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Watermass structure in the western Indian Ocean: Part I—Watermasses and their thermohaline indices

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सार—'हिंद महासागर समान्य जल राशि' की संकल्पना को प्रस्तुत कर, उसके अभिलक्षणों को परिभाषित किया गया है। जब विभिन्न तापमान और लवणता अभिलक्षणों वाली के एक, दो या उससे अधिक जलराशियों का हिंद महासागर की सामान्य जल सतह में घुसती है तो तापमान-लवणता संरचनाओं का निर्माण होता है। इस लेख में उसी संरचना पर चर्चा की गई है। पश्चिमी हिंद महासागर में विभिन्न जल राशियों के ताप-हेलाइन सूचकांक को व्युत्पन्न कर सारणीबद्ध किया गया है।

ABSTRACT. The concept of "Indian Ocean Common Watermass" is introduced and its characteristics are defined. The temperature-salinity structures which would result when one, two or more watermasses of different temperature and salinity characteristics penetrate into the layer of the Indian Ocean Common Water are discussed. The thermohaline indices of different watermasses in the western Indian Ocean are derived and tabulated.

1. Introduction

The structure of the watermasses of the Indian Ocean was first given by Sverdrup, Johnson and Fleming (1942) which was later modified by Mamayev (1975). An examination of the watermass structure at different locations in the Indian Ocean reveals the presence of several watermasses, namely Indian Ocean Central Water (IOCW), Indian Ocean Equatorial Water (IOEW), Antarctic Intermediate Water (AIW), Red Sea Water (RSW) Persian Gulf Water (PGW), Bottom and Deep Water (BDW) etc. These watermasses participate in the general circulation and the observed T-S structure at any locality is a result of mixing of these watermasses. Earlier investigations on the watermasses and their structure based on the observed salinity maxima and minima on the T-S diagrams show clearly the existence of conflicting views as regards to their spreading and transformation upon mixing (Lutjiharms 1972, Thomsen 1935, Tchernia Lacombe and Guibout 1958, Taft 1963, Warren, Stommel and Swallow 1966, etc). Warren, Stommel and Swallow (1966) have also suggested that the high salinities in the south Indian Ocean are the effect of the outflows of the Persian Gulf and Red Sea Waters and that the higher temperatures and salinities even at depths of 2000 m in the Arabian Sea are the result of downward fluxes of heat and salt from these outflows. The scatter diagrams showing the temperature and salinity values at the cores of the Persian Gulf and the Red Sea Watermasses indicate an increase in density as they spread out from their source regions (Wyrtki 1971, Premchand 1981). This phenomenon of increase in density upon mixing of different watermasses is of global significance (Wust 1936, Duing & Schwill 1967, McLellan 1957, Fofonoff 1956). A detailed study of these aspects will be presented in parts II and III of this paper.

2. Concept of 'Indian Ocean Common Watermass'

An examination of the T-S curves at several stations in the Indian Ocean shows extreme complexity with several salinity maxima and minima simultaneously occurring at the same location. Some of these are clearly due to the presence of the watermasses while some others are hypothetical or secondary in nature. Figs. 1 (a & b) show typical T-S curves at different locations in the Indian Ocean depicting the principal watermasses. Some of the observed salinity maxima and minima (for example, the salinity minimum overlying the Red Sea Water salinity maximum) need not necessarily be associated with any watermass.

The development of the real and hypothetical salinity maxima and minima in the vertical are schematised in Fig. 2. The observed characteristics would be different under different initial environmental conditions. When a high salinity watermass penetrates into a watermass of uniform salinity with depth

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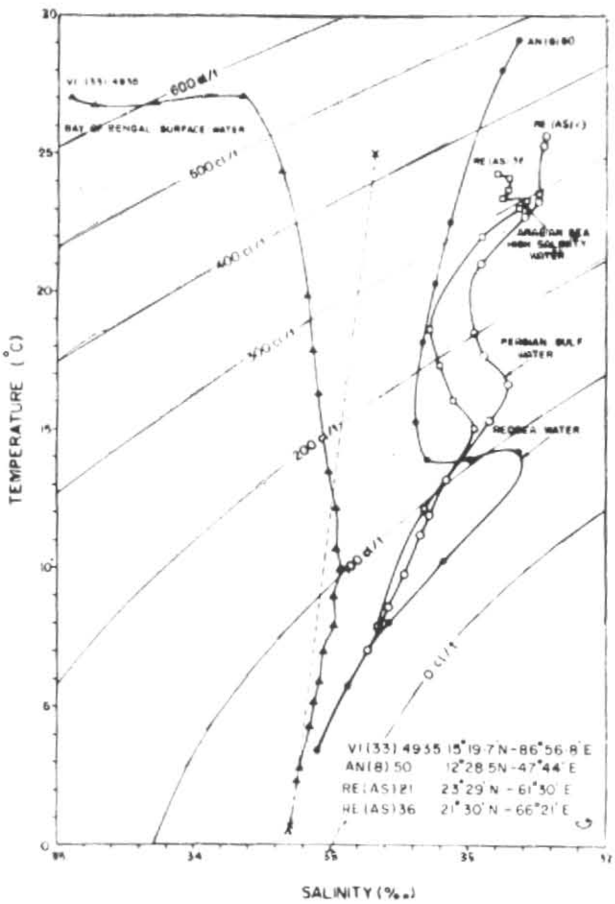

