

Water Masses & General Hydrography along the West Coast of India during Early March

V RAMESH BABU, M J VARKEY, V KESAVA DAS & A D GOUVEIA

National Institute of Oceanography, Dona Paula, Goa 403 004

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Structure of water masses along the west coast of India from Bombay to Trivandrum has been studied through vertical sections of temperature, salinity and density during 3-17 March 1977. The Arabian Sea high salinity water spreads south as a core along the coast at an average depth of 90 m. Influence of the Persian Gulf water in the southern part is found less significant. The northern limit of the Red-Sea water is 17°N. Low saline waters ($<34.2\text{‰}$) intrude into the southeastern Arabian Sea from the equator around 200 m. Off the Kerala Coast, low saline waters ($<34.5\text{‰}$) occupy the shelf area. A transition zone between 13° and 16°N separates surface waters of low temperature and high salinity in the north from the surface waters of high temperature and low salinity in the south. Sigma-t surfaces generally slope down towards south indicating very weak onshore flow in the upper layers.

Analysis on the spreading of water masses by Rochford¹ and Wyrki² suggests that some of the prominent water masses which have their origin in the northwestern Indian Ocean spread along the west coast of India. While several hydrographic investigations, confined to limited regions, have been made off the west coast of India³⁻¹⁴, very few studies are carried out on the structure of water masses¹⁵⁻¹⁷. Varadachari *et al.*¹⁸ have studied the regional variations in the characteristics of the water masses along the west coast from Bombay to Allepy based on the hydrographic data collected along 5 sections normal to the coast. In the present paper, the structure of water masses in the upper 1000 m along the entire coast from Bombay to Trivandrum for late winter is presented.

Materials and Methods

During the 16th cruise of *RV Gaveshani* (3-17 March 1977) 47 stations along 2 sections P_1 and P_2 were occupied (Fig. 1), sections P_1 and P_2 following more or less 100 and 1000 fm isobaths respectively. Across the shelves off Bombay and Trivandrum, 2 sections (A_1 and A_2) were also covered (Fig. 1).

Data on temperature and salinity were obtained by standard hydrographic casts. Ship board salinometer (AUTOSAL, accuracy $\pm 0.003\text{‰}$) was used to estimate salinity. For each station, temperature is plotted against depth, salinity and oxyty on a temperature-salinity (T-S) diagram. Various informations necessary for the construction of vertical distribution charts of temperature, salinity and density along the sections were read from station curves.

Results

Temperature—Vertical temperature distribution charts along the 4 sections are presented in Figs 2, 3A and 4A.

