Observations on the relationship between scattering layer and mixed layer

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High-resolution (stations at every 3 nautical mile interval) physical oceanographic measurements were carried out in the shallow waters (<150 m depth) of northeastern Arabian Sea during December 2003. Temperature and salinity data showed tri-layer structure, i.e. a strong thermocline sandwiched between an upper and a bottom homogeneous layer. Thickness of the surface homogeneous layer varied between 20 and 60 m, while that of the bottom layer varied from 23 to 85 m. Thermocline thickness varied from 7 to 20 m and the respective gradients from 0.12 to 0.4°C/m, with maximum gradient coinciding with minimum thickness. The temperature and salinity structure revealed two distinct watermasses in the surface and bottom homogeneous layers, with a strong thermocline in the transition zone. The dynamically unstable conditions in the upper and lower homogeneous layers and highly stable conditions in the thermocline result in the formation of the tri-layer structure in this region. When the thermocline was strong, the scattering layer was well demarked, whereas the layer was not well demarked when the thermocline was weak. Gradient in the thermocline is found to restrict the downward transfer of scatterers across the thermocline. This information can be utilized to estimate the depth of the surface mixed layer from echograms with a good degree of accuracy.

SCATTERING of sound at sea is a complex phenomenon because of the interrelated effects of ocean boundaries (surface or bottom) and/or by volumetric inhomogeneities. The intensity of reverberation, defined as that portion of sound received at the hydrophone which is scattered by ocean boundaries or by volumetric inhomogeneities, varies with the scatterers and also with the intensity of transmitted signal[1]. Suspended sediments, planktons, day and night migration of fishes and other species, etc. significantly influence scattering from the water column. The major source of volume scattering in the sea has been established to be biological; scattering depends on the characteristics of the marine organisms or other scatterers. At frequencies greater than 20 kHz, the dominant scatterers are zooplankton[1]. Various types of fish that possess a swim bladder (air-filled sac) are the major scatterers at frequencies between 2 and 10 kHz. In the coastal regions of northeastern Arabian Sea, intense fishing activity is noticed during most part of the year. Moreover, the presence of a comparatively strong thermocline, with surface and bottom isothermal layers, can also prevent the transfer of phyto- and zooplankton biomass, heat and momentum transfer, etc. from the surface[2]. Based on data taken from different oceanographic cruises, Pieper[3] has shown that high-frequency echo sounders should produce more detailed scattering profiles corresponding to measurable hydrographic parameters.

Szczucka *et al.*[2] conducted a field study consisting of 90-h series of backscattering measurement using an autonomous hydro-acoustic system with an echo sounder operating at 130 kHz. They have not observed backscattering below a depth where thermocline (~1.6°C/m) was pronounced, which apparently acted as an impassable barrier for vertically migrating organisms. However, for the Indian waters not much information is available on these aspects.

Recently, a high resolution spatial survey was carried out in the shallow waters of northeastern Arabian Sea (<150 m) during 17–23 December 2003, with stations at every three nautical mile interval (99 stations over a grid of 30×30 nautical miles). Vertical profiles of temperature and salinity were collected from these stations using a mini CTD system (accuracies: temperature $\pm$ 0.01°C, salinity $\pm$ 0.02 PSU, pressure $\pm$ 0.02% of 500 m). Inter-comparison of the mini CTD system was carried out with a CTD system available on-board various vessels, and other temperature-measuring instruments. The analysis revealed good agreement in the temperature and salinity values measured using various instruments. In addition, bathymetry data were collected along entire transects using MarimaTech, Denmark Echo-sounder operating at 33 kHz. During the survey, echogram and hard copy of oscilloscope displays (strength of echo signal versus distance) from the echo-sounder were also collected simultaneously with CTD casts from 37 stations covering different times of the day. The noisy and inconsistent bathymetry data were not considered while processing.

Generally, the ocean thermal structure consists of a homogeneous layer of few metres thickness in the upper layers, followed by a layer of strong stratification and a layer of weak stratification. In the northern Arabian Sea, with the onset of winter cooling, the surface homogeneous layer starts deepening, attaining more than 100 m depth during February/March[4,5]. Kumar and Prasad[4] attributed the deepening of the surface homogeneous layer to enhanced buoyant mixing process induced by enhanced evaporation and reduced insolation. Their results were mostly based on data collected from deep waters. However, our high-resolution data collected from the shallow waters of northeastern Arabian Sea during the initial stages of winter cooling, show some interesting features. Typical temperature and salinity profiles presented in Figure 1 highlight these features. These profiles are taken from three different locations along a transect perpendicular to the coast, where the depth is 50 m (Figure 1 *c*), 75 m (Figure 1 *b*) and 125 m (Figure 1 *a*). In all profiles, a strong thermocline is found to be sandwiched between an upper and a lower isothermal layer. Similar features are noticed in the salinity profiles also. This type of vertical structure, i.e. a strong thermocline/halocline sandwiched between surface and bottom homo-

