

Observations on Fine Structure in the Northern Arabian Sea

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Vertical profiles of temperature and salinity, obtained using a STD recorder, from the northern Arabian Sea revealed the presence of fine structures characterized by homogeneous layers separated by interfaces. The layers were generally regions of low stability. Fluctuations of temperature and salinity were maximum in the thermocline (about 0.5°C and 0.2‰ , respectively). Temperature showed an increased fine structure activity with the formation of seasonal thermocline. Deeper waters, below thermocline, showed the fine structure activity with less amplitudes of fluctuations and larger layer thicknesses. Blobs of temperature and salinity at about 180 m observed in the thermocline near the mouth of Persian Gulf may be due to gross overturning of internal waves. Possibility of double-diffusion as a causative factor for the layerings is also discussed.

FINE structures, (temperature and salinity structures of vertical scales from 1 to about 100 m) are observed everywhere in the sea and have become a subject of considerable interest. Continuous profiling systems have revealed many features which eluded conventional discrete sampling methods. Temperature and salinity do not vary smoothly with depth, but have many small structures superimposed on smooth profiles. The study of such structures is important as some of the mechanisms causing them are very efficient in the vertical transport of heat and salt.

A region rich in fine structure that has been studied in much detail is north-east Atlantic where the layers are found below the Mediterranean waters¹⁻³. Pingree⁴ has found that the microstructures are density compensating and attributed them to the lateral spreading of water masses. Dye experiments and observations using high resolution probes have shown that microstructures observed in Mediterranean thermocline are due to billow turbulence⁵ which derives energy from mean flow. Studies on fine structure have been carried out in the thermocline of Pacific using a towing system⁶. Roden⁷ also has studied temperature and salinity fluctuations with depth in Pacific.

Fluctuations of temperature and salinity in the thermocline can be caused by many factors like seasonal heating, advection, long period surface waves and internal waves. Overturning of internal waves and shear instabilities can also generate turbulent fluctuations. No information is available on fine structures from northern Arabian Sea, the region of present study. Hammon's study of medium scale structures is restricted to the western Indian Ocean⁸.

Methods

During the OCEANAVEX (oceanographic ravel expedition) a self-recording Bisset-Berman STD graphic profiler was used for collecting data for

fine structure studies. Data collection was undertaken from February to May 1974 and the area of study was beyond the continental shelf off Bombay to off Iran. The instrument gives an analogue record of temperature and salinity against depth with accuracies of $\pm 0.1^{\circ}\text{C}$, $\pm 0.05\text{‰}$ and ± 5 m for temperature, salinity and depth respectively and with respective resolutions of 0.05°C , 0.02‰ and ± 2 m. The instrument was lowered at a speed of 40 m/min. STD was operated up to 2000 m which is the range of instrument. Out of a total of 84 records, 50% were good traces, while in the remaining cases either the instrument failed or the noise was too much for fine structure studies.

ASTD record is shown in Fig. 1a. The temperature records were generally good, while salinity traces showed undesirable spikings at regions of high temperature gradient due to imperfect matching of the time constants of the temperature and salinity sensors. Thus the features A in Fig. 1b (blow up of upper part of Fig. 1a) are artifacts of the instrument. However, during digitization care was taken to avoid its effects. Slight difference in the depths of temperature and salinity structures are due to an offset of the pens.

Results

Some of the salient points of gross features are mentioned here. A deep mixed layer of about 100 m was present in northern part of study area during February. Observations made off Kathiawar in the same month showed the breakdown of main thermocline and the formation of seasonal thermocline. This is in agreement with earlier studies⁹. Seasonal thermocline was, however, noticed in the region further north during early April, indicating that the effect of summer heating spreads within a month to the head of the Arabian Sea. Seasonal thermocline is shown in Fig. 2. The observations made off Bombay, during May, showed that the main thermocline merged with seasonal thermocline