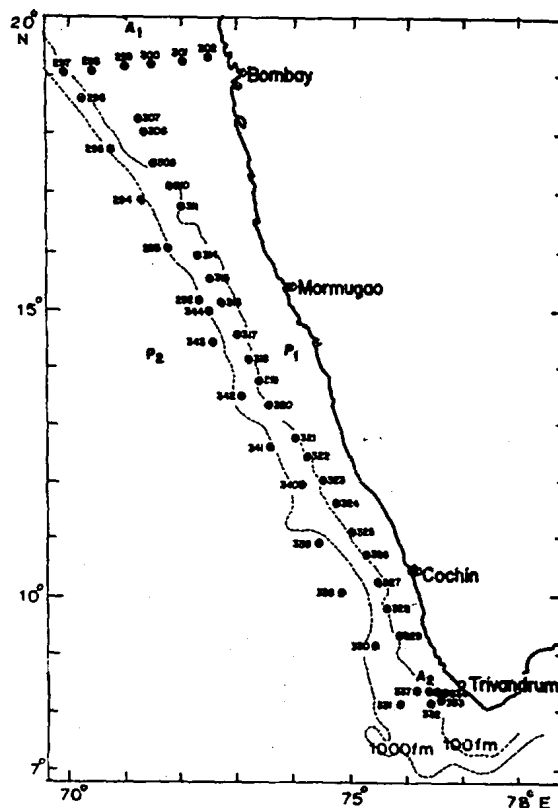


Fig. 1—Station locations

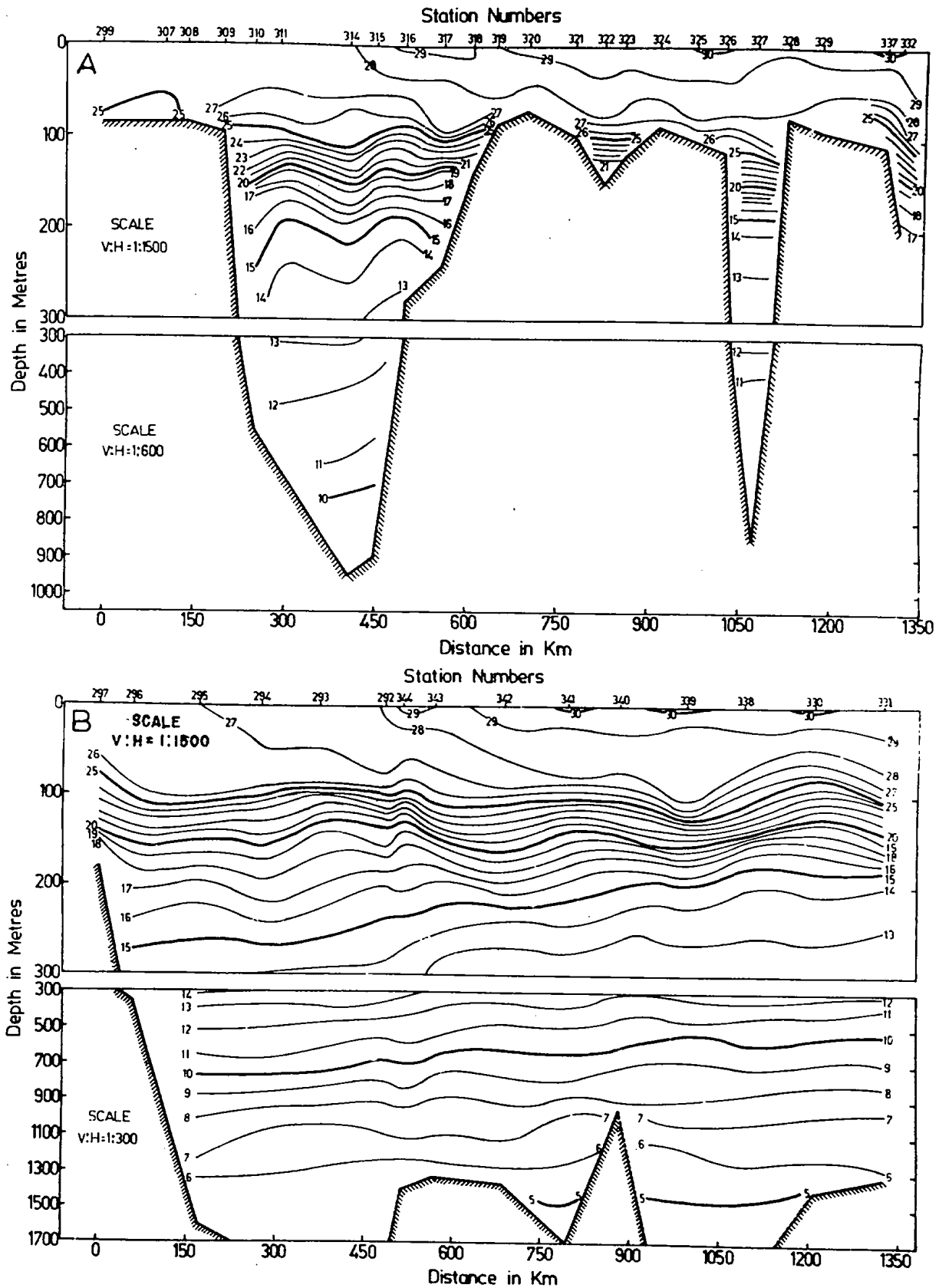


Fig. 2—Temperature along sections P₁ (A) and P₂ (B)

