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Salinity Extrema in the Arabian Sea

by

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With 9 Figures

Contents

Abstract	37
1. Introduction	37
2. Data and Method of Analysis	38
3. Results	38
3.1. Salinity maxima	38
3.2. Salinity minimum	44
4. Discussion	46
References	48

Abstract

Levitus (1982) climatology has been used to identify four extrema, three maxima and one minimum, in the vertical salinity profiles in the Arabian Sea. Their geographical distribution, depths, θ -S characteristics, and seasonal variability are described. Two of the maxima arise from the influence of Red Sea and the Persian Gulf Water. The third, which lies at the bottom of the Equatorial Surface Water, forms due to freshening at the surface of high salinity Arabian Sea near-surface waters. The dominant factors leading to the formation of the little known subsurface salinity minimum appear to be, (1) transport of the low salinity water by the northeast monsoon coastal current along the west coast of India and subsequent increase in the surface salinity of this water due to evaporation in the North Arabian Sea, (2) poleward coastal undercurrent along the west coast of India during the southwest monsoon. The θ -S characteristics of the four salinity extrema are used to put into perspective the structure of the Arabian Sea water masses.

1. Introduction

The Arabian Sea exhibits distinct horizontal salinity gradients in the upper 1000 m (Wyrski, 1971). This is due to the following reasons. The rate of precipitation minus evaporation varies markedly over the Sea. The precipitation varies from < 0.2 m annual average in the northern and western parts to 2.0 m in the southern and eastern parts. The southeastern corner of the sea is in communication with the eastern part of the N. Indian Ocean, the Bay of Bengal and the eastern equatorial ocean, where the annual precipitation can be as high as 4.0 m (see figure 2.6 in Gill, 1982). Also, the northern and western parts of the Sea are in communication with two mediterranean seas, the Red Sea and the Persian Gulf, which contribute high salinity waters to the Arabian Sea at depth of about 500 m and 200 m respectively. The salinity gradients vary seasonally in response to advection and diffusion of salt by a complicated array of processes, a

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manifestation of which is occurrence of salinity extrema, both maxima and minima, in the vertical salinity profiles. Study of these extrema can provide clues on the processes that cause them, and hence on the working of the sea.

Rochford (1964) examined the salinity profiles in the North Indian Ocean in the upper 1000 m and identified five salinity maxima. Of these, three were prominent. Two of them were named according to their assumed origins, the Red Sea and the Persian Gulf. The warm, salty waters known as Red Sea and Persian Gulf water enter the Arabian Sea from the northwestern side and spread down towards south and east. The influence of the Red Sea is felt over a wide distance over the Indian Ocean. There is evidence supporting the presence of Red Sea water in the southern Indian Ocean, at least up to 10°S (Wyrki, 1971). The vertical sections prepared by Grundlingh (1985) exhibit a salinity maximum due to Red Sea water in the Mossambic channel (about 20°S). After an inspection of vertical structure of the water mass in the Somali basin Warren et al. (1986) indicates warm saline inflows, in the intermediate layers, from Gulf of Aden and Persian Gulf.

Since Rochford's analysis, considerably more data have been collected. Advances in technology for handling the data has made available sets that provide a spatially averaged seasonal picture using data that have been put through rigorous quality checks. One such data set, compiled by Sydney Levitus, has during the last decade evolved to be the standard in the field of physical oceanography (Levitus, 1982). In our study we have used the (1°x1°) hydrography that this climatology provides to describe the spatial and temporal behavior of the salinity extrema in the Arabian Sea to provide a comprehensive look at the θ -S structure of the water column covered by the extrema. We will be concerned with the area north of the equator, and attention is focussed on the upper 1500 m of the water column.

2. Data and Method of Analysis

The climatological data files compiled by Levitus (1982) available on magnetic tapes were used for the present study. Annual data files containing temperature and salinity at 33 standard levels (up to a maximum of 5500 m) and seasonal files containing data at 24 levels (up to 1500 m) were available at 1°x1° latitude-longitude grids. The latter divide the year into four seasons: February-April, May-July, August-October and November-January. To identify and pick the salinity maximum/minimum from the salinity profile at each station we followed a simple procedure which scans for salinity maximum/minimum in a vertical salinity profile by considering 3 levels at a time. Among the 3 points considered, if the middle level has maximum/minimum salinity then the level was marked as the salinity extrema. The maxima/minima thus picked, were plotted on θ -S diagrams to group together the dominant maxima/minima. Finally, the extrema falling within the appropriate θ levels were plotted to prepare the charts showing the horizontal distribution during different seasons.

