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Watermass structure in the western Indian Ocean— Part II : The spreading and transformation of the Persian Gulf water

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सार — इस लेख में फारस की खाड़ी की जलराशि (पी. जी. डब्ल्यू.) के अरब सागर तथा हिन्द महासागर में फैलने तथा रूपान्तरण को प्रस्तुत किया गया है। अधिकांश अरब सागर में इस जलराशि की क्रोड या प्रमुख परत 250 से 300 मीटर की गहराई में, जो दक्षिण की ओर बढ़ती चली जाती है, पाई जाती है। क्रोड भाग की क्षारीयता यमन की खाड़ी में 37.9 प्रति हजार होती है जो भूमध्य क्षेत्रों में घट कर 35.1 प्रति हजार रह जाती है। इस जल राशि का फैलाव मुख्य रूप से भारत के पश्चिमी तट की ओर तथा दक्षिण में भारतीय तट से दूर होता है। ऊर्ध्वाधर मिश्रण को तेज करने की दृष्टि से इस जलराशि का यमन की खाड़ी में तेजी से रूपान्तरण होता है। अरब तट के साथ-साथ इस जलराशि के लाल सागर की जल राशि के साथ ऊर्ध्वाधर मिश्रण के कारण 250 से 800 मीटर की गहराई वाली समलवणीय परत बनती है जिसे "अरब सागरीय माध्यमिक जलराशि" नाम दिया गया है। अधिक गहरी परतों में पी. जी. डब्ल्यू. का प्रभाव अपेक्षाकृत अधिक तापमान तथा उत्तरी अरब सागर में सभी गहराइयों पर लवणता से परिलक्षित होता है। ऊर्ध्वाधर मिश्रण के परिणाम स्वरूप ताप तथा लवण के अधिवाहों का इस जलराशि के केन्द्र भाग के साथ-साथ अनुमान किया गया है।

ABSTRACT. The spreading and the transformation of the Persian Gulf Watermass (PGW) in the Arabian Sea and the Indian Ocean have been presented. The core layer of this watermass is found in the depth range of 250-300 m over most of the Arabian Sea with a tendency to deepen southwards. The salinity at the core decreases from 37.9‰ in the Gulf of Oman to 35.1‰ at the equatorial regions. Its spreading is found to be mainly towards the west-coast of India and southerly off the Indian coast. Owing to intense vertical mixing, rapid transformation of this watermass takes place in the Gulf of Oman. Vertical mixing of this watermass with the Red Sea watermass along the Arabian coast gives rise to an isohaline layer in the depth range of 250-800 m and this layer has been termed as 'Arabian Sea Intermediate Watermass'. The influence of PGW in the deeper layers is reflected by the relatively higher temperatures and salinities at all depths in the northern Arabian Sea. Downward fluxes of heat and salt as a result of vertical mixing are inferred all along the core of this watermass.

1. Introduction

The Persian Gulf with an average water depth of 25 m lies in an arid zone where evaporation exceeds precipitation. This climatological feature gives rise to the formation of a warm and high saline watermass which flows out into Gulf of Oman through the strait of Hormuz. Owing to seasonal changes and shallowness of the Gulf, the exchange of this high saline water with the waters in the Gulf of Oman is small and intermittent. This watermass after entering the Gulf of Oman at depths of 25 to 70 m sinks to a depth of 200-250 m prior to its spread in the Arabian Sea. Several investigators (Sverdrup, Johson and Fleming 1942; Tenhernia, Lacombe and Guibout 1958; Rochford 1966; Warren *et al.* 1966; Wyrtki 1971 etc) have studied on the spreading and transformation of this watermass and expressed conflicting views on the extent and influence of this watermass on the waters of the intermediate layers in the Arabian Sea. In this paper the spreading of the Persian Gulf Watermass (PGW) together with its percentage composition in the vertical and its influence on the watermass structure at the intermediate layers of the Gulf of Oman and the Arabian Sea are presented. The data and the methods of analysis are detailed by Premchand (1981).

2. The core of PGW and its salinity

Fig. 1 shows the topography of the core of PGW. The dashed line extending from Arabian coast to 80 deg. E, indicates the southern limit of this watermass. Salinity maxima attributable to PGW were also observed south of this limit at a few stations (Fig. 2). The absence or presence of the salinity maxima southward of this boundary would depend on the season. The salinity on the potential density surface (σ_θ= 27.2) indicates seasonal dependance (Bennett 1970). These seasonal variations will be more pronounced at the levels where the core of PGW appears (σ_θ= 26.6).