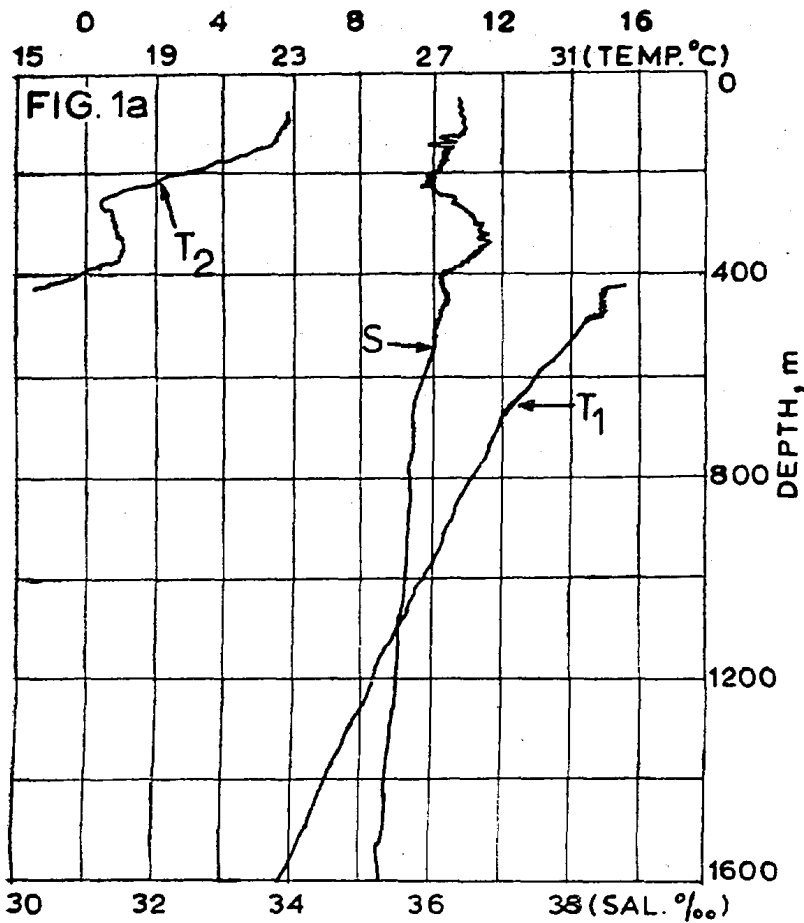
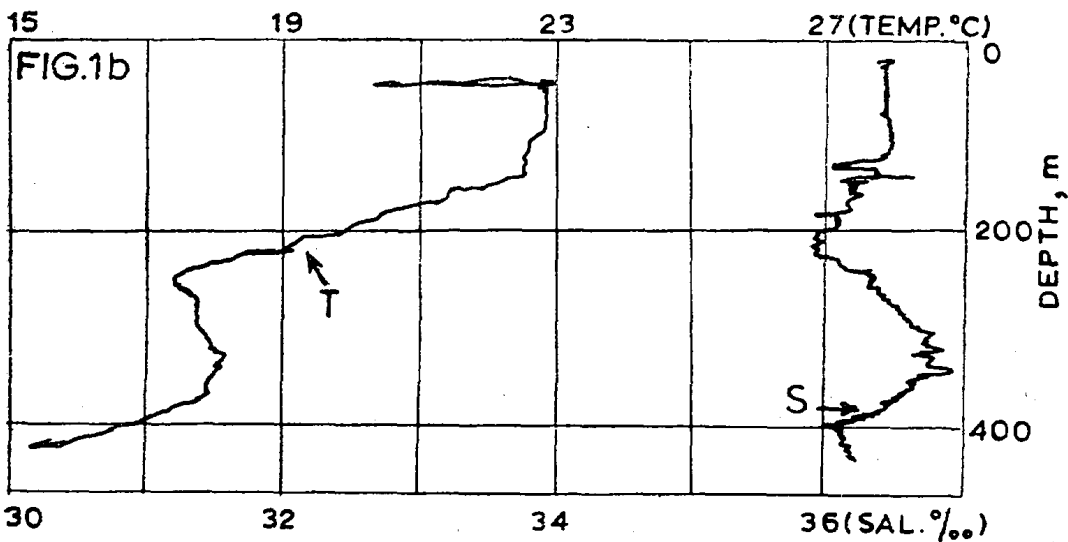


Fig. 1 — (a) STD record showing continuous profile of temperature (T_1 and T_2) and salinity (S) with depth. (b) Enlarged picture of the upper part of (a) (T —temperature and S —salinity)



leaving a very shallow mixed layer which is characteristic of the period of intense heating.