3. Results

3.1. Salinity maxima

Typical θ -S diagrams at a few locations in the Arabian Sea (Fig. 1) show the occurrence of three salinity maxima in the surface and intermediate layers (Fig. 2). A search for the θ -S signature of each of the maxima over the Arabian Sea showed that the

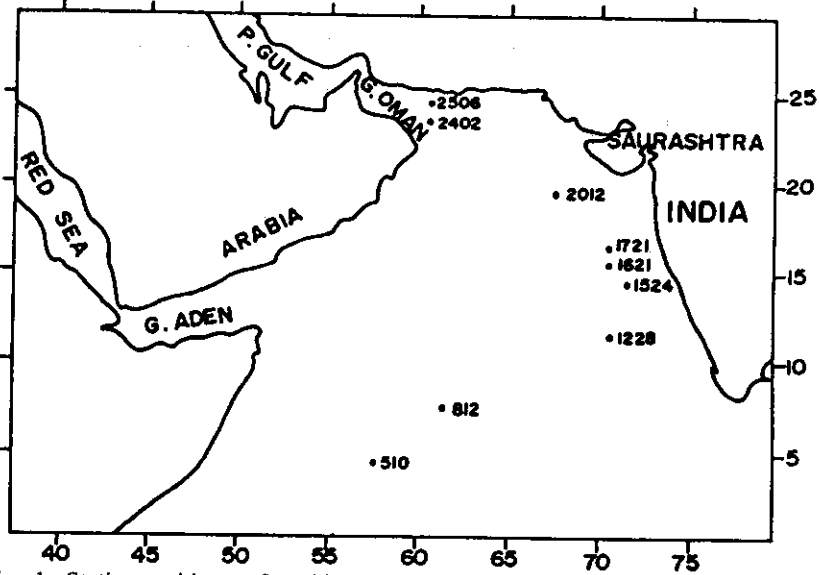


Fig. 1: Station positions referred in figure 2.

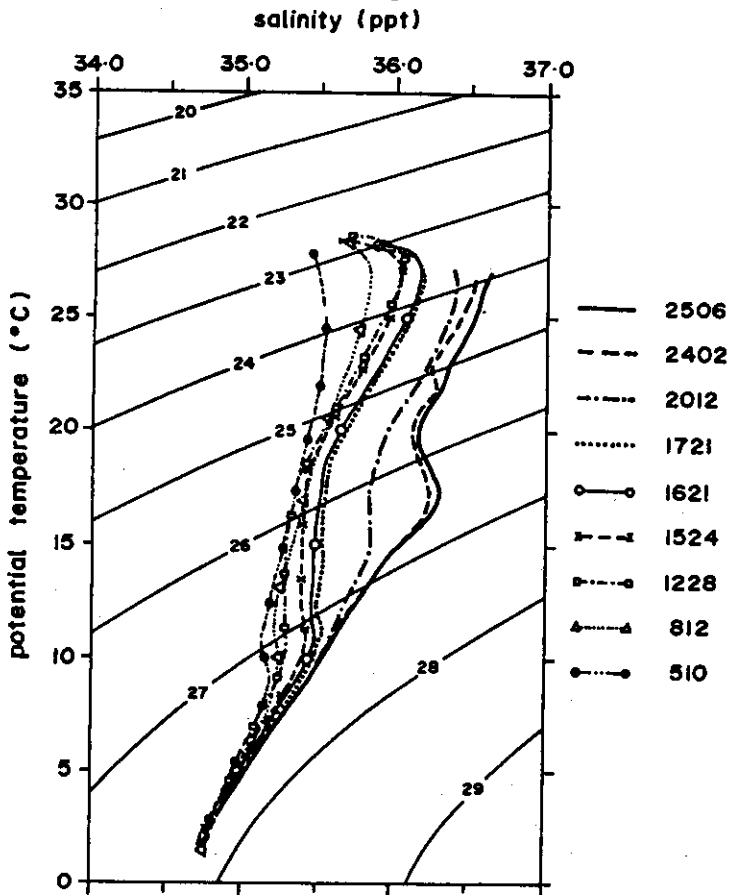


Fig. 2: Typical θ -S curves at locations shown in figure 1.

maxima occupy three bands characterized by the following θ ranges (Fig. 3): 27.0 - 27.4 gm cm^{-3} ; 26.2 - 26.8 gm cm^{-3} and 22.8 to 24.0 gm cm^{-3} . Following Rochford (1964), we call the first the Red Sea Water, the second the Persian Gulf Water and the third the Arabian Sea High Salinity Water. Described below are the characteristics of these maxima.