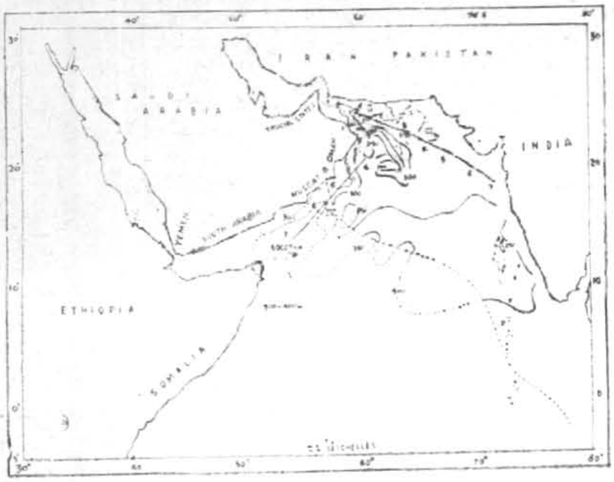


Fig. 1. Topography of the core layer of Persian Gulf water

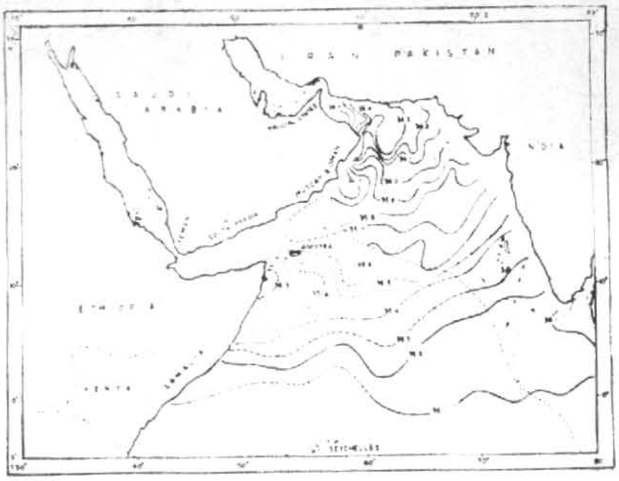


Fig. 2. Salinity distribution in the core layer of the Persian Gulf water

In Fig. 2 dashed isohalines south of the boundary are the result of averaging of all the available data irrespective of seasons.

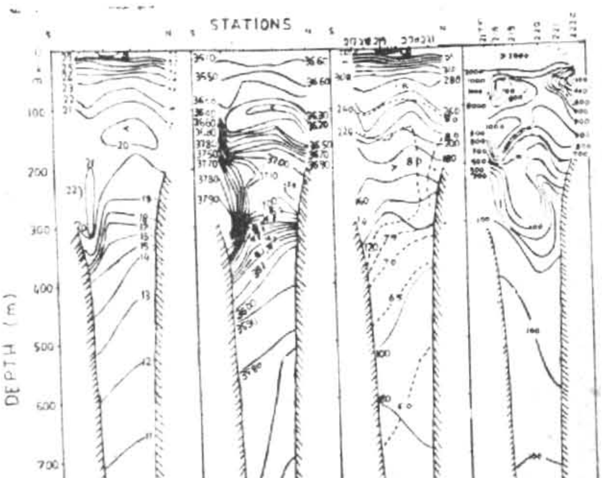
In the Gulf of Oman the core layer of this watermass has a salinity of 37.9 °/₀₀ and appears at depths of 200-250 m (*see* Fig. 3). As it spreads southeastwards the salinity at the core decreases rapidly to 35.1 °/₀₀ (Fig. 2) while its depth increases to 300 m (Fig. 1). Off the Arabian coast it is found at 300-400 m. In the Gulf of Oman the partially closed isohalines give an impression of a tongue-like distribution. As the PGW spreads into the Arabian Sea, the orientation of the isohalines becomes more and more zonal. Transformation of this core layer (as can be seen by the decrease in salinity) takes place rapidly north of 20 deg. N and slowly south of it.

In the Gulf of Oman the temperature of this core layer exceeds 22 deg. C (Fig. 3) and as the watermass spreads the core layer temperature decreases rapidly. In the area of Laccadive Sea, the core layer temperature is around 12 deg. C. The core of this watermass is bounded by 200-110 cl/t surfaces.

3. Property distributions in the Gulf of Oman

Two sections separated by a distance of about 150 km, were occupied by Commandant Robert Giraud across the Gulf of Oman during May 1961 (Fig. 1). Fig. 3 shows the distribution of temperature, salinity and thermosteric anomaly, stability and the density flux function (dashed lines in Fig. 3c) along the western section.

Along this section the surface temperature exceeds 28 deg. C. Temperature inversions are noticed between 200 & 300 m over most of the section. Low temperatures between 125-175 m are associated with low salinity (362.2 °/₀₀). The temperature inversions are associated with high salinity water 37.9-37.1 °/₀₀) and are noticed between 180 & 140 cl/t surfaces (between 200 & 300 m).



Figs. 3(a-d). Distribution of, (a) Temperature, (b) Salinity, (c) Thermosteric anomaly and density flux function and (d) Vertical stability in the Gulf of Oman

The stability distribution shows low values coinciding with layer of maximum salinity. Fig. 3(c) shows that the isolines of density flux function intersect the isanosteres between 100 & 400 m and indicates intense vertical mixing (Veronis 1972). Immediately below and above these depths, these sets of isolines run parallel to each other indicating isopycnal mixing. Vertical mixing is also indicated at greater depths. The salinity distribution along this section shows that a layer of low salinity (36.2 °/₀₀ is sandwiched between two high salinity layers around 125 m depth (between 260 & 240 cl/t).

