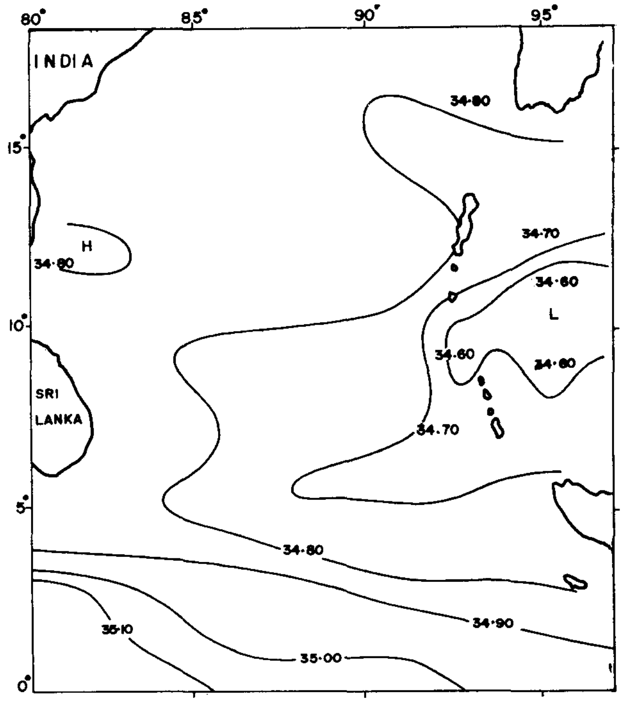



Fig. 5 — Salinity on 300 cl/t surface in the Bay of Bengal

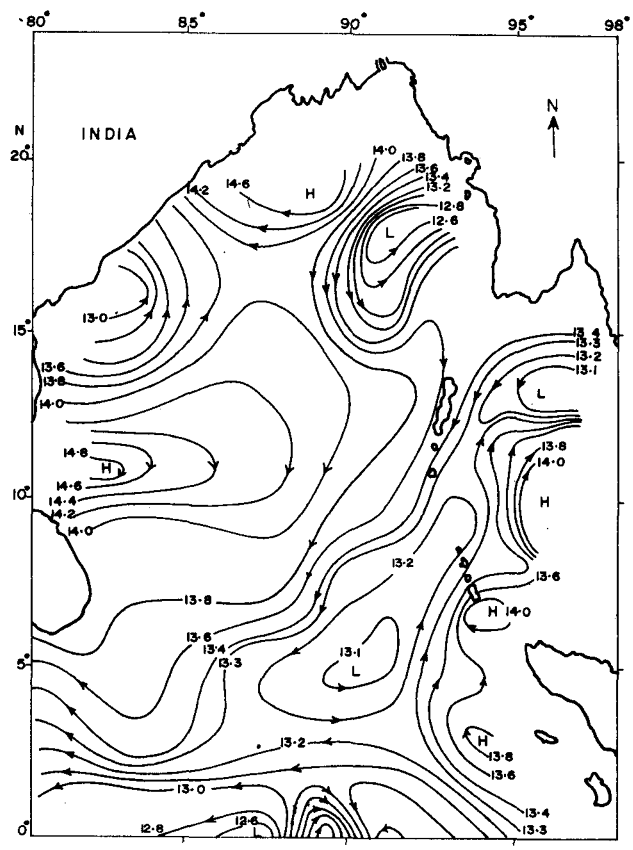



Fig. 6 — Acceleration potential (J/Kg) on 300 cl/t surface in the Bay of Bengal

minimum on this surface are due to equatorial waters. When this flow enters the Arabian Sea, the low salinity water penetrates on 300 cl/t isanosteric surface. The salinity minimum observed along 15 and 19°N is a consequence of this penetration. Thus, the vertical salinity structure in the Arabian Sea is further modified seasonally by mixing of these waters with the overlying Arabian Sea High Salinity Water and the underlying Persian Gulf Water. It may be indicated that, this is a seasonal phenomenon. This also gives a clue to the maintenance of salt balance in the Arabian Sea. Thus, it appears that the transformation of Arabian Sea high salinity watermass and Persian Gulf watermass is very much augmented by the presence of this watermass during fair weather season. The intersection of the isolines of the density flux function and thermosteric anomaly in the regions of occurrence of this watermass is an indication of active vertical mixing whereby it is transformed and gained salt. In the absence of a comprehensive data set to draw the 300 cl/t isanosteric surface during winter, the low salinity waters seen between sts 2518 and 2516 on 15°N and at st 2564 on 19°N seem to be connected by a line of flow. The increase in salinity is about $0.5 \times 10^{-3}$, in about 450 km stretch which is substantial.

During December, the Arabian Sea comes under the influence of a general cyclonic flow, the low salinity waters from the Bay of Bengal also participate in the circulation. The low salinity waters in the depth range of 100 to 200 m in the western regions along 19° and 15°N are probably the result of the great anticlockwise flow.