The entire depth range was divided into 2 zones in the following study depending on the nature of fine structures, the upper region (0-400 m) of intense activity and lower deep region (below 400 m) of comparatively less activity.

Layers in the thermocline — Apart from the inversions and the salinity maxima and minima, characteristic of this region, thermocline showed complex structures. Weak inversions, sharp dis-

continuities, homogeneous layers and steps were observed. Temperature and salinity layers had a thickness of 2-30 m, the majority being in the range of 5-20 m. One particular feature of temperature which appeared to be formed by the merging of 3 layers had thickness of about 40 m (Fig. 3a). With the formation of seasonal thermocline many small layers of about 2 m were observed. The effect of the formation of seasonal thermocline on salinity structures, if any, could not be ascertained due to the spiking in the trace. Temperature

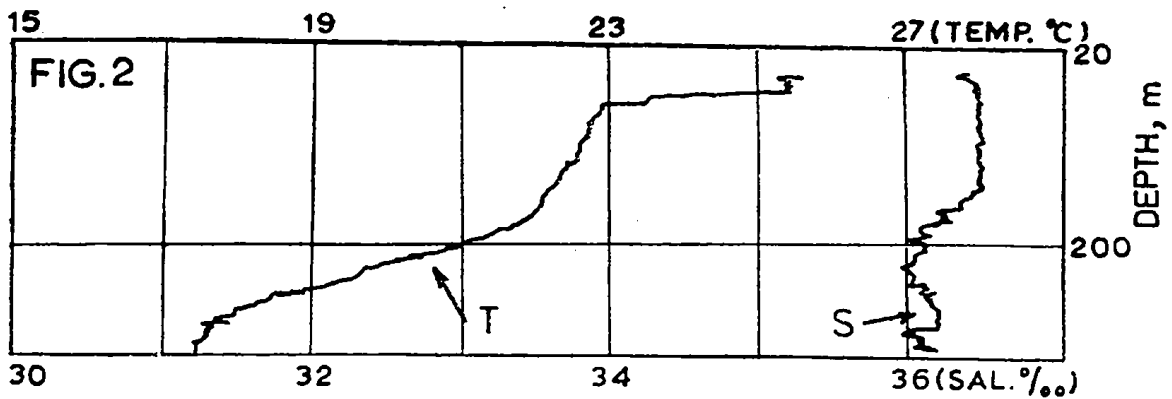


Fig. 2 — Record depicting seasonal thermocline (T-temperature and S-salinity)

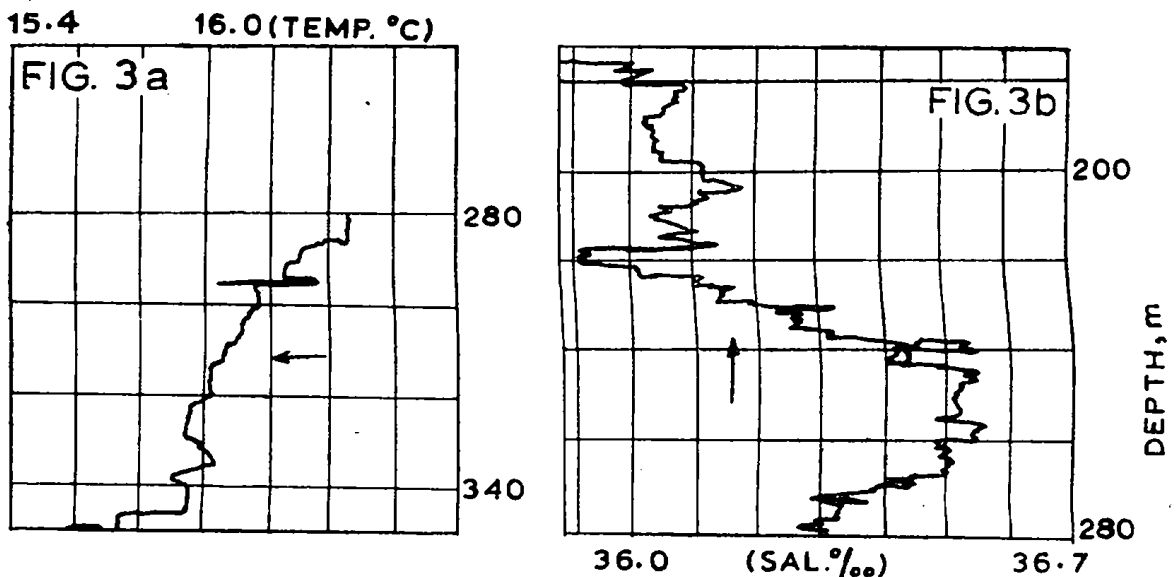


Fig. 3 — (a) Formation of a thick temperature layer. (b) Salinity step formed by the merging of several steps