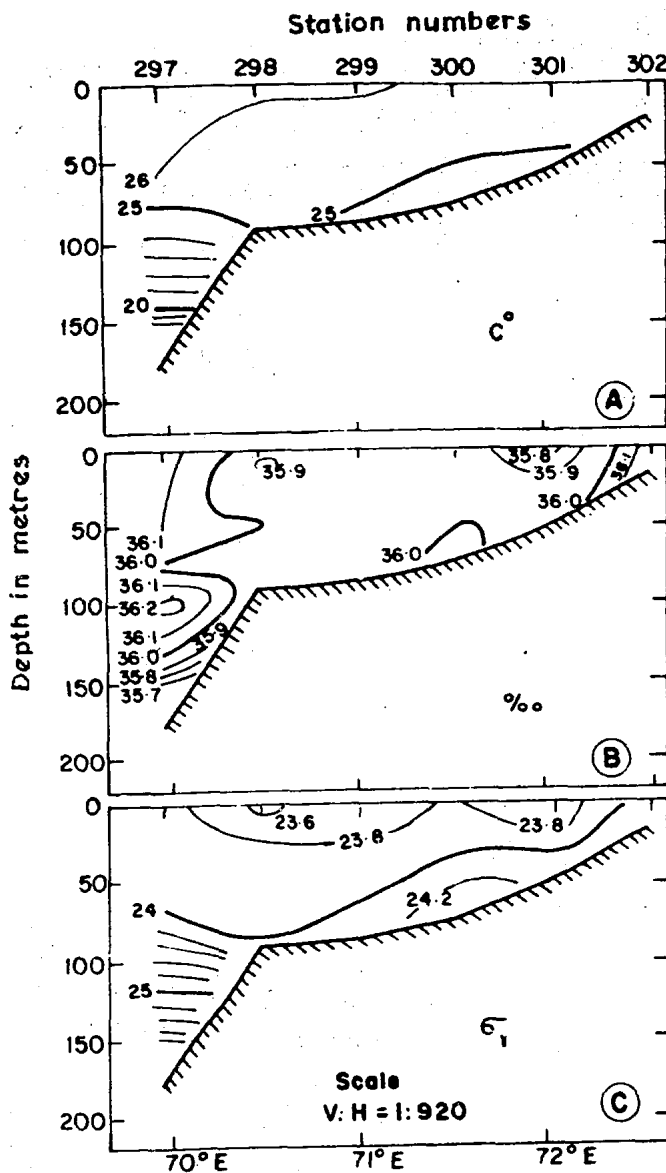


Fig. 3

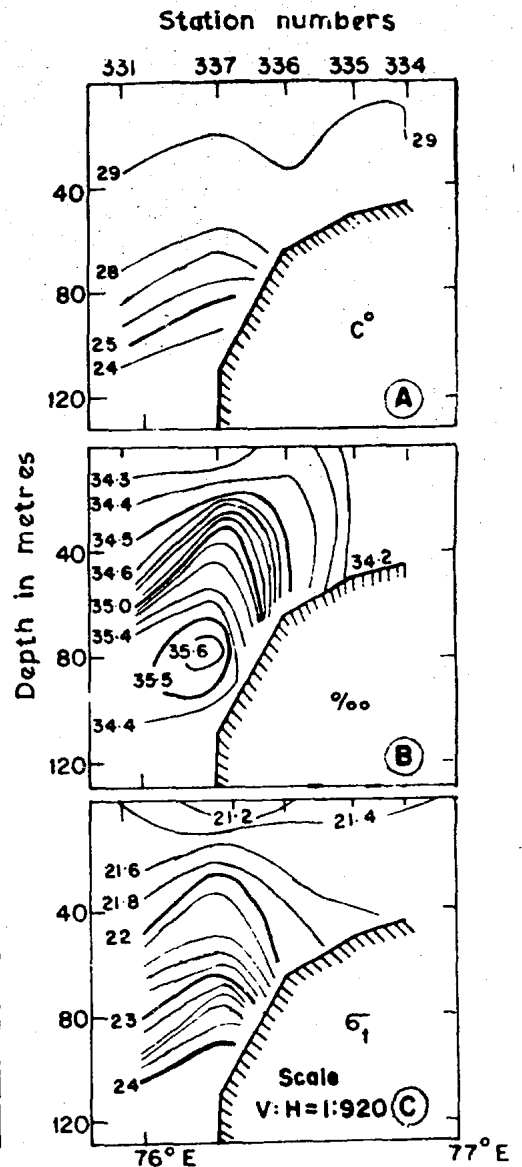


Fig. 4

Figs 3 and 4—Temperature (A), Salinity (B) and density (C) along sections A₁ (3) and A₂ (4)

