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THE SALINITY MINIMUM IN THE ARABIAN SEA*

J. S. Sastry

Health Physics Division, Bhabha Atomic Research Centre, Bombay

Abstract

Various theories on the occurrence of the salinity minimum in the Arabian Sea are briefly reviewed. A special case of transformation by mixing of three water types, two of which have the same density but different temperatures and salinities, is discussed. It is shown that the salinity minimum of the Antarctic Intermediate Water 'moves' progressively to higher steric levels when this water mass mixes with the Red Sea, the Persian Gulf and the Arabian Sea High Salinity Water masses. The model suggests that the Antarctic Intermediate Water penetrates into the northern regions of the Arabian Sea. The peculiarities in the vertical temperature salinity structure at a few stations in the Arabian Sea are related to the mixing modes.

Introduction

Tracing the salinity minimum continuously from the South Indian Ocean to the Gulf of Oman, Tchernia, Lacombe and Guibout (1958) have suggested that the Antarctic Intermediate Water crosses the equator in the Western Indian Ocean and penetrates to the northern regions of the Arabian Sea. Taft (1963), however, points out that these salinity minima cannot be connected by a line of flow since these are located on different specific volume anomaly surfaces. While Taft's oxygen distribution on the 125 cl/t potential specific volume anomaly surface indicates northward transport of oxygen-rich water of 60°E, this salinity distribution on the same surface shows the penetration of low salinity water of Equatorial Pacific origin through the Banda Sea upto about 10°S, 60°E. Warren, Stommel and Swallow (1966) have shown that this low salinity water which occurs in the depth range of the Somali Basin salinity minimum cannot be the source of the salinity minimum in the Somali Basin since the oxyty of the low salinity water is appreciably lower than that associated with the Somali Basin salinity minimum. Thus they have ruled out the possibility of northward transport of this low salinity water in large quantities. They attribute the Somali Basin salinity minimum primarily to the penetration across the equator of the Subtropical Subsurface Water, a layer of decreasing salinity associated with an oxygen maximum, overlying the high salinity core of the North Indian Water.

The temperature - salinity relationships at several stations in the Arabian Sea show that the salinity structure is quite complicated. Mixing and interpenetration of different water masses seem to result in the peculiar T-S characteristics. An analysis of these peculiarities in relation to the occurrence of the salinity minimum in the Arabian Sea is presented here.

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Data: Atlantis stations AN 49, AN 56, AN 79, AN 81 and AN 84, Anton Bruun Station A0107 and Requisite station REAS04 are from the data sheets issued by the National Oceanographic Data Center, Washington, D. C. Discovery station DI 1756 is from Discovery Investigation Station List: 1935-1937. Albatross Station AL 196 is from Swedish Deep-Sea Expedition Reports.

TYPICAL CHARACTERISTICS OF WATER MASSES IN THE INDIAN OCEAN

To understand the salinity structure in the Arabian Sea, an adequate knowledge of the characteristics of the typical water masses in the Indian Ocean is necessary. The water mass structure in the Arabian Sea can be given in terms of the following six water masses: Arabian Sea High Salinity Water, Persian Gulf Water, Red Sea Water, Antarctic Intermediate Water, Subtorpical Subsurface Water and Equatorial Pacific Water. Figure 1 shows the location of stations used in the present analysis and the temperature-salinity relationships at these stations are shown

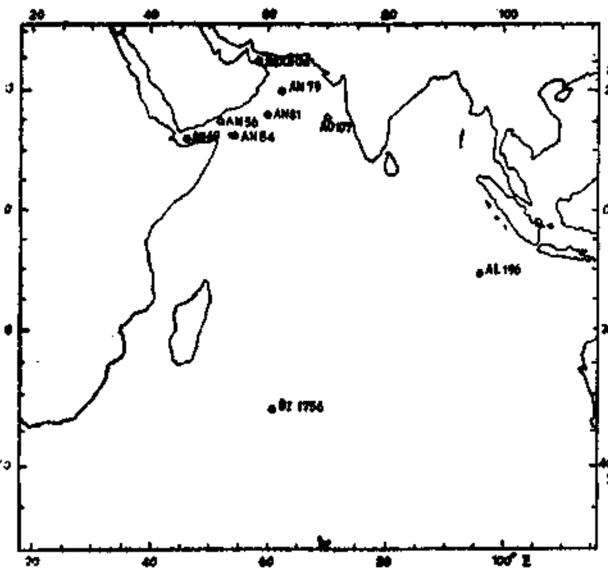

Fig. 1. Station location map.