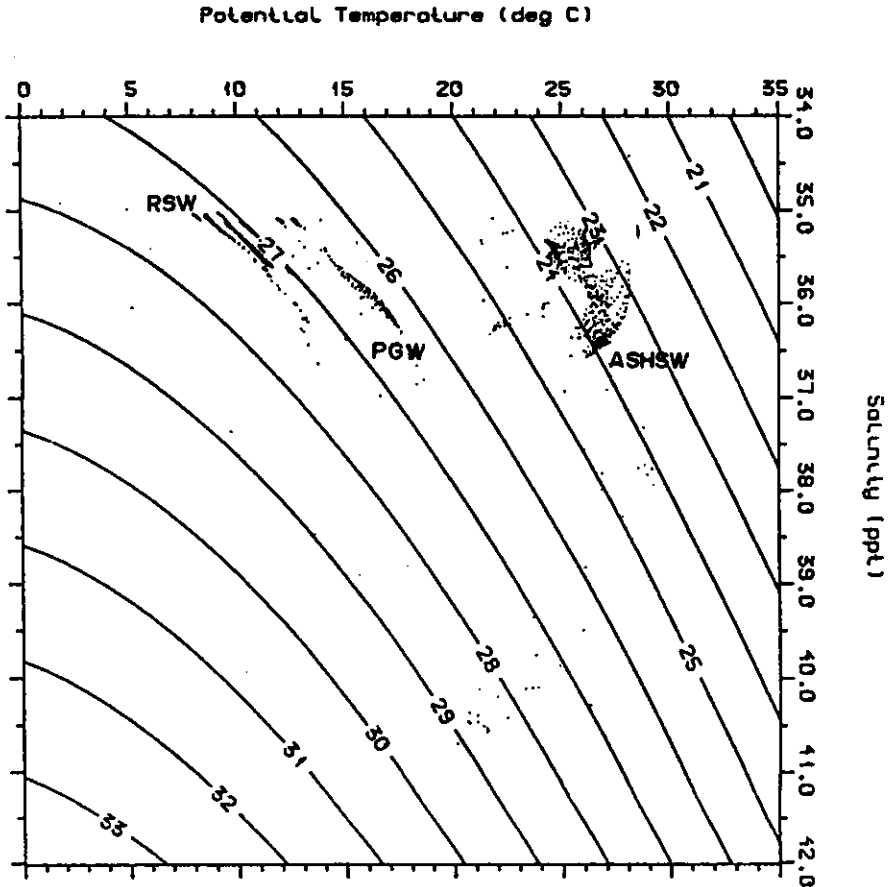


Fig. 3: A plot of θ -S signature of all salinity maxima encountered in the Arabian Sea. RSW: Red Sea Water; PGW: Persian Gulf Water; ASHSW: Arabian Sea High Salinity Water.

3.1.1. Red Sea Water

Marked by θ values between 27.0 and 27.4 gm cm^{-3} , this salinity maximum forms due to the spillage of high salinity water from the Red Sea into the Gulf of Aden over the sill separating the two basins (Fedorov and Meschanov, 1988). The processes leading to the formation of this water are most active during winter seasons. The estimated flux of RSW reaches a maximum of $0.57 \cdot 10^6 \text{ m}^3 \text{ s}^{-1}$ during October to May (Patzert, 1974) and drops to 12% of the winter value in early summer and further drops to 6% towards the end of summer (Maillard and Soliman, 1986). In the Gulf of Aden the salinity maximum is found at a depth of around 400 m, has salinities in excess of 36.1 ppt and potential temperature of about 11°C. In comparison to the other seasons, the salinities are highest during November-January. The spread of the water into the

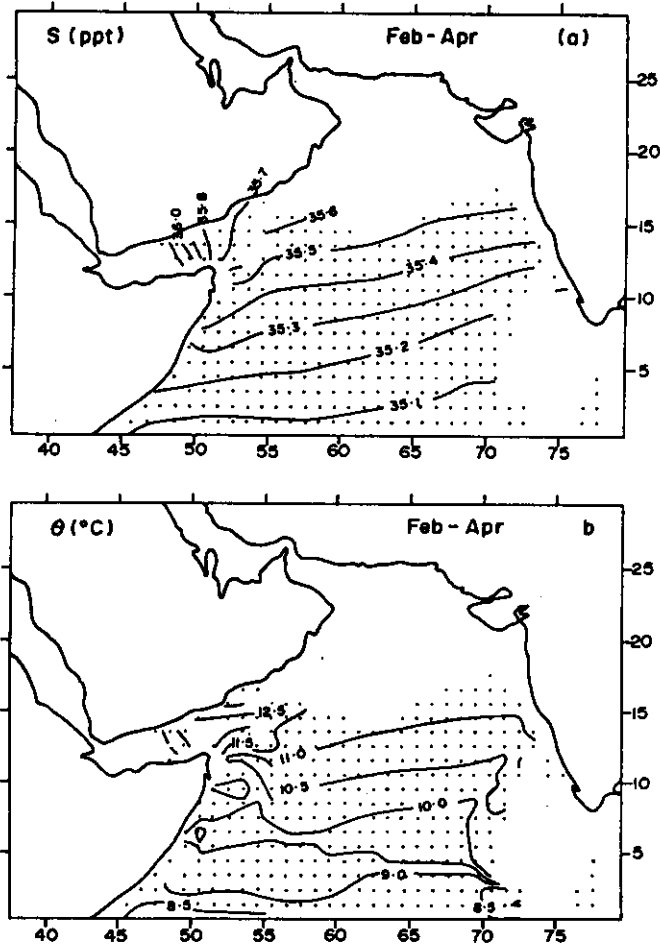


Fig. 4: Distribution of RSW (Red Sea Water) (a) salinity (ppt) and (b) temperature ($^{\circ}\text{C}$). Dots show the station locations where the RSW occurs.