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geneous layers, is known as a tri-layer structure. However, the characteristics of the profiles, viz. thickness of the upper and lower homogeneous layers, thickness of the thermocline and its gradient, show large variability both on spatial and temporal scale. In general, thickness of the surface homogeneous layer varies from 30 (Figure 1 *c*) to 65 m (Figure 1 *a*), while in the case of the lower layer the variability is from 20 (Figure 1 *c*) to more than 35 m (Figure 1 *b*). The most striking feature is the presence of a sharp thermocline (0.22°C/m in Figure 1 *b* to 0.14°C/m in Figure 1 *c*) over a small depth range. Thickness of the thermocline is of the order of 15, 7 and 5 m respectively, in Figure 1 *a–c*.

It is worth mentioning that similar variability is noticed in the salinity profiles also, which is quite unique. The temperature and salinity fields clearly indicate the presence of two distinct water types in the upper and lower homogeneous layers. The upper homogeneous layer in the shelf region (Figure 1 *b*, *c*) is occupied by waters with comparatively higher temperature and lower salinity than in the lower homogeneous layer (difference of 0.2 PSU in Figure 1 *b* and 0.3 PSU in Figure 1 *c*). However, beyond the continental slope (Figure 1 *a*), comparatively warm and high saline water is found to be present above the cold and low saline water (difference of 0.4 PSU). The contrasting feature observed in the thermohaline fields between the continental shelf and beyond the slope region may be associated with the prevailing circulation pattern, which needs to be investigated further.

The Richardson number *Ri*, a measure of the degree of turbulence in the water column, is much greater, 0.25 in the thermocline/halocline zones, while in the rest of the water column it is less than 0.25. This situation indicates dynamically stable conditions in the thermocline and unstable conditions in the upper and lower homogeneous layers. Static stability ($\delta\rho/\delta z$) also shows similar results. These two criteria suggest that a highly stratified layer is sandwiched between two layers of weak stratification, which is responsible for the formation of a tri-layer structure in this region.

Even though only a few typical profiles are presented in Figure 1, similar features are observed in the entire region of northeastern Arabian Sea during December. This type

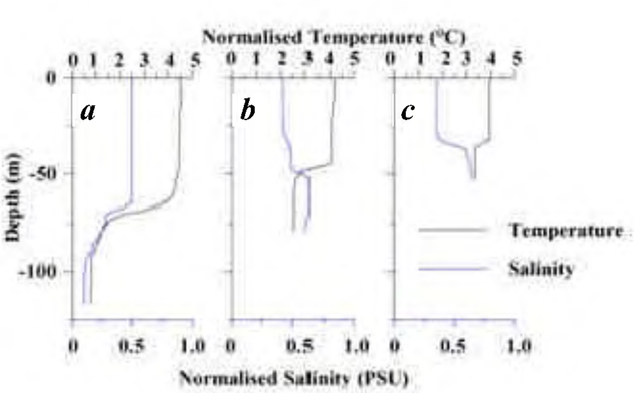

Figure 1. Typical temperature and salinity profiles (normalized).

of tri-layer structure in temperature and salinity profiles has not been reported so far for Indian waters. Studies have indicated that the tri-layer, especially when a strong thermocline/halocline is present, prevents the transfer of biomass, heat and momentum across it. In the following section, the transfer of scatterers across the thermocline is discussed utilizing the echo-sounder data.

During the spatial survey, simultaneous measurements of temperature profiles using mini CTD and echogram with the echo-sounder were collected from 37 stations covering different times of the day. Analysis of the echograms showed a thick patch of layer known as scattering layer, with a demarked boundary in the water column at the surface layer, when the transmitting power was more than 60%. This layer was found to disappear at lower transmitting power (<60%). Thus, to achieve the best result, the transmitting power of the echogram was fixed at 70% of 2 kW transmitting power. The echograms, hard copy of oscilloscope displays (strength of echo signal versus distance) and the corresponding temperature profiles at selected stations, defined as S1, S2, S3 and S4, are presented in Figure 2. In the oscilloscope record, the major signal corresponds to the echo from the bottom at each station. In addition, a secondary signal, though of lesser magnitude compared to the first one, is also clearly evident in all the records. The signal that is scattered at the surface layer is seen in the echogram as a dark patch. On closer examination, it is seen that these signals correspond to the top of the thermocline (Figure 2 *a–d*). Below this depth, the signals are found to be weak. At station S1, the oscilloscope record shows weakening of scattered signal below 50 m depth (Figure 2 *a*). Lower boundary of this layer (48 m) coincides with the top of the thermocline (48 m). Similar results are noticed at stations S2 (Figure 2 *b*), S3 (Figure 2 *c*) and S4 (Figure 2 *d*), where the scattering layer thickness was 50, 34 and 43 m respectively. The corresponding depths of the top of the thermocline at these stations are 47, 37 and 37 m respectively.