TABLE 1

Station data used along Sections III and IV

Station No.	Ship	Cruise No.	Originator's station No.	Lat. (°N)	Long (°E)	Date (1961)
			Section III			
1	RE	AS	04	24°32′	58°29′	19 Mar
2	CG	3	209	23°25′	60°12′	8 May
2	RE	AS	26	22°30′	62°33′	22 Mar
4	RE	AS	37	21°28′	62°29′	24 Mar
5	RE	AS	51	20°29′	66°30′	15 Mar
6	CG	3	187	18°59′	68°34′	22 Apr
7	VI	31	4714	17°22.7′	71°03.5′	3 Apr' 60
			Section IV			
1	CG	3	213	24°17′	58°57′	9 May
2	CG	3	201	22°37′	60°01′	1 May
3	RE	AS	45	20°31′	60°28′	17 Mar
4	CG	3	253	19°04′	58°50′	21 May
5	CG	3	257	17°29′	56°42′	22 May
6	CG	3	259	15°51′	55°09′	23 May
7	CG	3	261	14°02′	53°30′	24 May

Along the eastern section high salinity (37‰) is observed in the depth range of 175-300 m. Overlying this high salinity water is the low salinity water similar to that along Secion I. Between 300 and 500 m depth, the structure of the isotherms is similar to that of the isohalines. The salinity maximum nearly coincides with the 160 cl/t surface. Between the surface and 100 m, the isotherms and isohalines run parallel to each other. Lowest values of stability are associated with high salinity and *vice versa.* Intense vertical mixing in the depth range of 100-400 m and isopycnal mixing below this depth are inferred from a comparison of isanosteres and isolines of density flux function. Along both sections, the isohalines and the isolines of the density flux function are parallel whenever intense vertical mixing is indicated.

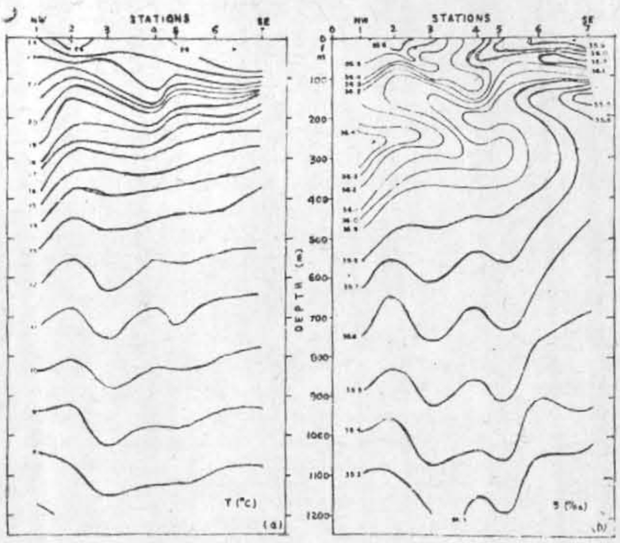
An examination of property distributions along the two sections clearly shows the transformation of PGW in the Gulf of Oman. The salinity of the Persian Gulf water decreases from a maximum of 37.9‰ to around 37.0‰ as it spreads eastward. The value of salinity minimum observed overlying the core of the Persian Gulf watermass increases westward from 36.0‰ to around 36.2‰. The temperature inversions seen in the depth range of 200-300 m along the western section are more or less absent in the eastern section, a probable indication of intense heat transfer.

4. Persian Gulf watermass in the Arabian Sea

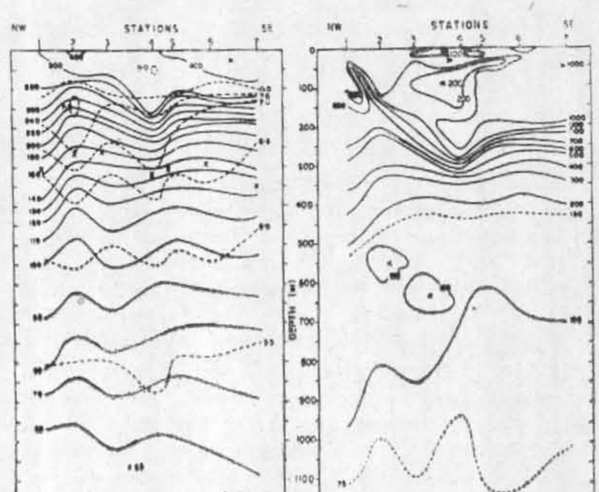
With a view to study the percentage composition in the vertical of this watermass as it spreads in the Arabian Sea, two Sections III and IV were chosen (Fig. 1) and the property distributions along these two sections are presented below :

4.1. *Property distributions in the northern Arabian Sea*

The stations along Section III were occupied during the spring 1961 except station 7 which was occupied



Figs. 4(a-b). I Distribution of (a) Temperature and (b) Salinity along Section III



Figs. 4(c-d). II Distribution of (c) Thermosteric anomaly and density flux function and (d) vertical stability along Section III

in spring 1960 (Table 1). Though the actual dates of observations fall in March through May it is believed that the property distributions presented in general, represent the general spring conditions at depths exceeding 100 m. Strong gradients within the thermocline are seen off the west coast of India. The isotherms, rise upward towards east, in the thermocline. Below 600 m, the isotherms show wavy pattern (Fig. 4a).