Surface temperature generally decreases from south to north with a transition zone of large horizontal gradients between 13° and 16°N (Fig. 2). Within this zone, the isotherms in the surface layer slope down towards south. Very weak thermal gradients are observed in the mixed layer, north of the transition zone, while the thermal gradients in the south are relatively stronger. The top of the thermocline is found at an average depth of 100 m except in the south, where it shallows to a depth of about 75 m at station 330 (Fig. 2B). Assuming 15°C isotherm as the bottom of the thermocline, its thickness increases towards north where it is > 200 m (Fig. 2B). Below the thermocline,

isotherms in general slope up towards south and thermal gradients are relatively weaker in the southern part (200-300 m depth range) compared to the northern part.

Waters are almost isothermal across the inner shelves off Bombay and Trivandrum respectively (Figs 3A and 4A). Off Trivandrum, isotherms in the thermocline (Fig. 4A) show a rising tendency towards the coast and continue to the depth of about 55 m which is an indication of the starting of upwelling in this region.

Salinity—Figs 3B, 4B and 5 present vertical distribution of salinity along the various sections.

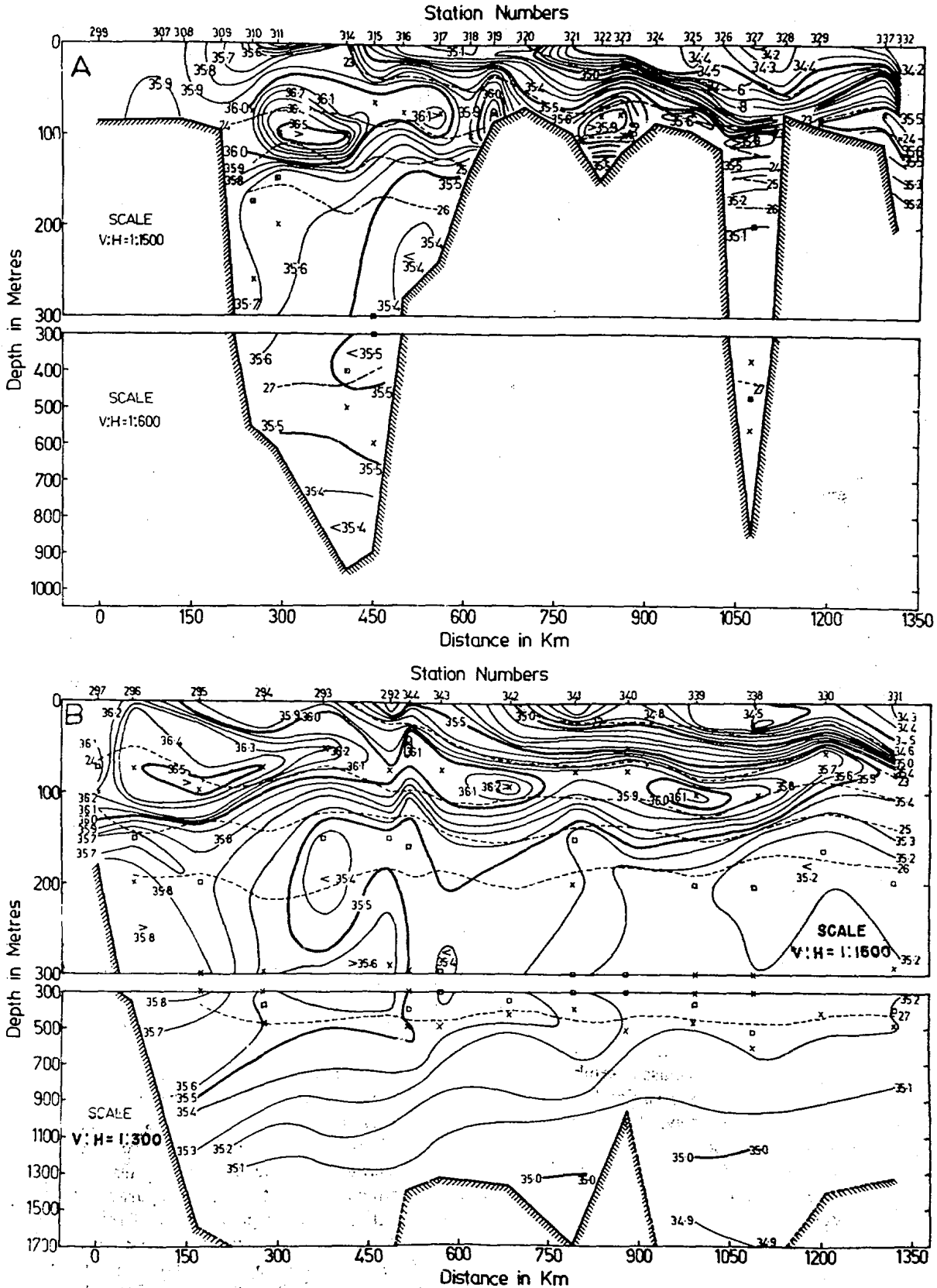


Fig. 5—Salinity along sections P₁ (A) and P₂ (B) (X, maximum and □, minimum)

Isopycnals are superimposed wherever necessary for comparison. Surface salinity decreases towards south (about 36.2 to 34.2‰). The temperature transition zone also separates high saline surface waters in the north from low saline surface waters in the south. At the surface, low saline pockets are observed along the coast. Among these, the prominent one is at st 327 ($< 34.2‰$; Fig. 5A).

Below the surface, salinity distribution shows several maxima and minima (Fig. 5B). A layer of salinity maximum is present in the depth range 50 to 100 m. The core of this salinity maximum generally sinks southward to a depth of 100 m at st 339. Further south, it rises (about 75 m) at st 330. Salinity in this core decreases southward from 36.5 to 35.5‰.