in Fig. 2. As is evident from Fig. 2, the salinity maximum of the Red Sea Water and the salinity minimum of the Antarctic Intermediate Water occur at about the same steric level (80 to 100 cl/t). The salinity maxima of the Persian Gulf Water and of the Arabian Sea High Salinity Water are found at about 180 and 360 cl/t levels respectively. As the Red Sea Water and the Persian Gulf Water flow out into the Arabian Sea, their salinities are very much reduced by mixing. The salinity maximum of the Red Sea Water decreases to 35.36 - 35.51 ‰ at 10° N, 56° E (Taft, 1963). Similarly the salinity maximum of the Persian Gulf Water is reduced to about 35.6 ‰ at about 10° N, 60° E (Rochford, 1964). On the other hand, the salinity minimum of the Antarctic Intermediate Water, as it moves north, increases to about 34.7 ‰ at 12° S (Taft, 1963). Further, Rochford (1964) could trace the Red Sea Water and the Persian Gulf Water as far south as 10°S.

TRANSFORMATION OF T-S CHARACTERISTICS BY MIXING

Ever since Helland-Hansen (1916) pointed out the usefulness of the temperature-salinity relationship to characterise the water masses, the T-S diagram has been widely used to study the transformation of water masses by the processes of mixing. If two water masses are mixed, the mixture will have a definite T-S curve. In case these two water masses have the same density, but different temperatures and salinities, the resulting mixture will be slightly denser than either of the parent water masses and sinking may result (Von Arx, 1962). The general case of mixing of three water masses has been discussed by several authors (Sverdrup, Johnson and Fleming, 1942; Defant, 1961; Neumann and Pierson, 1966; etc.).

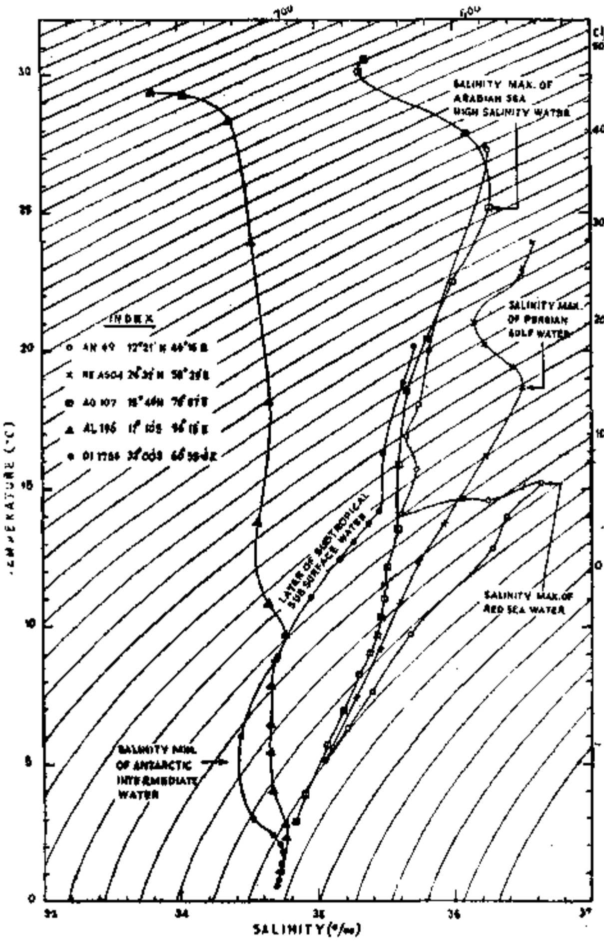

Fig. 2. Temperature-salinity relations of the typical water masses in the Indian Ocean.