The salinity distribution (Fig. 4b) shows that the core of PGW appears at depths of 275 m and at slightly deeper levels towards east. At surface, the salinities are high and the high salinity water (ASHSW due to excessive evaporation over the Arabian Sea) is located above 300 cl/t surface (Figs. 4b and 4c). The thickness and depth of occurrence of this watermass (ASHSW) are governed by the changing meteorological conditions over this region. Between these two high salinity waters is sandwiched a layer of low salinity and is clearly the result of the presence of two high salinity watermasses immediately above and below (*see* Fig. 2, Part I).

The distribution of thermosteric anomaly (Fig. 4c) shows that the salinity maximum of PGW appears at 160 cl/t surface in the Gulf of Oman and at lower steric levels eastwards as can be seen by the crosses representing the salinity maximum. The salinity minimum overlying the core of the Persian Gulf watermass is seen between 240 & 260 cl/t surfaces.

At the surface the stability values are generally high and variable (Fig. 4d). The stability contours labelled 900, 800, 700 (CGS units) slope downwards from a depth of 50 m at station 1 to about 300 m at station 4. Below this high stability zone, the stability decreases rapidly upto 500 m and more slowly thereafter. The salinity minimum layer is embedded in the zone of strong stratification ($>$1000 CGS units).

The isanosteres and the isolines of the density flux function (dashed lines in Fig. 4c) intersect each other at depths of 100-600 m upto about station 3. These sets of lines, on the eastern side tend to become parallel at 100-200 m. Considerable vertical mixing in the Gulf of Oman at depths from 100 to 600 m and nearly isopycnal mixing above 200 m close to the Indian coast are, therefore, inferred. All along the core of this watermass, considerable vertical mixing is present.

For the study of the percentage composition of this watermass triangles of mixing were constructed following Mamayev (1975) with the thermohaline indices of ASHSW (T=26.8°C, S=36.50‰), Hypothetical Watermass (H_1) (Corresponding to the layer of low salinity T=17.55°C, S=35.10‰), PGW (T=19.17°C, S=37.12‰) and the Bottom Water (T=0.6°C, S=34.70‰) (Premchand 1981 and Table 1, Part I). The above four watermasses appear in the depth domain, one below the other, in the above sequence. While calculating the percentage composition, only three watermasses are considered at a time and the influence of the fourth watermass on mixing is neglected. After constructing the triangle of mixing, the percentage composition of PGW and the bottom watermass were evaluated by superposing the individual *T-S* curves on the triangle of mixing for all stations along this section. Fig. 5 shows that in the Gulf of Oman, the percentage composition of PGW is around 70 (at its core around 275m) and decreases to 30 towards east. The influence of this watermass extends to depths exceeding 2000 m, transmitting both heat and salt into the deeper layers. In the upper layers, its influence is felt upto station 3. In the zone of the salinity minimum, the isolines of the percentage composition of this watermass show a rapid decrease. The distributions of salinity and the percentage content of this watermass show asymmetry in the vertical around the core layer. This is probably related to the vertical stability distribution. The influence of bottom water decreases upward from the bottom and completely ceases at a depth of about 200 m.