Another layer of salinity maximum between 200 and 300 m is encountered in the northern regions (north of 14°N) as a core while around the same depth, salinity minimum ($< 35.2‰$) is observed in the southern part. Between 400 and 500 m, another maximum is observed at most of the stations south of 17°N and the salinity values of this maximum decrease from 35.6 to 35.2‰ towards south. Below 500 m, the salinity gradually decreases to 35.0‰ around 1100 m.

Density—Vertical distribution of density (σ_t) along different sections is presented in Figs 3C, 4C and 6.

Offshore waters in the surface layer are comparatively less stratified in the northern region than in the south (Fig. 6). However, Figs 3C and 4C show that the inner shelf waters off Bombay are more stable than those off Trivandrum.

The σ_t lines in the upper mixed layer generally have gentle down slope southwards up to sts 326 and 339 indicating a very weak onshore flow (Fig. 6). Southward steeper slope of isopycnals off Trivandrum, indicates strong onshore flow at subsurface depths and thus confirms the presence of upwelling at about 50 m.

Weak σ_t gradients in 200-300 m are seen to be associated with the low saline tongue ($< 35.2‰$) in the southern part (Fig. 6B).

Water masses—Characteristics of all the salinity maxima and minima observed in the region of study for the upper 1000 m layer are shown in Fig. 7.

Several salinity maxima and minima are identified and grouped into 4 different watermass assemblages. Assemblages of each group, except Arabian Sea high salinity water (Fig. 7, I) has a tendency to be oriented parallel to σ_t lines. The properties of these water masses along the west coast of India are presented in Table 1 along with the corresponding values given by Rochford¹ and Wyrki².

Discussion

Relatively high temperature within the surface layer associated with moderate thermal gradients in the