Arabian Sea is marked by an increase in the depth of the salinity maximum, and decrease in its salinity and temperature (Fig. 4 a & b). The area covered by the maximum does not vary appreciably from season to season, and its northern extent is marked approximately by the latitude of 18°N . The southern and eastern boundary of the influence is believed to be south of 10°S and 100°E (Rochford, 1964). The depth of the salinity maximum changes from about 500 m in the north to about 800 m near the equator. From the north to the equator the salinity of the maximum (Fig. 4) decreases to from higher than 35.6 ppt to less than 35.1 ppt and its potential temperatures drops from 11°C to about 9°C .

3.1.2. Persian Gulf Water

The potential density of the Persian Gulf Water (PGW) salinity maximum ranges between 26.2 and 26.8 gm cm^{-3} . Unlike the area covered by the RSW the area covered by the PGW varies markedly from season to season. It is maximum during November-January (Fig. 5a) and minimum during May-July (Fig. 5b). The PGW salinity maximum

forms when high salinity waters from the Persian Gulf spill over the 75 m deep sill into the Gulf of Oman. Though not much is known about the amount of water formed and its variation from season to season, from figure 5 it appears that the water formation is most active during November-January, the season of northeast monsoon which brings cold continental air to the North Arabian Sea. Note that the RSW formation also peaks during this time.

During November-January the PGW is found in the Arabian Sea everywhere north of about 18°N and in two branches to the south. One of these is found along the west coast of India and the other along the coast of Arabia. The branch along the coast of Arabia disappears during February-April. The depth of the core of PGW is about 200 m in the Gulf of Oman, and is found at deeper depths to the south, the maximum being about 400 m. In the Gulf of Oman the PGW is characterized by salinity of 36.8 ppt and potential temperature of 18°C. To the south, the salinities decrease to a minimum of about 35.0 ppt (Fig. 5 a & b). The temperature too decreases from 19.0°C in the north to 12.5°C in the south (Fig. 6 a & b).

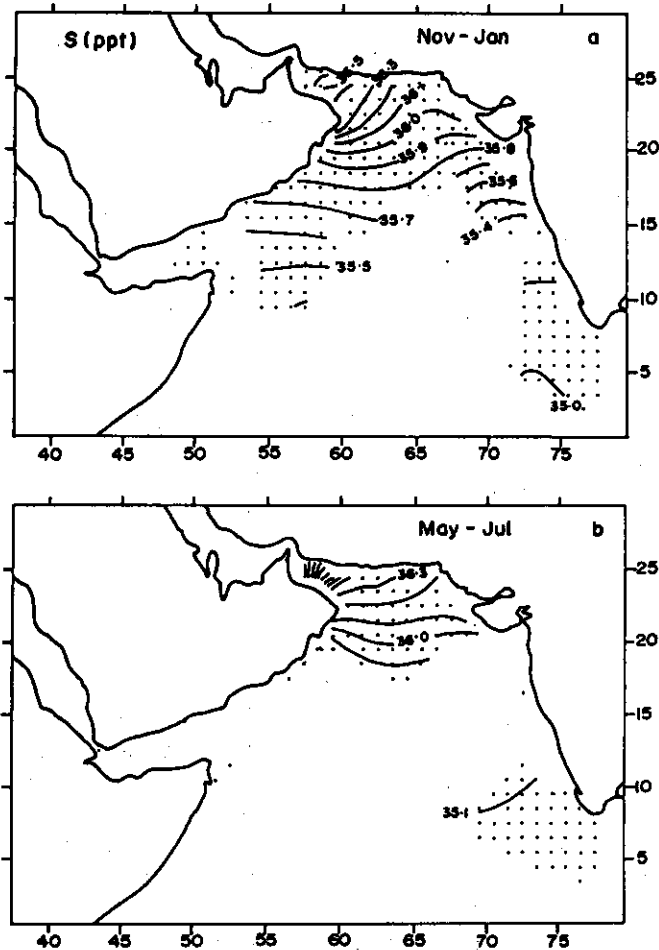


Fig. 5: Distribution of salinity (ppt) in the PGW (Persian Gulf Water) November-January and (b) May-July. Dots show the station locations where PGW occurs.