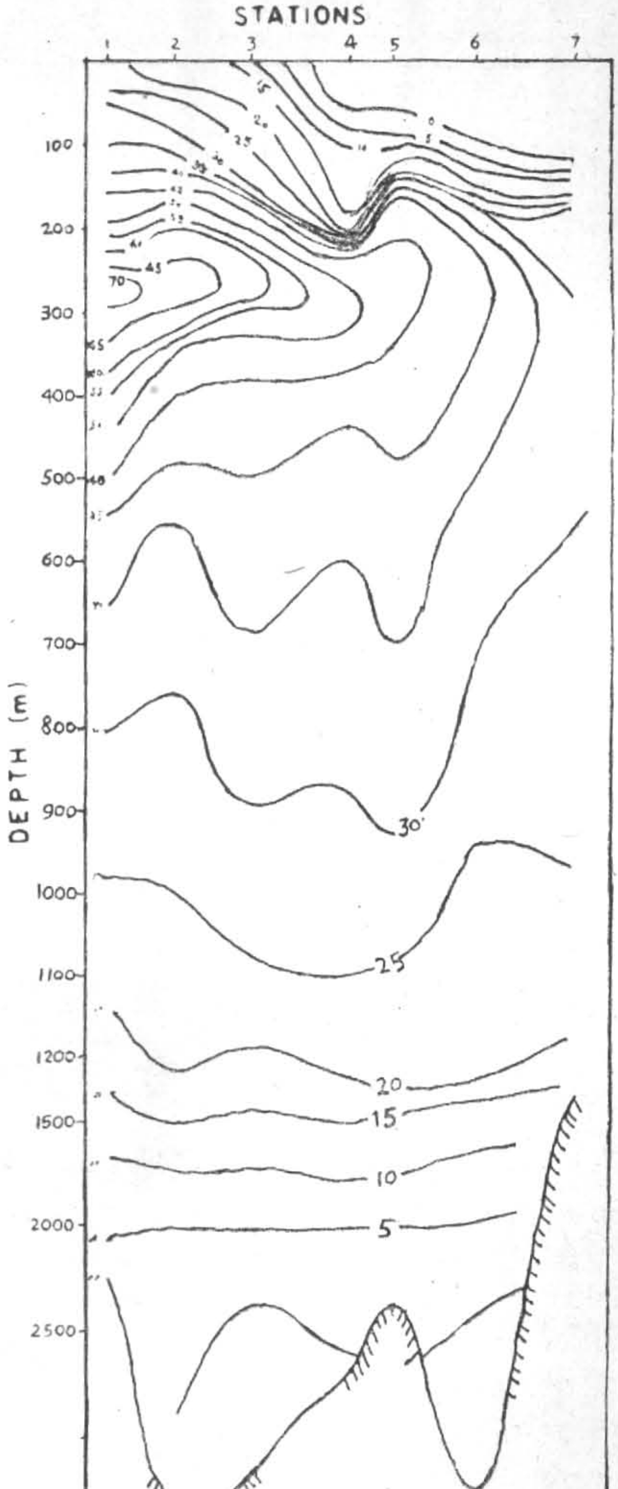


Fig. 5. Percentage compostion of the Persian Gulf water along Section III

Fig. 6 shows a comparison between the observed (Station 185, 18° 55'N-66° 06'E, 'Commandant Robert Giraud') *T-S* structure and that computed using percent composition of watermasses between stations 5 and 6 (Fig. 1) based on the theory of triangles of mixing. The coincidence of the two *T-S* curves is remarkable below about 150-200 m and gives confidence in the application of the theory of triangles of mixing in deriving the watermass structure.

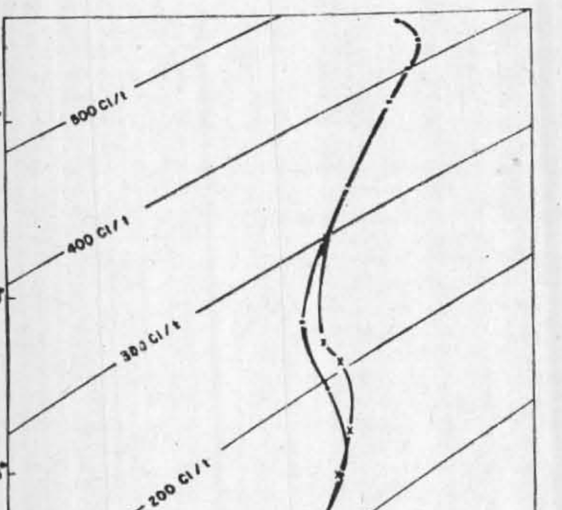
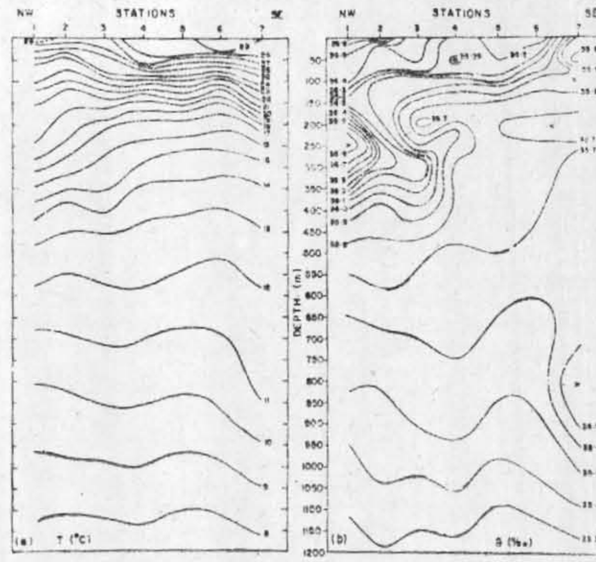
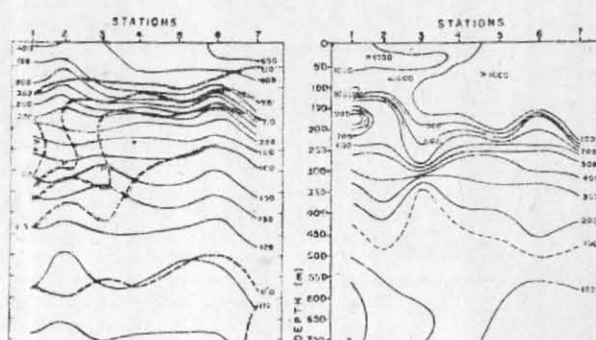


Fig. 6. Computed and observed *T-S* structure in the Arabian Sea



Figs. 7 (a&b). Distribution of (a) Temperature and (b) Salinity along Section IV



Figs. 7 (c&d). II Distribution of (c) Thermosteric anomaly and density flux function and (d) Vertical stability along Section IV

4.2. *Property distributions along the Arabian coast*

Section IV originates in the Gulf of Oman and later runs parallel to the Arabian coast (Fig. 1). Except station 3 which was occupied in March 1961 all other stations have been occupied in May 1961 (Table 1).