We shall consider a special case of mixing of three water types, two of which have the same density but different temperatures and salinities. Stockman (1946) had given an analytical theory of T-S curves and established a set of theorems based on their geometry which are of practical significance. His first theorem states that "the geometrical position of points with a value of parameter Z=O, characterising the transformation of the 'nucleus' of the intermediate water mass with the course of time, represents the principal median of the triangle of mixing drawn from that apex of the triangle with corresponds to the intermediate water mass". In the foregoing analysis, we shall make use of this theorem with certain limitations. He assumes that the intermediate water mass is of limited extent while the upper and bottom water masses extend to + and − respectively from the boundaries of the intermediate water mass. However, in the present analysis the salinity maximum of the Red Sea water and the salinity minimum of the Antarctic Intermediate Water are located at the same steric level. The salinity maximum of the Persian Gulf Water (or that of the Arabian Sea High Salinity Water) is at a different steric levels We may still construct the mixing triangle based on the above theorem; keeping in mind the limitations regarding the vertical extent of the three water masses.

Further in these studies as well as those of Stockman (1946) it is assumed that (1) the vertical eddy diffusivity is uniform and (2) any water mass may be uniquely characterised by a single point on the T-S diagram. These two assumptions though not realistic in nature, have been made specifically for presenting the model.

For simplicity, we shall consider the transformation when mixing progresses between the three water types, namely the salinity maximum of the Persian Gulf Water (I), the salinity minimum of the Antractic Intermediate Water (II), and the salinity maximum of the Red Sea Water (III). Figures 3 and 4 show the probable modes of mixing and transformation of water types II and III. The temperatures and salinities chosen for the water types I, II and III in Figs. 3 and 4 nearly correspond to the values mentioned earlier.

DISCUSSION

The broken line in Fig. 3 shows the principal median of the triangle of mixing drawn from the apex II (T_{II} S_{II}). At the initial moment of mixing, t=0, the T-S curve may be thought to consist of two straight lines, I-II and II-III. With time, the initial T-S structure is modified and the successive T-S curves are schematially shown by the four curves labelled t_1, t_2, t_3, and t_4. In such a system as we have assumed, the salinity of the salinity minimum of the Antarctic Intermediate Water not only increases with time but is also found to 'move' progressively to a higher steric level. Thus with the chosen parametric values, the increase in thermosteric anomaly of the salinity minimum of the Antarctic Intermediate Water from the initial to the final stages of mixing is about 26 cl/t. If, however, we consider the temperatures and salinities of these water types at their respective regions of their formation, the increase in thermosteric anomaly of the salinity minimum of the Antarctic Intermediate Water could be slightly more. Thus Taft's (1963) criticism that the salinity minima cannot be connected by a line of flow does not seem to be entirely justified.

Warren, Stommel and Swallow (1966) give the most plausible explanation for the Somali Basin salinity minimum. As mentioned earlier, they consider that the northward moving Subtropical Subsurface Water, a layer of salinity transition and an oxygen maximum, lies above the high salinity core of the North Indian Water to result in the Somali Basin Salinity minimum. In fact, they say that "if a layer in which salinity decreases with depth is also characterised by a relative maximum in oxygen concetnration, and comes to overlie high saline water below, the result will be formation of layer having a salinity minimum as well as an oxygen maximum; and the salinity minimum will not in general coincide with the oxygen maximum". This scheme is a possible one and looks obvious at first in that the salinity and oxygen distributions in the Somali Basin by Warren, Stommel and Swallow (1966) have similar features.