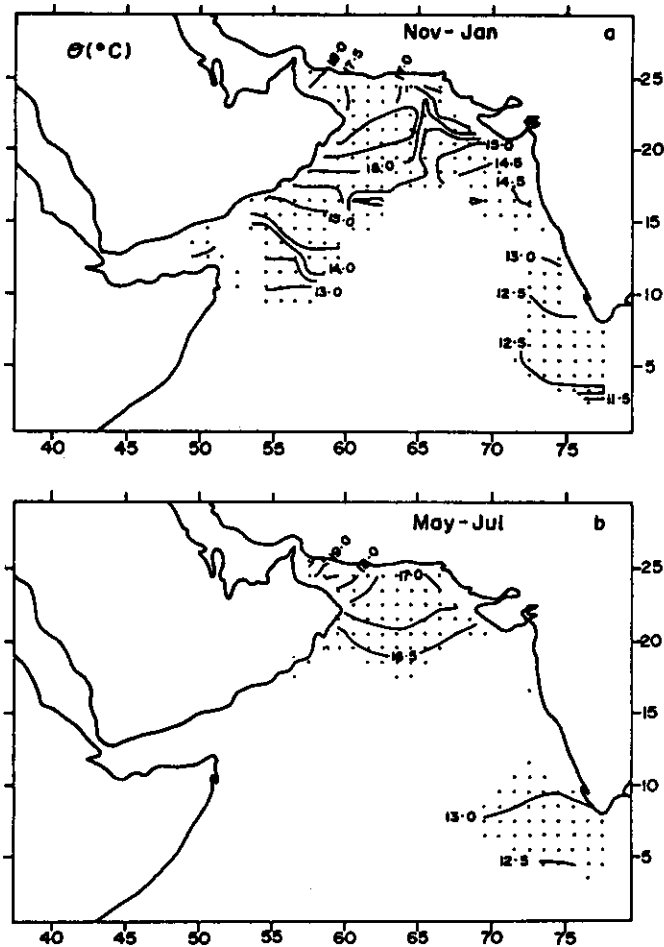


Fig. 6: Distribution of temperature ($^{\circ}\text{C}$) in the PGW during (a) November-January (b) May-July. Dots show the station locations where the PGW occurs.

3.1.3. Arabian Sea High Salinity Water

The shallowest of the three salinity maxima, the ASHSW, has potential density in the range of $22.8 - 24.0 \text{ gm cm}^{-3}$. The ASHSW lies at the bottom of the Equatorial Surface Water described by Darbyshire (1967). The area covered by the maximum varies from season to season. It builds up during May-July and stays more or less the same during August-October (Fig. 7a). The coverage decreases during November-January and is lowest during February-April (Fig. 7b). We identify this maximum with salinity maximum D of Rochford (1964), who also named it as ASHSW. The depth of the maximum is shallowest, close to 20 meters in the northern Arabian Sea and is deepest 100 m in the south. On an average the maximum is observed at 50 - 75 m. The salinity increases from around 35.3 ppt in the south to more than 36.7 ppt in the north. The potential temperature is generally $26 \pm 2^{\circ}\text{C}$.