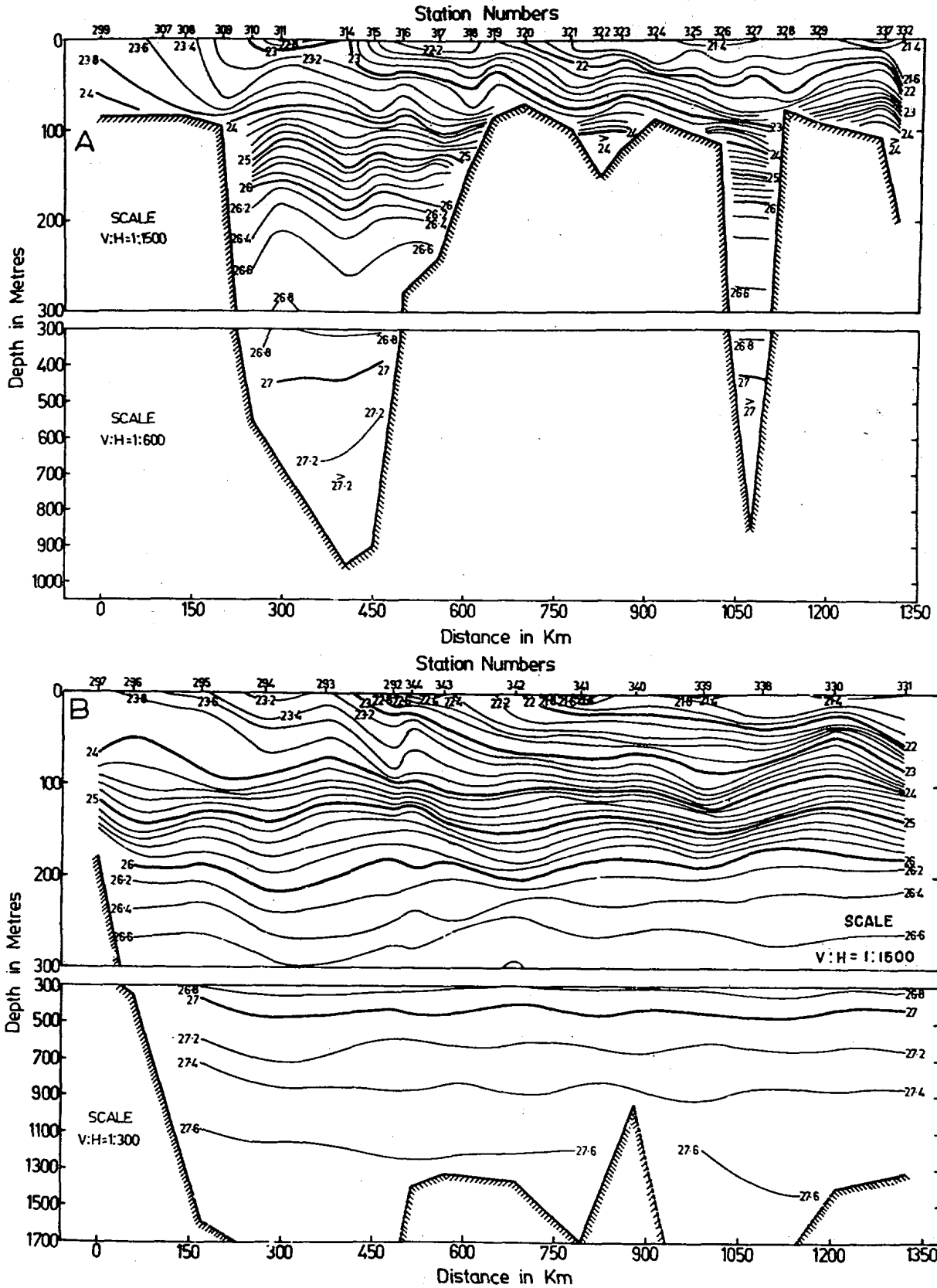
southern part shows the seasonal heating effect. Thermocline gradually spreads towards north with its thickness varying from < 100 m in the south to > 200 m in the northern part with corresponding decrease in its thermal gradient. This latitudinal variation in the characteristics of thermocline is more or less similar to that observed by Sastry and D'Souza²⁰ in summer. Presence of low thermal gradients in the thermocline around 250 m in the northern part suggests horizontal movement of water masses.

Low saline waters ($< 34.5‰$) in the shelf region of the southwest coast of India are the result of their advection from south during the northeast monsoon season. This water appears to come from Bay of Bengal as seen from Wyrki's² map. Darbyshire²¹ has also explained low surface salinities as due to Bay of Bengal waters which join the northward flowing Equatorial surface water in winter. The low saline pocket ($< 34.2‰$) observed off Cochin (st 327) may be due to the influence of land drainage through the large back water system opening into the sea near Cochin as a result of stray rainfall. Examination of weather records reveals that heavy rainfall (about 3 cm) has occurred at Cochin within the short period of 3 days prior to the observations at this station.

The spreading of the Arabian Sea high salinity water towards south as a core along the entire coast between 80 and 100 m is most conspicuous. This water forms at the surface further north¹⁷ of the present region of study as a result of excess evaporation over precipitation. The source region of this water mass is subjected to shift due to year to year fluctuations in the atmospheric conditions over the Arabian Sea because of its shallow nature.