However, the salinity and oxygen distributions along four zonal sections in the Arabian Sea (Sastry and D'Souza, 1971, D'Souza and Sastry; 1971), reveal certain interesting features. Along 5°N, the salinity minimum in general located close to the 120 cl/t surface (but above the 100 cl/t surface) and the oxygen maximum is distinctly seen at about 100 m above the salinity minimum. At 10°N, the salinity minimum is still found at about the same steric level as at 5°N. The oxygen maximum, however, coincides with salinity minimum at some stations while at other stations it is found at about 100m above the salinity minimum as at 5°N. Further north, except at a couple of stations, the salinity minimum is generally found between 200 and 300 cl/t surfaces without any corresponding oxygen maximum as in the southern sections. This sudden shift in the location of salinity minimum, north of about 10°N, does not seem to result by the penetration of Subtropical Subsurface Water into the Arabian Sea overlying the high salinity core of the North India Water.

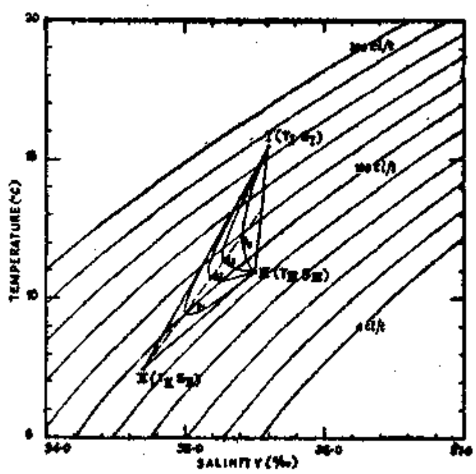

Fig. 3. Transformation of salinity minimum of the Antarctic Intermediate Water.

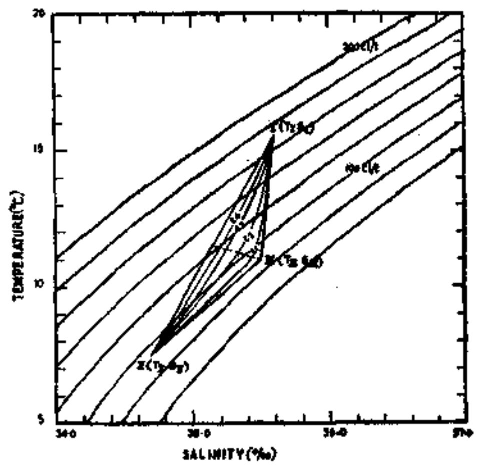

Fig. 4. Transformation of salinity maximum of the Red Sea Water.

The occurrence of the salinity minimum at progressively increasing steric level may be viewed as a result of the process of transformation by mixing of the Antarctic Intermediate Water. The Antarctic Intermediate Water, moving north, spreads and mixes with the southward moving Red Sea and Persian Gulf Waters. As mixing between these water types progresses, the thermosetric anomaly of the salinity minimum of the Antarctic Intermediate Water gradually increases as illustrated in Fig. 3. In the initial stages of mixing the oxygen maximum will be found above the salinity minimum and further mixing will bring these closer together. (It may be mentioned that by reconstructing Fig. 3 with the point T_{II} S_{II} coinciding with the oxygen maximum, the thermosteric anomaly would not alter significantly). North of about 12°N, the Red Sea Water ceases to be a major water mass contributing to the mixing while the Arabian Sea High Salinity Water assumes greater importance for the process of mixing. Since thesalinity maximum of the Arabian Sea High Salinity Water occurs at about 360 cl/t (see the T-S curve for 'Anton Bruun' station 107), further transformation of the salinity minimum of the Antarctic Intermediate Water will be accompanied by a sudden shift of this salinity minimum to a higher steric level.