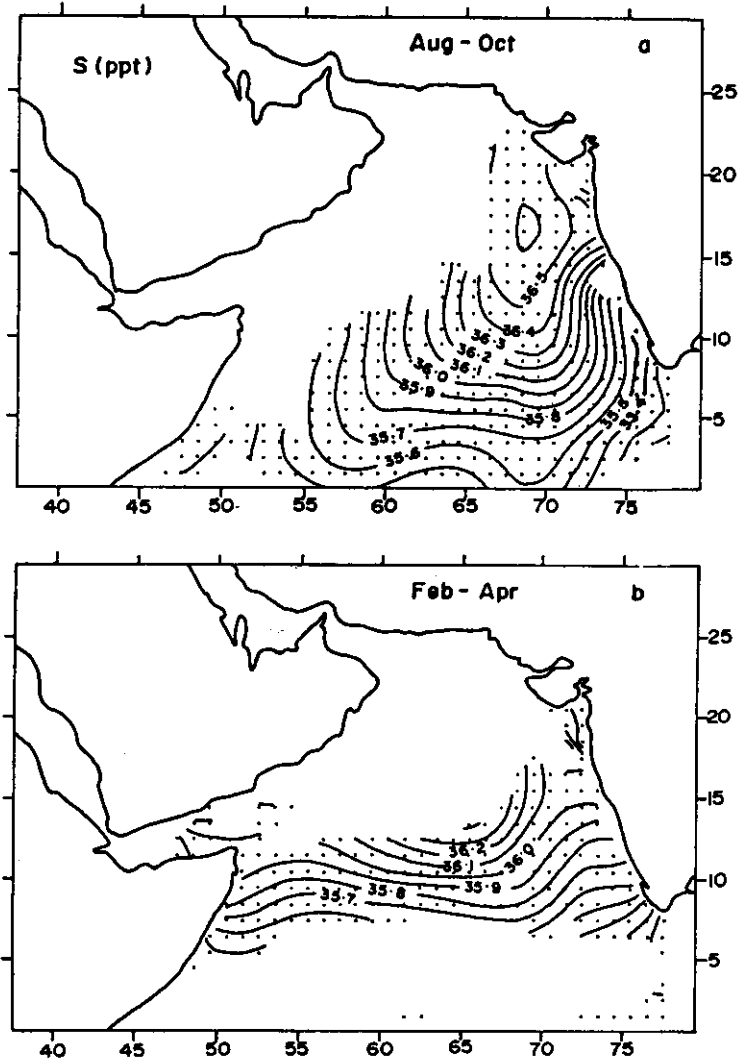


Fig. 7: Distribution of salinity (ppt) in the ASHSW (Arabian Sea High) during (a) August-October and (b) February-April. Dots show the station locations the ASHSW occurs.

3.2. Salinity minimum

Before we describe the only salinity minimum we identified in our analysis of the Levitus data, a note of caution is in order. Our aim in identifying the salinity maxima in the vertical profiles of salinity has been to determine the source of processes that actively enhances the salinity at a depth. In searching for a salinity minimum our objective has been to identify a source or process that actively reduces the salinity. It is important to note that a salinity minimum need not always arise because of the effect of such a source or process. Consider, for example, a situation in which two sources of high salinity water lead to two salinity maxima at two depths. A salinity minimum can then arise between the two maxima. However, this minimum does not arise because of

an active source or process of low salinity water. Examples of this type of salinity minimum are common in the Arabian Sea. A minimum with σ_θ of about 26.9 is found in regions which have both RSW and PGW. Also, a minimum at a depth of 400 m is often found in those areas of southern Arabian Sea which have both ASHSW and RSW. No active process or source leading to lowering of salinities can be associated with these minima. Hence we have ignored them.

The only salinity minimum we could associate with an active process leading to lowering of salinity is in the σ_θ range of 25.5 - 26.5 gm cm^{-3} . The salinity minimum which we shall refer to as Arabian sea Subsurface salinity Minimum (ASSM), is found at a depth of approximately 150 m. The areal extent of ASSM is the highest during November-January (Fig. 8a) when it is found north of 15°N, and along the coast of

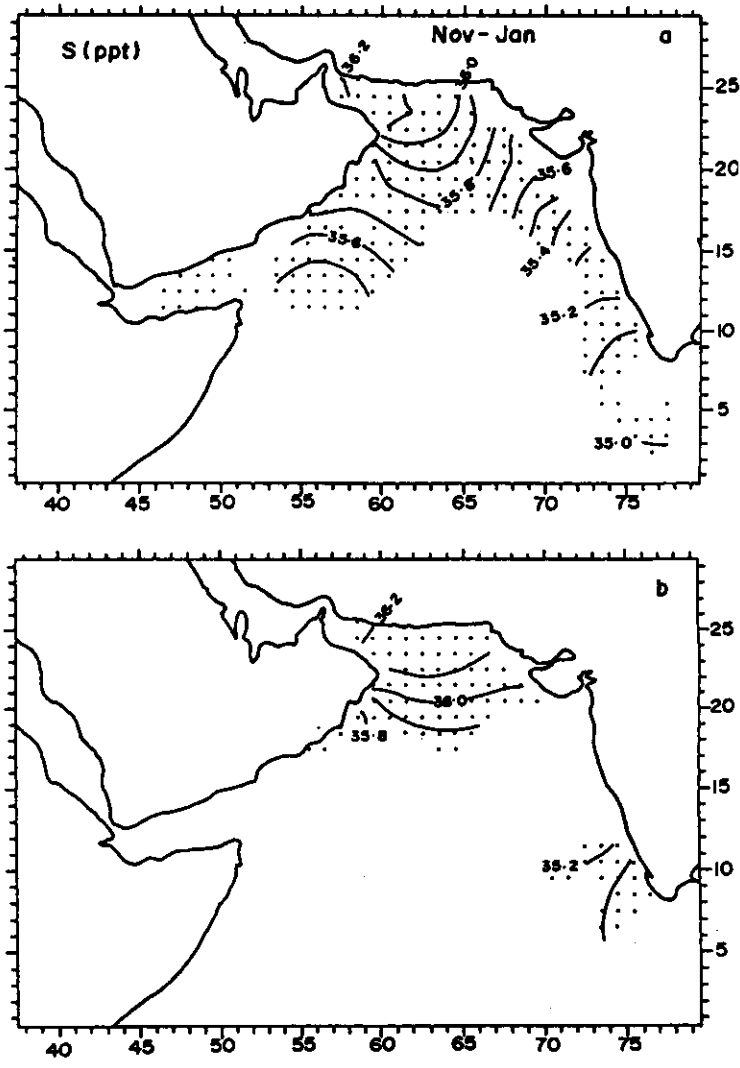


Fig. 8: Distribution of salinity (ppt) in the ASSM during (a) November-January (b) May-July. Dots show the station locations where the ASSM occurs.