At the depths of around 200 m, a low salinity tongue ($< 35.2‰$) is seen extending from south (Fig. 5B). The salinity minimum observed in this tongue falls between the σ_t surfaces of 26.2 and 26.3. In the southern region, dissolved oxygen minimum values are relatively higher (0.7-1.0 ml/litre) compared to the corresponding values (< 0.5 ml/litre) in the northern region (Fig. 8). The presence of high oxygen content in the oxygen minimum layer coinciding with the low salinity tongue in the south indicates that the north equatorial region may be probable origin of the low salinity water.

Persian Gulf water is present as a core around 250 m in the northern region only and loses its identity towards south. South of 14°N, its presence as a core cannot be ascertained. However, few stray maxima are observed around σ_t 26.6 in the southern part and these could be attributed to the penetration of this water mass into these regions as pockets from west. Its presence is indicated around 200-400 m in all the sections worked out by Varadachari *et al.*¹⁸, whereas studies made by Wyrki² and Sharma²² show that the



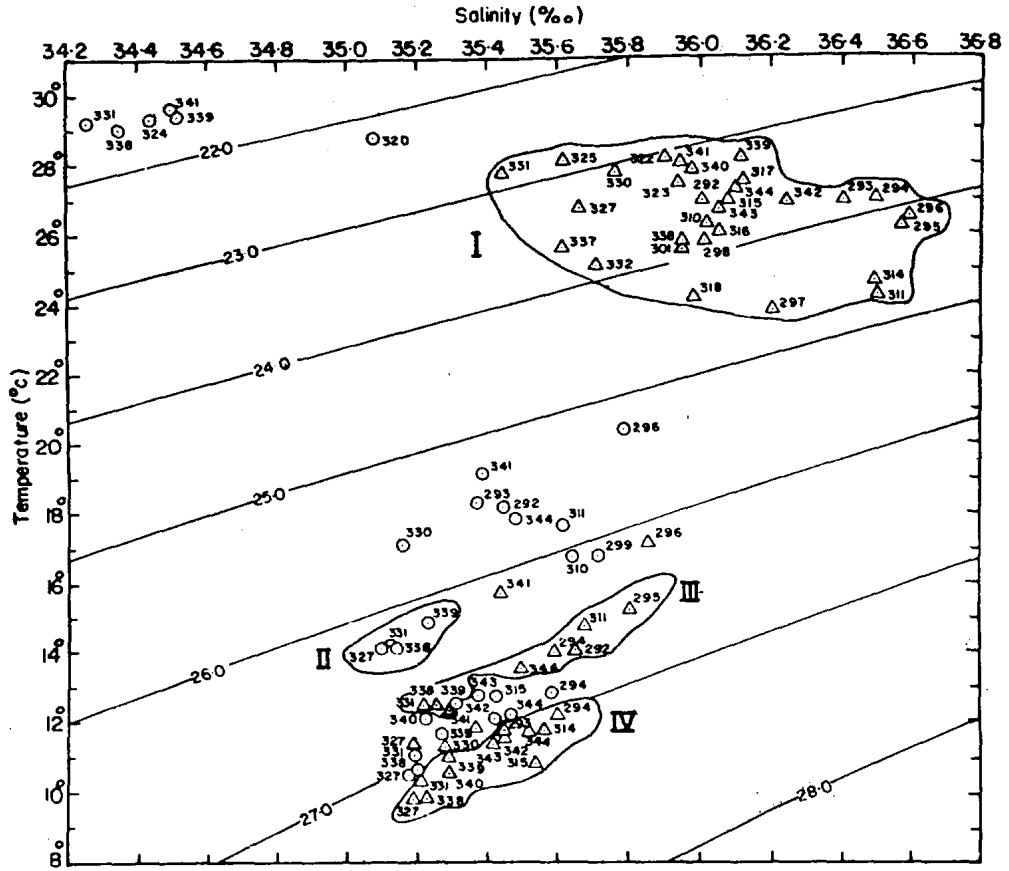


Fig. 7—Salinity-temperature characteristics of all salinity maxima (Δ) and minima (\odot) in the upper 1000 m