In the Gulf of Oman, the isotherms diverge within the thermocline whereas off the Arabian coast they converge with comparatively strong temperature gradients (Fig. 7a). In the depth range of 150-400 m, the isotherms slope downwards northwest in the Gulf. Around 750 m the isotherms slope down south from station 6.

The salinity distribution (Fig. 7b) shows broadly similar features to that of Section III. The surface salinities are high below which a salinity minimum layer is present. The PGW could be seen clearly by the tongue like distribution of the salinity contours bounded by 36.8-35.8 $^{\circ}/_{\circ\circ}$ in the depth range of 150-500 m. The core of this watermass appears at deeper levels upto station 3. Southward of station 4 this watermass could not be identified by its salinity maximum. At station 7, a salinity maximum is seen around 800 m which is clearly of the Red Sea origin. At stations 5 and 6 in the depth range of 200-800 m the salinity variations are small and this layer may be regarded as unihaline. Fig. 7(c) shows the thermosteric

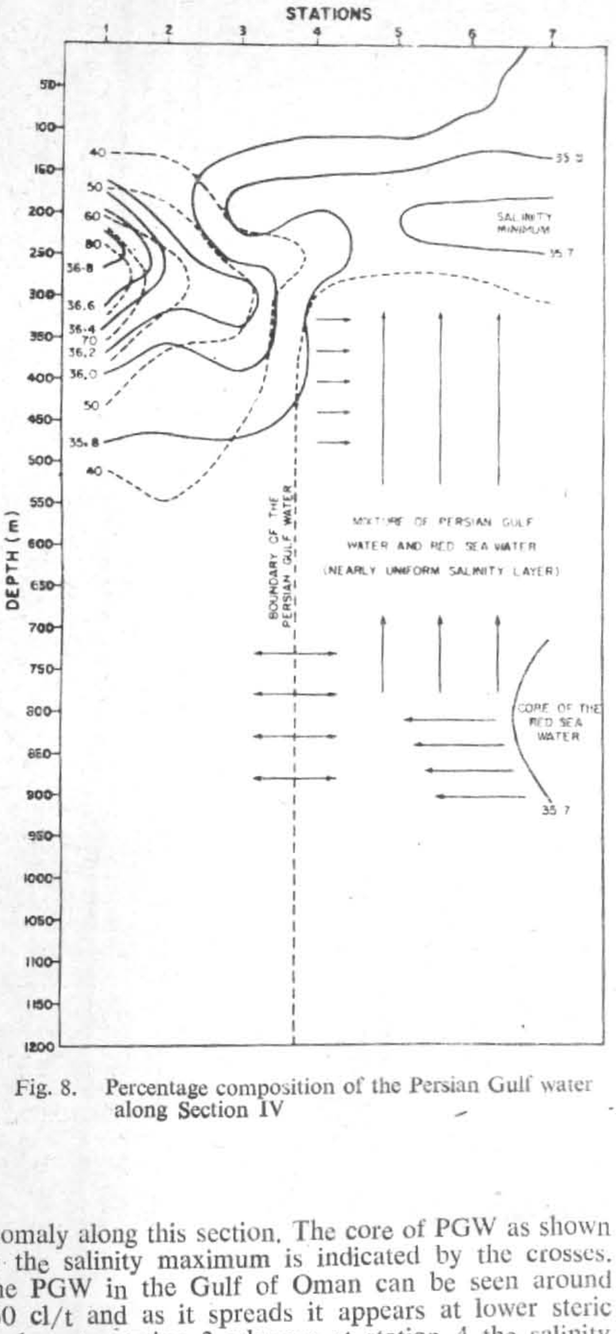


Fig. 8. Percentage composition of the Persian Gulf water along Section IV

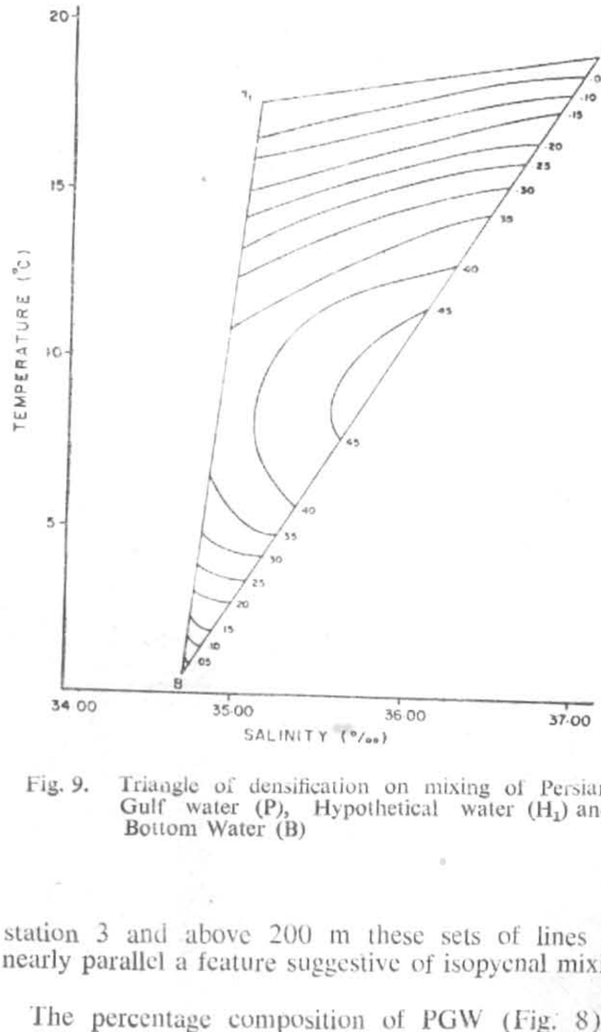


Fig. 9. Triangle of densification on mixing of Persian Gulf water (P), Hypothetical water (H_1) and Bottom Water (B)

anomaly along this section. The core of PGW as shown by the salinity maximum is indicated by the crosses. The PGW in the Gulf of Oman can be seen around 160 cl/t and as it spreads it appears at lower steric levels upto station 3 whereas at station 4 the salinity maximum is found at about 175 cl/t surface, followed by a hump in the salinity distributions (Fig. 7b). The Red Sea Watermass is located between 90 and 110 cl/t.

Fig. 7(d) shows that below a depth of 500 m the stability values are nearly uniform (100 CGS units). Within the thermocline the values are relatively high and exceed 1000 CGS units. The density flux function (Fig. 7c) showed a variation between 8 and 5 units. In contrast to the earlier section, the isolines of density flux function and isohalines are nearly parallel as those in the Gulf of Oman (Fig. 3). A comparison of the density flux lines and isanosteres show considerable vertical mixing in the core layer of PGW and also in the core layer of the Red Sea Watermass. South of station 3 and above 200 m these sets of lines are nearly parallel a feature suggestive of isopycnal mixing.