India. During May-July (Fig. 5b) and August-October the distribution is patchy with detached pools. The salinities in the core of ASSM vary from about 36.2 ppt in the north to 35.1 ppt in the south. The potential temperature varies from 19° in the north to about 16°C in the south. The likely causes behind this distribution are discussed in the next section.

4. Discussion

Of the four extrema identified in the previous section, the causes behind the RSW and PGW are well known. In this section we first examine the processes that lead to the formation of the ASHSW and ASSM. We then use the signatures of the four extrema to put into perspective the θ -S structure of the Arabian Sea.

Rochford (1964) attributed the ASHSW to the northeast monsoon circulation of the surface waters. However, it appears that this is only one of the mechanisms that leads to the ASHSW. High salinity waters form in the North Arabian Sea, because evaporation exceeds precipitation. Their dilution occurs due to two processes: (1) effect of precipitation and (2) advection of low salinity surface waters. The first is most active during the southwest monsoon. During this season the surface circulation in the open Arabian Sea has the eastward and southward moving monsoon current (Wyrтки, 1973). Along the west coast of India a southward moving coastal current occurs (Shetye et al., 1990). The southeastern Arabian Sea receives about 1 - 2 m of rainfall annually (Gill, 1982) and most of it occurs during the southwest monsoon. The precipitation dilutes the southward and eastward moving high salinity surface waters of the Arabian Sea leading to the subsurface maximum, the ASHSW. The dilution of the surface waters is stronger in the eastern equatorial belt of the North Indian Ocean where the mean annual precipitation is as high as 4 m. After the withdrawal of the southwest monsoon the low salinity surface waters move westward (Wyrтки, 1973). A branch of this flow moves northward along the west coast of India as the northeast monsoon coastal current (Shetye et al., 1991) and another, somewhat larger branch, continues to move westward zonally. The signatures of the zonal westward flow can be seen well in April, but the northward coastal flow disappears by February (Cutler and Swallow, 1984). The advection of low salinity surface waters into a region of higher surface salinities of the Arabian Sea has an effect, similar to that produced by precipitation, of generating a subsurface maximum, the ASHSW. The net result of precipitation is to leave behind the ASHSW in the southern and eastern Arabian Sea during June-October (Fig. 7a). During November-January the minimum is seen along the west coast of India whereas during February-April it forms a zonal belt in the southern Arabian Sea (Fig. 7b).

Unlike the ASHSW, which occupies the southern and eastern parts of the Arabian Sea, the ASSM is found in the northern and western parts of the sea. Its signatures are developed best during November-January. The ASSM is only a few tens of meters thick and has not received much attention so far. Recently Banse (1990) has pointed out to its occurrence in the northwest Arabian Sea. Shetye et al. (1992) propose that the main cause for the formation of the ASSM is the northeast monsoon coastal current off the west coast of India (Shetye et al., 1991). The current carries low salinity water and is about 400 m deep by the time it reaches approximately 20°N. Though not much known about the behaviour of the current farther north, it appears that the flow moves parallel to the coastline of Pakistan, widens and mixes with ambient waters, by the time it reaches the Arabian coast on the western side of the basin. The current is expected to

reduce the salinity of the ambient waters. Though the depth up to which its influence is felt is not known, it is likely that it is felt at least up to the depth of about 200 m in view of the fact that the current is about 400 m off the northern tip of the west coast of India. The mixed-layer in the northern Arabian Sea is generally less than 125 m deep during the northeast monsoon. In view of our assumption that the current's influence is felt at least up to 200 m is valid, salinities in the depth range 125 - 200 m would be reduced. In the mixed-layer there would be an increase in salinity due to evaporation by cold dry continental winds of the northeast monsoon. The evaporation is known to continue under the influence of solar radiation even after the withdrawal of the northeast monsoon. The combined effect of the northeast monsoon coastal current and evaporation would cause the recharge of the salinity minimum in a layer tens of meters thick with a mean depth of about 150 m.

There are couple of other reasons that could be responsible for enhancing the ASSM ~~minimum~~ along the west coast of India. There occurs along the southwest coast of India an undercurrent which carries lower salinity waters of the southern origin has a salinity minimum associated with it (Shetye et al., 1990). Shetye et al. (1992) propose that at approximately 20°N, off the coast of Saurashtra, India, the cooling by the northeast monsoon cool dry winds can enhance the density of shelf waters sufficiently to form a mass of subsurface water which spreads at a depth of 150 m recharging the salinity minimum there. At present, not much is known about this mechanism.