fluctuations at the interfaces varied, generally, from 0.1° to 1°C with a maximum value of 1.8°C. Majority of salinity variations were between 0.02 and 0.3‰. However, high value of about 0.4‰ was observed at steps which looked like the formation of few steps (Fig. 3b).

Thickness of temperature interfaces were mostly about 2 m. However, thick interfaces of about 5-10 m were also present. Some smooth steps which appeared to be formed by smoothing of a series of steps had a thickness of about 20 m. Thickness of salinity interfaces ranged from about 2 to 15 m and majority were <10 m.

Layers below thermocline — Below 400 m, both temperature and salinity decreased with depth (Fig. 1). Thickness of temperature layers varied from 5 to 25 m, majority being between 10 and 20 m. As many as 20 layers were observed in 1 trace. The interfaces were smooth. However, superimposed on them were very small sharp steps which were not well resolved. Temperature variations at the steps were from 0.05 to 0.1°C. Unlike those observed in the thermocline, the structures of temperature observed before and after the formation of seasonal thermocline were similar. Salinity layers

were thicker and varied between 40 and 100 m. Very thick layers of 160 m were also observed. The discontinuities were sharper and the thickness ranged from 2 to 5 m. Still smaller steps though seemed to be present were beyond the resolution of the instrument. Salinity changes ranged from 0.01 to 0.1‰. However, an extreme value of 0.2‰ was observed.

Discussion

Most of the temperature and salinity layers were density compensating and were of low stability, running parallel to the σ_t lines. The thickness of layers increased with depth while the amplitude of variations decreased. Similar features were reported from north Atlantic¹⁰. Hamner⁸ found that the amplitudes decreased with depth. He also observed the layers to have a horizontal extent of 5-10 km. In the Irish sea, layers of 1-10 m thickness were found to have a horizontal extent of 1-3 km¹¹. During the present study the horizontal extent of the layers could not be ascertained properly as the stations were separated by about 55 km. However, few structures of about 20 m thickness

were observed in the thermocline of neighbouring stations in somewhat similar forms.

Double-diffusive convection — When both temperature and salinity decrease with depth — each contributing in the opposite sense towards density — salt fingers can be set up. Salt fingering is one of the double-diffusive processes and extensive studies on double-diffusion have appeared¹²⁻¹⁴. These processes are capable of producing layerings. The present study area of the Arabian Sea is characterized by the presence of high saline waters in the upper layers, below which both temperature and salinity decrease with depth. As this is the favourable condition for salt fingers to develop, the deeper parts of the study region is a potential area for the formation of finger like convection and layerings as its consequence.

Linder¹⁵ studied formation and destruction of fine structure by double-diffusive processes in the presence of inherent variation in properties (as observed in nature). He further extended his results on 'diffusive regime' to the 'fingering' case to explain the increasing layer thickness with depth reported from Tyrrhenean Sea. In the present study also an increase in layer thickness was observed with depth. The temperature steps were, however, diffuse in deeper regions. This can happen if the limiting conditions are reached and further breakdown is due to molecular diffusion. As the heat diffuses faster, the temperature profile will be smoother.

Fine structures can be destroyed by the merging of layers to form larger layers homogenous in temperature and salinity¹⁶. This may be the cause for some of the structures observed in the thermocline (Fig. 3a and b). Exactly similar features were, however, not observed for the other solutes, viz. salinity and temperature corresponding to those in Fig. 3a and b respectively (not shown in figure). As the conditions in nature are different from those in the laboratory such deviations are expected,

specially in the thermocline where other factors like effect of surface waves, billow turbulence, etc. can be more pronounced. Horizontal variations of properties can also produce double-diffusion. Such variations are present in the upper region of the study area and might have contributed to the observed steppy structures. Garret⁶ observed increased mixing at local sites where both temperature and salinity either increased or decreased with depth and attributed them to double-diffusive instabilities. The presence of such local sites in the upper region of the study area, presumably due to interleaving of water masses, is also likely to contribute to layering.