The percentage composition of PGW (Fig. 8) is evaluated for the northern portion of the section with the same thermohaline indices as were used for evaluating the percentage composition for the earlier section. Superimposed on these are the isohalines presenting the cores of PGW, Red Sea Water and the intermediate salinity minimum. Southward of station 4 the *T-S* diagrams do not show any salinity maximum that can be associated with PGW. Northward of station 7 the Red Sea Water could not be traced by its salinity maximum. On the other hand the watermass structure between stations 4 and 7 shows a nearly isohaline layer. Large scale mixing is envisaged in the entire layer between 250 & 800 m resulting in the formation of a nearly uniform salinity structure. In the northern portions, the mixture will have a higher content of PGW and on the southern side Red Sea Water contributes for higher salinities. These features are depicted

Fig. 10. *T-S* diagrams showing the core layer densification along Section III

TABLE 2

Observed and computed thermosteric anomalies (cl/t) of the core of the PGW along section towards west coast of India

Station No.	Observed	Computed
1	165	155
2	152	157
3	157	160
4	162	150
5	143	145
6	132	137
7	131	120

schematically in the Fig. 8 where approximate boundary of the Persian Gulf Water is shown and southward of this boundary only a mixture of PGW and Red Sea waters could be traced. This is the reason for the absence of Red Sea water in the northern Arabian Sea and this feature further determines the southern limit of the Persian Gulf water. This is in agreement with the boundary depicted for this watermass in Figs. 1 and 2.

5. Densification upon mixing of PGW

Fig. 9 shows the nomogram for densification of PGW when it penetrates into 'common water'. The watermasses participating in mixing are : (1) Hypothetical Watermass (H_1) above and (2) Persian Gulf Watermass (P) at intermediate levels and (3) Bottom water (B) below. The thermohaline indices corresponding to these watermasses are the same as the ones considered for the computation of percentage composition of PGW.

According to Fofonoff (1961), the greatest contraction on mixing takes place when mixing occurs between watermasses with large differences in temperature. The salinity has a much less effect on contraction. The PGW and the hypothetical watermass (H_1) have nearly equal temperatures and hence the contraction would be minimal. The maximum increase in density due to mixing of the Arabian Sea high salinity water above and the Persian Gulf water below with hypothetical water in between is only 0.09 m σ_t units. On the other hand when mixing progresses with the penetration of PGW into 'Common Water' a 50 : 50 mixture of PGW & B (Fig. 9) results in a maximum increase in density (σ_t) of 0.47 (on the side PB). On the side PH_1, mixing of watermasses has little effect upon density.