Fig. 1(a). Temperature-salinity diagrams at a few typical stations in the north Indian Ocean

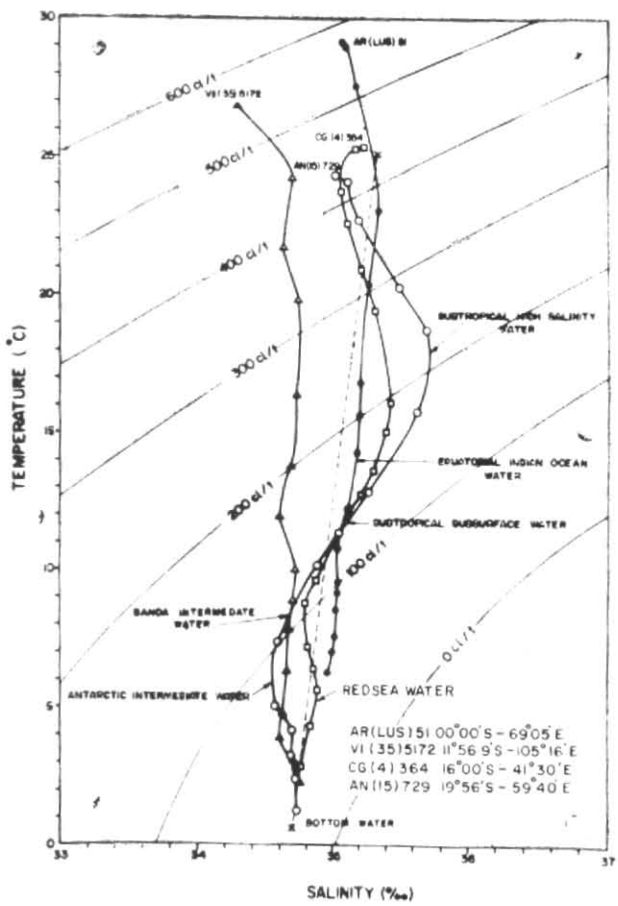

Fig. 1(b). Temperature-salinity diagrams of a few typical stations in the south Indian Ocean

TABLE 1

T-S indices of different watermasses in the Indian Ocean

S. No.	Watermass	Temperature (°C)	Salinity (‰)	Sigma-*t* (g/cm³)	Thermosteric anomaly (*cl/t*)	Source
1	Arabian Sea High Salinity Watermass	26.80	36.50	23.933	398.3	Authors
2	Persian Gulf Watermass	19.17	37.12	26.622	142.5	,,
3	Red Sea Watermass	17.65	37.14	27.014	105.3	,,
4	Antarctic Intermediate Watermass	5.20	34.30	27.119	95.4	Mamayev (1975)
5	Antarctic Bottom Watermass	0.60	34.70	27.851	26.1	,,
6	Subtropical Subsurface Watermass	16.00	35.60	26.227	180.0	Authors
7	Tropospheric Equatorial Watermass	25.00	35.30	23.589	431.2	,,
8	Hypothetical Watermass (H_1)	17.55	35.10	25.478	251.2	,,
9	Hypothetical Watermass (H_2)	13.00	35.00	26.411	159.7	,,

The above indices are at 95% confidence limits.