Having identified the mechanisms for the generation of the four salinity extrema, we can now relate to these mechanisms the observed θ -S structure of the surface and intermediate waters summarised in figure 1. This is done in figure 9. The θ -S signature of the equatorial waters of the Indian Ocean are known to fall closely to a straight line between the points $T = 4^{\circ}\text{C}$, $S = 34.9$ ppt and $T = 17^{\circ}\text{C}$, $S = 35.25$ ppt (Sverdrup et al., 1940). This water mass, known as the Indian Ocean Equatorial Water (IOEW) covers the mid depths i.e. from couple of hundred meters to 1000 m. In general, the waters of the Arabian Sea have salinities higher than those of IOEW. Contributing to the increase are the influxes of high salinity waters from the two mediterranean seas: the Red Sea and the Persian Gulf. Evaporation in the North Arabian Sea increases the surface salinities, a manifestation of which is the salinity maximum ASHSW. The salinity minimum, ASSM, is the consequence of high precipitation in the eastern Indian Ocean. In addition to the signatures of these four extrema, we have shown in figure 9 the signatures of commonly identified water masses of the Arabian Sea.

It may be noted that Rochford (1964) had identified five salinity maxima. The ones not identified by our procedure are his salinity maximum C and E. It is likely that these water masses have restricted areal distribution and hence are important only to the small scale oceanography. Shetye et al. (1990) have pointed out to the presence of Rochford salinity maximum C off the west coast of India. Such small scale features seem to have been averaged out in the climatology that we have used in our study.

We do not have clear evidence to support the major flow paths of high salinity water mass suggested by Rochford (1964) in his figure 23. For example, Rochford did not show the branch of PGW along the west coast of India as we see in our analysis (Fig. 5a). Perhaps, Rochford missed this branch due to the non availability of data in that region. Rochford (1964) and Shapiro and Meschanov (1991) suggest four main flow path for RSW propagation. In addition, Shapiro and Meschanov (1991) show that the spreading of RSW occurs partially as high salinity isolated patches (lenses). Of course,

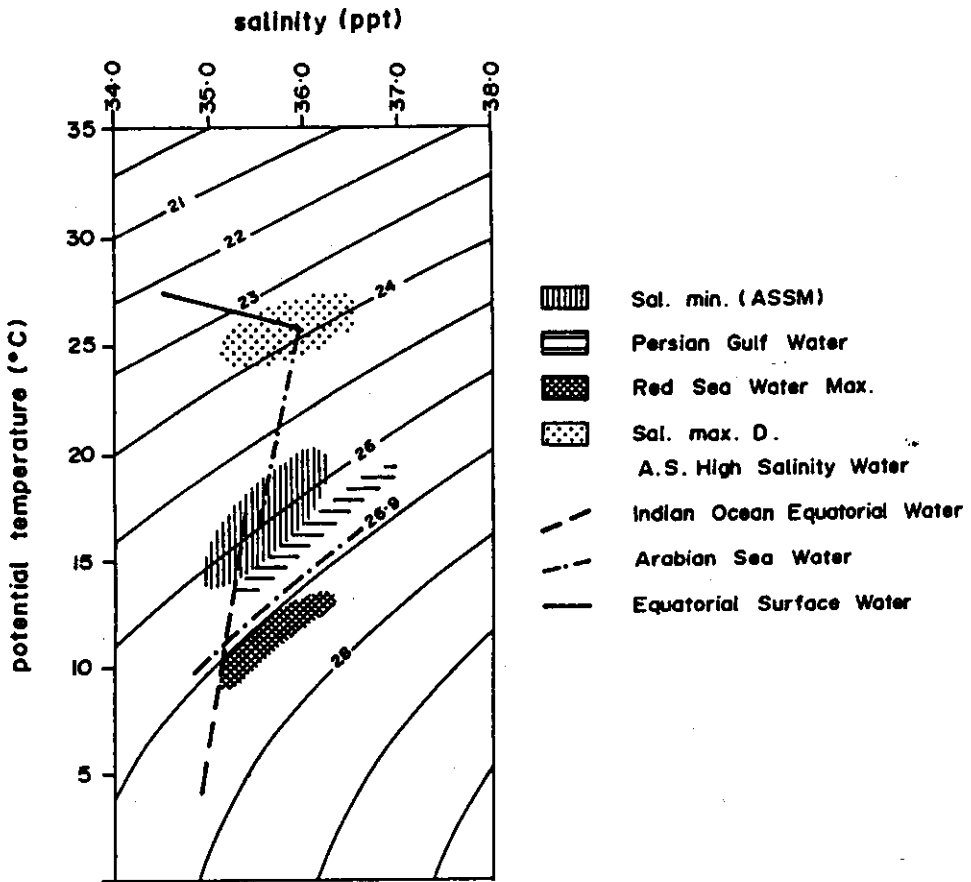


Fig. 9: Schematic potential temperature-salinity diagrams for near surface intermediate-depth layer water masses in the Arabian Sea.

such transient features cannot be expected in our climatological data set. However, note that the mean salinity distribution in the core of RSW presented by Rochford and by Shapiro and Meschanov is close to the pattern obtained by us.

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