The T−S structure in the present study shows 3 groups of salinity maxima and 1 group of salinity minima as classified below:

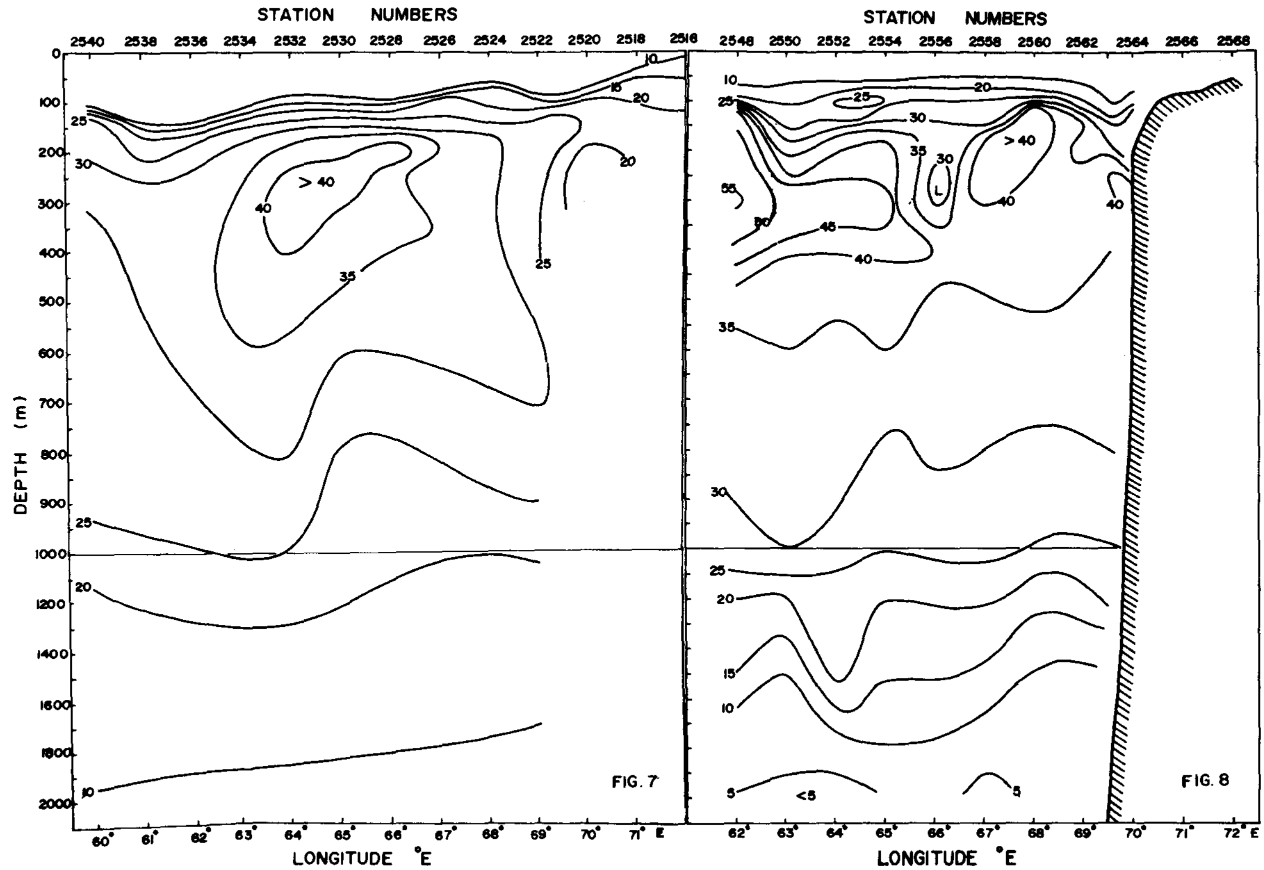
(1) The Arabian Sea high Salinity Watermass occurring around 440-360 cl/t isanosteric surfaces ($T > 25°C$; $S > 36.4 \times 10^{-3}$) between surface and 80 m.

(2) The Persian Gulf Watermass appearing between 120 and 160 cl/t surfaces and occurring around 200-350 m.

(3) The Red Sea Watermass appearing around 100 cl/t and occurring between 500 and 700 m. At some stations this watermass has been seen as an isohaline layer in the above depth range.

(4) The group of salinity minimum represents the Andaman Sea low salinity watermass which appears around 320 cl/t and occurring around 100 m.

Based on this, the mixing characteristics of diffe-




Figs. 7 and 8 – Percentage composition of Persian Gulf water along 15°N (7) and along 19°N (8) rent watermasses have been studied by constructing the triangles of mixing[6]. The low salinity waters originating in the Bay of Bengal has been assigned the following thermohaline index T = 18.6°C and S = 34.5 $\times 10^{-3}$.

The percentage composition of Persian Gulf Watermass along the 2 sections, 15° and 19°N, is shown in Figs 7 and 8 respectively. On 19°N, the percentage composition is around 55 at 300 m depth. The percentage composition of this watermass decreases eastward and extends to the entire section. The influence of this watermass is clearly seen up to 2000 m, contributing to the higher salinities and temperatures at greater depths. On 15°N, the Persian Gulf Water penetrates in the central regions and is shown to be 40%. Here also its influence is felt to deeper depths. On the other hand the influence of the Antarctic Bottom Water is seen extending up to 200 m in the northern Arabian Sea. These studies further indicate that the rapid watermass transformation takes place in the upper layers.

## Acknowledgement

The authors express their gratitude to Dr V V R Varadachari, former Director and Dr H N Siddiquie, Director for their interest in this work.

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