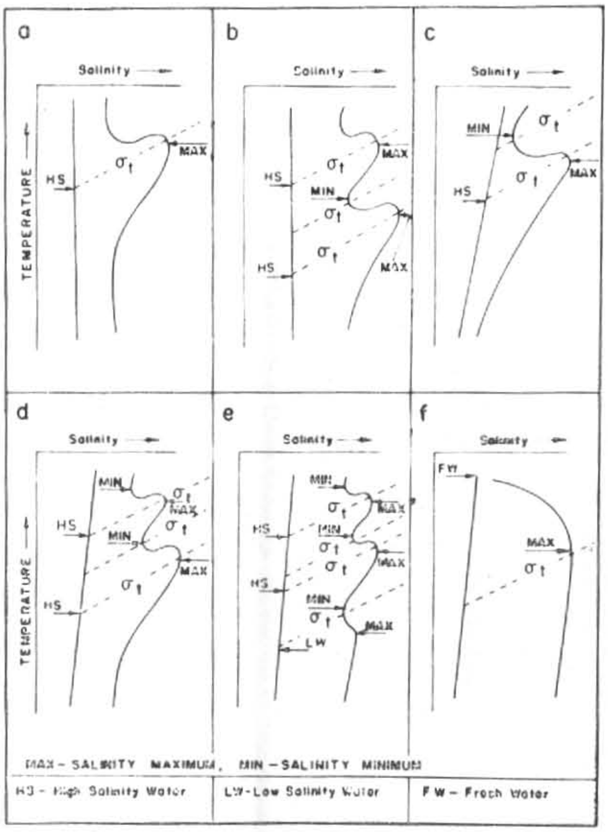

Fig. 2. Schematic diagram showing the development of salinity minima and maxima in the T-S plane

the salinity structure is deformed resulting in a salinity maximum (Fig. 2a). On the other hand when two high salinity watermasses at different levels penetrate into the isohaline layer (Fig. 2b) a salinity minimum appears sandwiched between the two high salinity cores. In this case the salinity minimum is not associated with any particular watermass. Fig. 2(c) shows the case when a high salinity core penetrates into a layer of decreasing salinity with depth. A salinity minimum could be observed overlying the high salinity core which is once again not associated with any specific watermass. In such cases the salinity minimum appears to be more pronounced near the source region of the high salinity water. As the high salinity water spreads and looses its characteristics both the maximum and minimum become less pronounced. Fig. 2(d) shows the transformation when two high salinity watermasses penetrate into a salinity transition layer. When a low salinity water penetrates into a layer of salinity transition a secondary maximum develops below the core of low salinity (Fig. 2e). The development of a salinity maximum in the intermediate layers when freshwater discharges takes place at the surface (as in the case of Bay of Bengal) is shown in Fig. 2 (f). These figures suggest that the observed vertical *mass structure* in the interior of the ocean could be conceived to have formed as a result of penetration and subsequent mixing of watermasses into a layer of an ideal watermass which could be visualised to exist far away from the source regions of all other watermasses and uninfluenced by any and further stratified as shown by the straight line in the schematic diagram.

The penetration of the watermasses like PGW, RSW and AIW would deform the idealised structure and the salinity maxima and minima associated with these high and low salinity cores could then be treated as anomalies. The watermass in the equatorial Indian Ocean is far removed from the source region of all other watermasses and has the characteristics of uniform salinity with depth in the tropospheric waters. The thermohaline index of this watermass could be taken as $T = 25.0$ deg. C and $S = 35.3‰$. The Bottom Water (BW) in the Indian Ocean is of circumpolar origin and has a temperature of 0.6 deg. C and salinity of 34.7‰. The line joining the thermohaline indices of the above two watermasses could be taken to represent its mean structure in the Indian Ocean in the absence of any other watermasses and this is now named as "Indian Ocean Common Watermass" and is shown by the dashed line in Figs. 1(a & b).

The salinity maxima and minima appearing as anomalies will be more pronounced in tht neighbourhood of source regions. For example, the penetration of Mediterranean Water into the Atlantic Ocean gives rise to a salinity minimum (overlying the high salinity core) and this minimum is more conspicuous near the strait of Gibralter and becomes less prominent farther away from the source region (Needler and Heath 1975, Mamayev 1975). The thermohaline index of this salinity minimum will be one of a secondary nature.

3. Thermohaline indices of the watermasses in the Indian Ocean

An examination of T-S curves in the northern Arabian Sea reveals that associated with the PGW a salinity minimum could always be identified around 250 *cl/t* (Fig. 1a). The thermohaline index of this hypothetiral watermass (H_1) is taken at the intersection of the 250 *cl/t* steric surface with the T-S line of the "Common Watermass" and occurs at T = 17.55 deg. C and S = 35.1‰. Similarly in the region of Gulf of Aden where RSW is more pronounced a salinity minimum appears around 140 *cl/t* (Fig. 1a). It is to be noted that the density of the core of PGW nearly coincides with the density of this salinity minimum (overlying the core of RSW). The thermohaline index of this hypothetical watermass at T = 13.0° C and S=35.0‰. Based on an examination of several T-S curves in the entire Indian Ocean and from a survey of the existing literature the thermohaline indices of the watermasses have been derived and are listed in Table 1. These thermohaline indices will be extensively used to describe the steady state watermass structure and the transformation upon mixing of the Persian Gulf and Red Sea Watermasses and the resulting densification of their core layers in latter parts.

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