The *T-S* curves (Fig. 10) for the stations along section extending from Gulf of Oman to west coast of India, indicate that the salinity maximum of PGW is found at lower steric levels as the watermass spreads (*see* also Fig. 4b). The density of core layer of this watermass increases towards the west coast of India. An evaluation of the thermosteric anomaly at the depth of salinity maximum has been made using the percentage composition of the various watermasses participating in the mixing processes and are given in Table 2 along with the observed values. The differences are within 10% of the observed values. A similar feature is seen upto station 3 along Section IV. For reasons mentioned, the salinity maximum at station 4 appears at a higher steric level and had there been no erosion of the core of PGW by mixing the salinity maximum would have been at a lower steric level.

6. Discussion

Rochford's (1964) analysis of the vertical structure of the watermasses in the north Indian Ocean shows five watermasses in the upper 1000 m in the Arabian Sea high salinity watermasses based on their sources identified as Red Sea, Persian Gulf and the Arabian Sea high salinity watermasses based on their sources of origin. He could not assign any origin for the other two watermasses although one of these watermasses is confined to the northern parts of the Arabian Sea and the other to the equatorial regions. He traces the Persian Gulf water in the Bay of Bengal and in the Indian Ocean upto about 10 deg. S. He opines that eastward penetration of PGW takes place mostly along the equator. *The Atlas of the International Indian Ocean Expedition* (Wyrtki 1971) depicts the southern boundary extending from Somali coast through the central Arabian Sea, off the southwest coast of India upto 10 deg. S at 110 deg. E. Varadachari, Murty and Reddy (1968) and Rao & Jayaraman (1967) have expressed similar views. However, Sharma (1976) opines that the influence of this watermass on the salinity distribution in the Arabian Sea is marginal and its presence is limited to only 15 deg. N. Recently, Verma, Das and Gouveia (1980) have contended that the outflow is not primarily along the west coast of India and further mentioned that this watermass could be traced only in patches. Hamon (1967) mentions that PGW might not be as wide spread as Rochford (1964) has indicated. The temperature-salinity-depth records between 10 deg. N and 5 deg. N do not indicate any clear evidence of a salinity maximum that could be associated with this watermass. A marked salinity maximum is found close to the Arabian coast though the detailed shape of the maximum varies from station to station. The medium scale structure in the temperature-salinity distribution which could be associated with the watermass between 5 deg. and 10 deg. N has disappeared in the equatorial regions.

According to Tenhernia (1951), the Persian Gulf could be an important source for high salinity water in the Arabian Sea. He has further suggested that the intermediate salinity maximum may be described as Arabian Sea Water — meaning that the Persian Gulf and Red Sea watermasses could give rise to a watermass of high salinity. This is in conformity with the formation of a nearly isohaline layer at the interface between the Persian Gulf and Read Sea watermasses as shown in Fig. 8. Hamon's Fig. 4(a) suggests a nearly uniform salinity layer in the depth range of 300-800 m off the Arabian coast.

The watermass structure in Bay of Bengal shows typically a layer of low salinity at surface and a salinity maximum at intermediate depths [*see* Fig. 1(a), Part I]. The influence of low salinity water extends upto depths of 250-300 m where the actual *T-S* curve intersects the *T-S* structure of the Common Watermass. The salinity maximum which can be taken as an anomaly is seen at 100 and 80 cl/t surfaces appearing at depths of 750 m and the observed structure can result as a process of transformation of Common Water at surface. This could as well be due to the influence of the waters of Red Sea origin and thus preclude the presence of PGW in the Bay of Bengal as suggested by Rochford (1964); Wyrtki (1971). It may also be envisaged that the isohaline layer which forms due to mixing of Red Sea watermass and PGW (Fig. 8) penetrates into the Bay of Bengal. As a result of this process and subsequent mixing the salinity of the isohaline layer progressively decreases and these processes could give rise to the observed *T-S* structure in the Bay of Bengal. These studies show that the influence of the Persian Gulf water is limited to northern and eastern Arabian Sea.

It is possible that a salinity maximum whose origin could not be traced by Rochford (1964) might result by the process of mixing as seen at station 4 along the section adjoining the Arabian coast (Fig. 7b). The salinity structure along this section shows that a weak salinity maximum could be located at station 4. This maximum does not represent the core value of PGW but it could still be attributed to the presence of PGW as explained in the schematic diagram and necessarily its extent would be limited.

7. Summary

The salient features of the present investigation are summarised below :

(1) Rapid transformation of the Persian Gulf watermass takes place in the Gulf of Oman.

(2) Vertical Mixing processes are more predominant in the transformation of this watermass along its core.

(3) The zone of formation of an isohaline layer in the Arabian Sea between 300 and 800 m is at the boundary of the Red Sea and Persian Gulf watermasses and this layer could be named as the "Arabian Sea Intermediate Water".

(4) The major spreading of this watermass is primarily towards the west coast of India and further southwards.

(5) The percentage composition of this watermass in the vertical suggests that its influence extends to deeper levels.

(6) As this watermass proceeds, the density of the core layer increases.

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