Another interesting observation is that when the gradient in the thermocline is strong, the scattering layer is well defined and the corresponding signal in the oscilloscope record is prominent. It is also to be noted that below the thermocline zone, minimum scatterers are found in the echogram. Madhupratap *et al.*[5,6] reported that the Arabian Sea is one of the most significantly productive regions of the world, with fairly high biological production in its northern parts during winter. They also suggested that in this region the concentration of meso-zooplanktons was higher in the mixed layer compared to that at deeper levels. Moreover, their vertical migration appears to be low. The concentration of more scattereres, as evident from the echogram, suggests that the strong gradient in the thermocline acts as a barrier for the transfer of scatterers across it. For example, the thermocline gradients at stations S1, S2, S3 and S4 were 0.17, 0.12, 0.23 and 0.4°C/m respectively. It is to be noted that the scattering layer was well demarked at

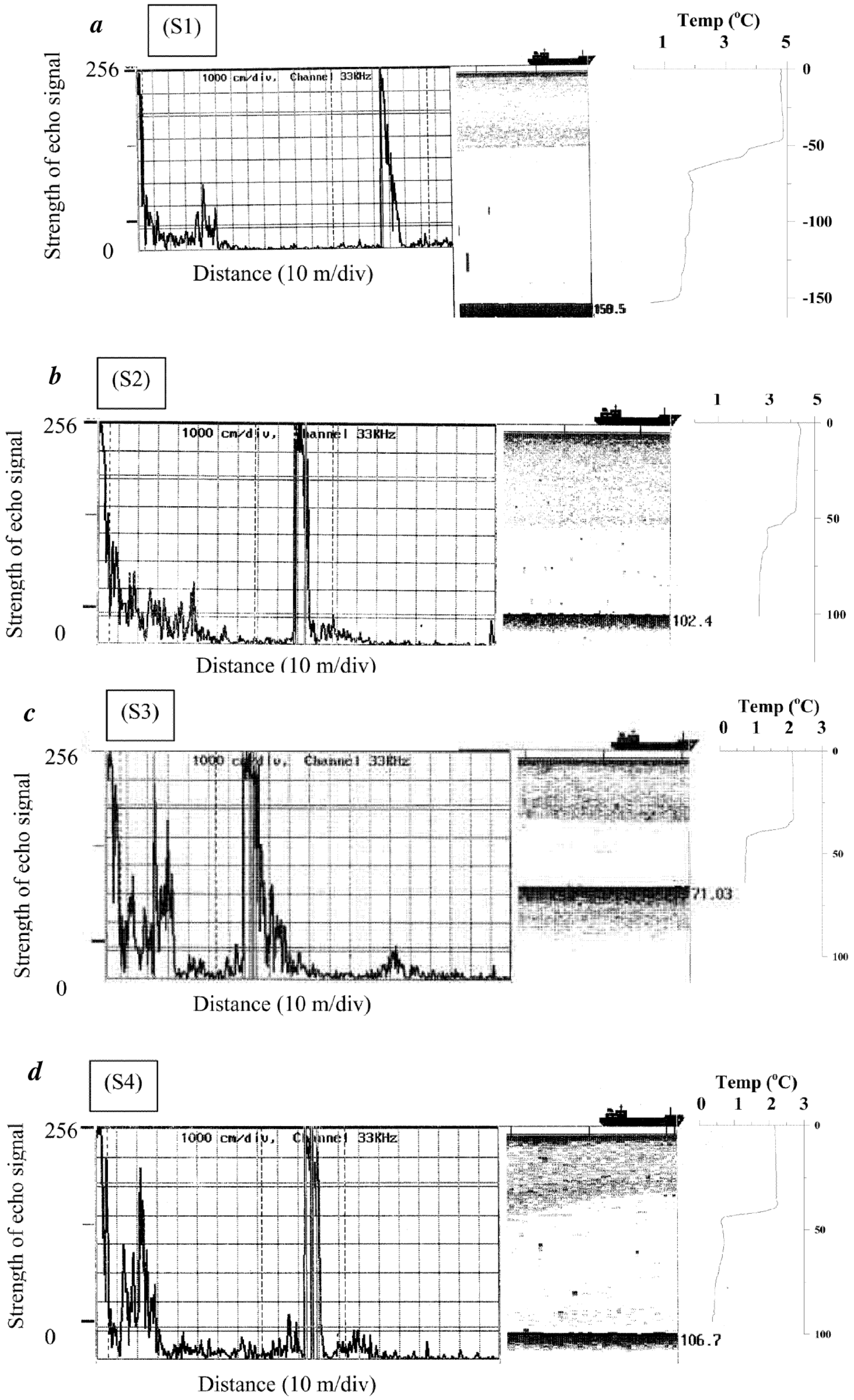

Figure 2. Echogram and temperature profiles at stations (***a***) S1, bottom depth 158 m; (***b***) S2, bottom depth 102 m; (***c***) S3, bottom depth 71 m and (***d***) S4, bottom depth 107 m.