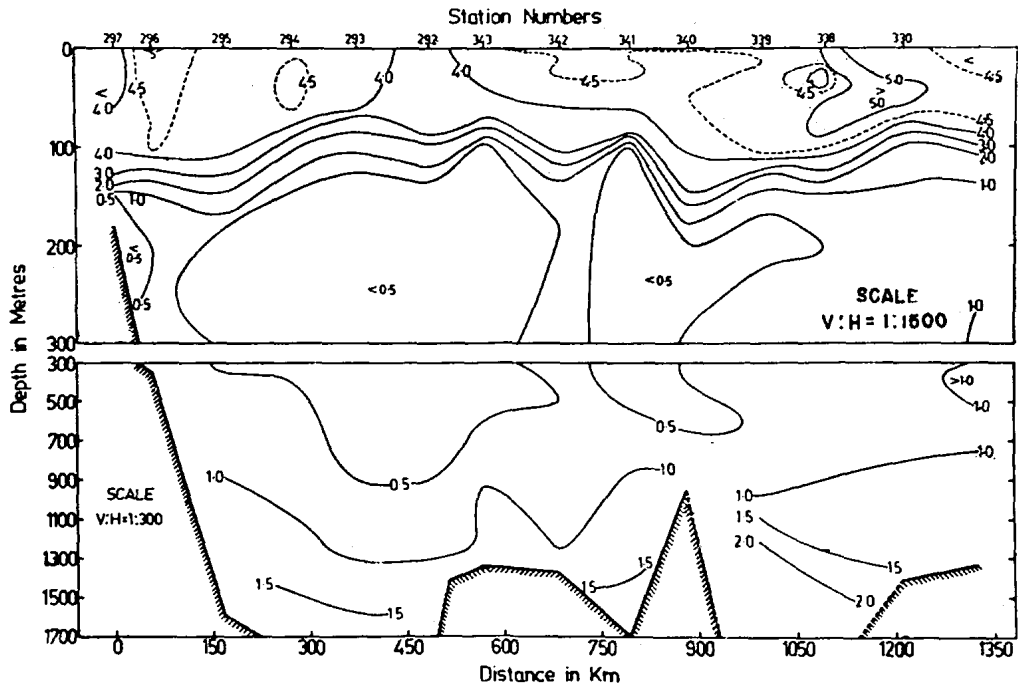


Fig. 8—Dissolved oxygen along section P₂

Table 1—Characteristics of Water Masses along the West Coast of India

[Values represent range]

	Temperature (°C)	Salinity (‰)	Depth (m)	σ_t
Arabian Sea high salinity water				
O	24-28	35.5-36.6	50-100	23.0-24.7
R	20-28	36.0-36.3	75-100	23.2-24.7
W	26-28	35.8-36.2	~60	~24.0
Sub-surface Equatorial water				
O	14-15	35.1-35.2	~200	26.2-26.3
Persian Gulf water				
O	12-15	35.2-35.8	200-300	26.6-26.8
R	10-16	-do-	250-300	26.2-26.8
W	12-15	-do-	~280	~26.6
Red Sea water				
O	10-13	35.2-35.6	400-600	27.0-27.3
R	7-13	35.2-35.7	375-500	-do-
W	10-12	35.2-35.6	~570	~27.2

 O = Observed; R = Rochford¹; W = Wyrski²

influence of the Persian Gulf water is less significant in the extreme southeastern Arabian Sea and the equatorial regions respectively.

South of 17°N, the presence of Red Sea water is indicated in 400-500 m as several salinity maxima in this depth range are seen to fall around σ_t 27.1 (Fig. 7). Sastry and D'Souza²¹ have also pointed out the conspicuous absence of Red Sea water in the northern Arabian Sea. It spreads south along the west coast and loses salinity from 35.6 to 35.2‰. The depth of this salinity maximum is fairly constant along the coast (~450 m) and is in agreement with Rochford¹ whereas Wyrski² has indicated its presence at relatively deeper depths of about 570 m (Table 1).

Salinity minimum, observed around 300-500 m at most of the stations, appears to be clearly due to sandwiching effect of the 2 high saline water masses (Persian Gulf and Red Sea waters) spread at different depths. This minimum cannot be attributed to the movement of intermediate low salinity water mass as

observed in the other areas of the Arabian Sea, due to the conspicuous absence of oxygen maximum associated with the salinity minimum.

Acknowledgement

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