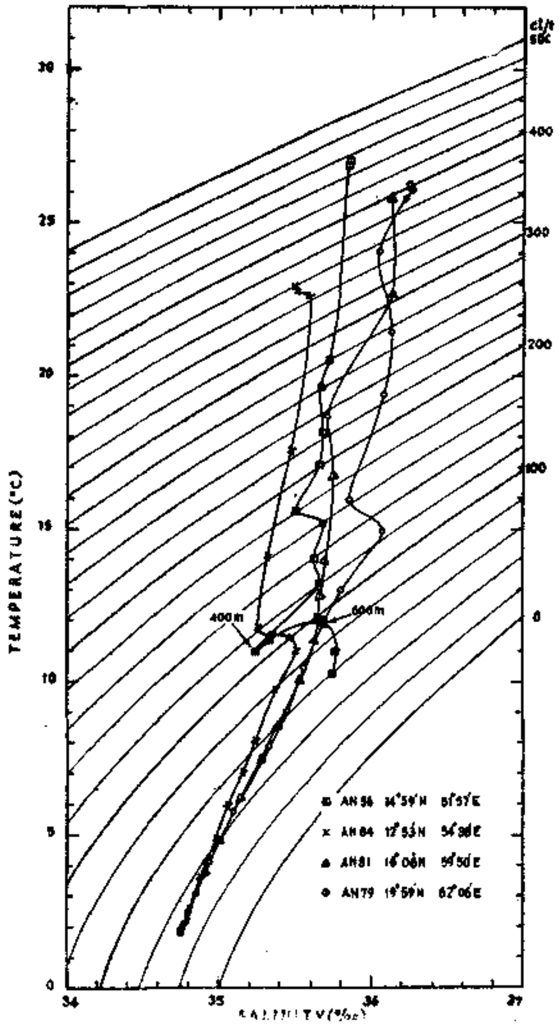

Fig. 5. Temperature salinity relations pertaining to the transformation of the salinity maxima of the Red Sea Water.

Thus the variations in the location of the salinity minimum in the Arabian Sea may be attributed to the complicated process of transformation by mixing of the Antarctic Intermediate, Red Sea, Persian Gulf and Arabian Sea High Salinity Water masses.

At several stations in the northern Arabian Sea, the T-S curves do not show a salinity maximum which corresponds to the Red Sea salinity maximum. It is somewhat puzzling to explain the absence of the Red Sea Water in northern Arabian Sea especially when it is realised that the Antarctic Intermediate Water (whose salinity minimum appears at about the same steric level as that of the salinity maximum of the Red Sea Water) could be traced in those regions. In order to explain this anomalous behaviour, we shall consider the transformation of the salinity maximum of the Red Sea Water when it mixes with the other two water types (Fig. 4).

As mixing progresses, the salinity of the salinity maximum is reduced while the thermosteric anomaly of the salinity maximum increases. Further, as the salinity of the salinity maximum erodes, this water type looses its characteristic tracer property, the salinity maximum, by which it can be identified. Thus when mixing takes place between these three water types, the 'core' method to trace the Red Sea Water by its salinity maximum alone may lead to erroneous conclusions.

In Fig. 5 are shown the T-S curves for 'Atlantis' stations 79, 81 and 84. Station 84 is located close the Socotra (Fig. 1) and the salinity maximum at about 90 cl/t is undoubtedly of the Red Sea Water. At station 79, the salinity maximum occurs at about 120 cl/t and is clearly of the Persian Gulf Water. At station 81, located almost midway between stations 79 and 84, the T-S curve does not show any salinity maximum that could be associated with the Red Sea Water. As illustrated in Fig. 4 the Red Sea Water has lost its characteristic property giving rise to a rather simple T-S relationship at station 81.

In reality, the two modes of mixing visualised here simultaneously affect the water mass structure. Further, if the other water types (Arabian Sea High Salinity Water, Subtropical Subsurface Water and Equatorial Pacific Water) are also taken into consideration, the resulting vertical salinity will be more complicated as is evident from the T-S relationships in the Somali Basin (Warren, Stommel and Swallow, 1966).

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DISCUSSION

T. BALACHANDRAN: Since density is a function of temperature and salinity, how can 2 water masses of same density with varying temperature and salinity exist?

J. S. SASTRY: Density is a function of salinity, temperature and pressure, *i.e.* D=f (s, t, p). That means higher salinity and lower temperature can be equalised with lower salinity and higher temperature.