stations S1, S3 and S4, where the thermocline gradient was stronger (>0.17°C). When the thermocline was weak, the scatterers are found to penetrate beyond the thermocline.

Information from echograms is further utilized to study the depth of the surface mixed layer. In the literature, there are several methods to determine the mixed layer depth

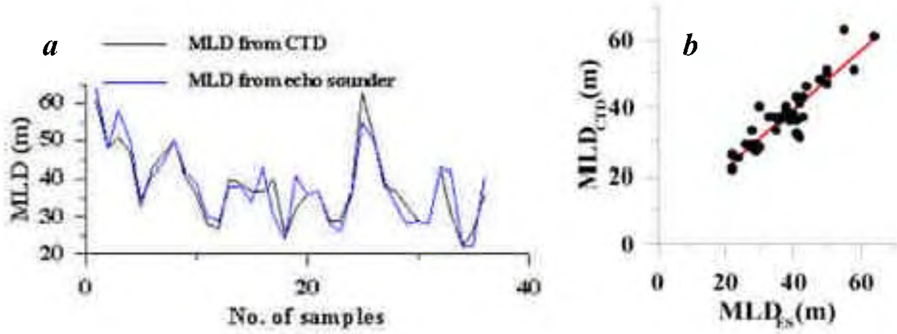

Figure 3. ***a***, Comparison between MLD derived from temperature profiles (MLD_{CTD}) and echo sounder (MLD_{ES}) at typical stations. ***b***, Scatter diagram between MLD_{CTD} and MLD_{ES}.

(MLD), viz. based on temperature, density, sound speed, their gradients, etc. Each method has its own merits and demerits. However, in the present case, as the thermocline gradient is strong, all methods of estimation of MLD will almost focus to the same result. In most diurnal-scale studies, MLD is defined as the depth where 0.2°C drop from sea surface temperature (SST) occurs in individual temperature profiles[7]. Here also, we compared the MLDs derived from individual temperature profiles based on 0.2°C drop from SST, with the thickness of the scattering layer derived from echograms (Figure 3 *a*). Comparison of MLDs derived from both measurements shows good agreement, as indicated by the standard deviation which is less than 4 m. The scatter diagrams between the MLDs estimated from temperature profiles and those derived from the echo sounder (Figure 3 *b*) also showed good linear relationship, which suggests that this approach can be utilized for the estimation of MLDs. The results presented here are preliminary; for conclusive remarks more quantitative data at wide range of frequencies at different seasons are required.

During December 2003, a high-resolution oceanographic survey was carried out in the shallow waters of northeastern Arabian Sea. A mini CTD system was utilized to collect temperature and salinity data from several stations. Temperature data collected from this region showed presence of a tri-layer structure, i.e. a strong thermocline sandwiched between an upper and a lower isothermal layer. Both the static and dynamic stability criteria indicate unstable conditions in the upper and lower homogeneous layers and stable conditions in the thermocline. This suggests the presence of strong mixing processes in the upper and lower homogeneous layers and weak mixing in the thermocline zone, resulting in the formation of the tri-layer structure. Thermocline thicknesses varied from 7 to 20 m and the gradients from 0.12 to 0.4°C/m. The gradient in the thermocline was found to be maximum when thickness of the thermocline was minimum (7 m). It was also found that the magnitude of the gradient in the thermocline restricted the transfer of scatterers across this zone. When the thermocline was strong (>0.17°C), the scattering layer was found to be well demarked. In such cases, a comparatively strong scattered signal is evident in the oscilloscope record. When the thermocline was weak, the scatterers penetrated beyond the thermocline. Comparison of the mixed layer estimated from individual temperature profiles and from the thickness of the scattering layer, showed good agreement. This suggests that the thickness of the scattering layer obtained from the echogram can be utilized to estimate the depth of the surface mixed layer with a good amount of accuracy. The results presented here are the observational evidence elucidating the tri-layer structure in the northeastern Arabian Sea during winter, the relationship between scattering layer and thermocline gradient and the estimation of mixed layer from the echogram. This information is vital in the field of anti-submarine warfare operations.

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