Internal waves — Some of the features observed at 2 or 3 neighbouring stations at different depths (within 10-20 m) seemed to be related. This might be due to the presence of internal waves which undulated the medium. Some interesting features observed at a station in the northern part of study area (24° N and 61°23' E) are shown in Fig. 4. A double maxima of temperature and salinity in the thermocline and a homogeneous layer of about 35 m thickness around 180 m were observed. Such features are possible from interleaving of water masses near the entrance of Persian Gulf. Even though inversions or layers of uniform temperature associated with Persian Gulf salinity maximum were observed in the northern region of study area at about 350 m, the features of Fig. 4 were absent, save, somewhat similar structures found at about 55 km west and 110 km south of this station. T-S diagram also showed the presence of a loop-like structure. Hence, this solitary feature found at this station at about 180 m depth must have some causative factor other than advection. Though double-diffusion is capable of generating layers, it cannot be responsible for large inversions like those observed at the depth of about 180 m as seen in Fig. 4. Theoretical and laboratory studies¹⁶ have proved that internal

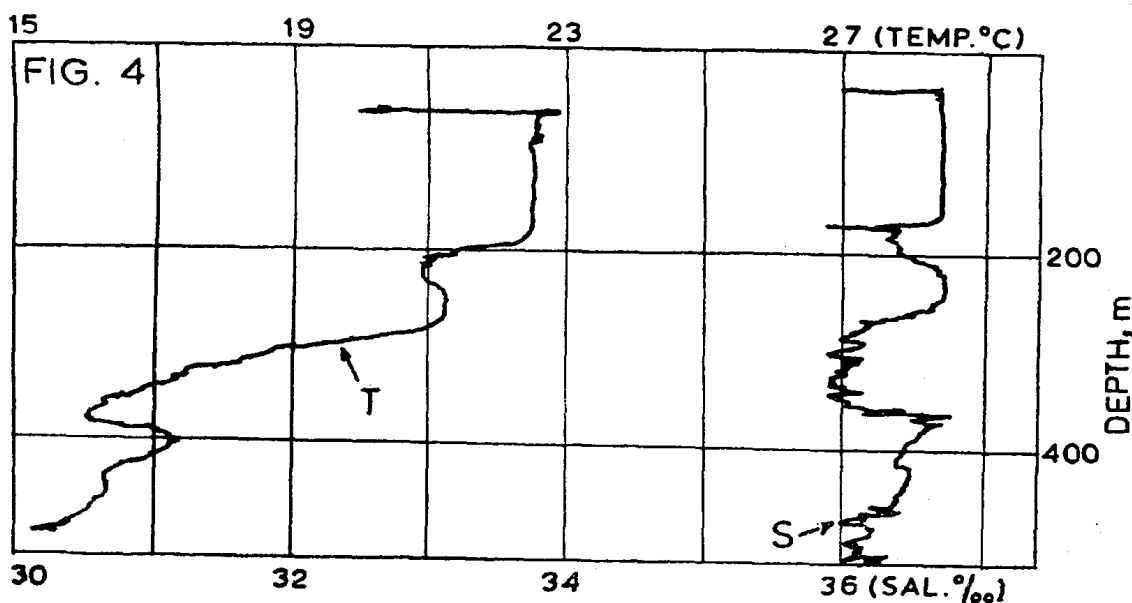


Fig. 4 — Trace showing a double maxima in the thermocline (T — temperature and S — salinity)

waves break as their amplitude increases. This gravitational overturning can generate blobs in the vertical profile which are later smeared out by other agents to produce homogeneous layers. Thus the blobs of temperature and salinity observed at this station appears to be caused by the breaking of internal waves in the immediate vicinity of this station. Though the horizontal velocity measurements were not available to check the breaking criterion, N^2 (N is the Väisälä frequency) showed negative values at this station indicating instability probably caused by breaking of internal waves. At a neighbouring station (about 55 km south) stratification was stable. As breaking of an internal wave may not completely destroy the wave structure, in the neighbouring stations either the waves did not break or the features caused by breaking were modified by other agents. Foster and Carnak¹⁷ suggested that the breaking of internal waves might be the cause for the temperature and salinity steps observed in the Weddel Sea.

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