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The Sound Channel Characteristics in the South Central Bay of Bengal

P.V. Hareesh Kumar

Abstract - Environmental data collected along 92.5ºE between 2.7ºN and 12.77ºN during late winter show a permanent sound velocity maximum around 75 m and an intermediate minimum between 1350 m and 1750 m. The axis of the deep sound channel is noticed around 1700 m. The shallower axial depth (~1350 m) between 7.5ºN and 10.5ºN coincides with the cyclonic eddy. Within the sonic layer (SLD), Eastern Dilute Water of Indo-Pacific origin and Bay of Bengal Watermass are present whereas its bottom coincides with the Arabian Sea Watermass. Sound speed gradient shows good relationship with temperature gradient (correlation coefficient of 0.87) than with salinity gradient. A critical frequency of 500 Hz is required for the signal to be transmitted through a channel of 50 m thickness and it increases to ~1 kHz for a layer of 20 m. Within SLD, salinity there is 1.54 m/s increase in sound per 1 psu increase in salinity. In the thermocline, the sound speed decreases by 1.95 m/s per degree drop in temperature, whereas at deeper depths pressure effect dominates (@ 1.4 m/s per 100 m depth).

Index Terms - Bay of Bengal, Sonic Layer Depth, SOFAR Channel, Critical frequency, Watermass.

I. INTRODUCTION

Information on the sound speed structure of the ocean is very much essential in a wide range of scientific and strategic applications. It is the prime source of energy to probe into the ocean interior, as the ocean is almost opaque to the electromagnetic radiation. Strategically sound is used for long range underwater communication, detection of underwater targets, etc. It is a common source to determine the depth of the ocean. Acoustic tomography is a tool for monitoring the large scale oceanic features [1]. In the ocean, the propagation of sound depends on temperature, salinity and pressure. Out of this, pressure does not show any seasonal or spatial variation; but only changes with depth. On the other hand, temperature and salinity shows both temporal and spatial variations. Generally, sound speed is estimated from the depth, temperature and salinity using standard equations. In the surface layers, sound speed increases with depth. The depth upto which the sound increases in the vertical is known as the sonic layer depth (SLD) or the surface duct. Generally, temperature is uniform within the SLD, but salinity may increase with depth. Within the SLD, sound rays from a shallow source propagate with multiple reflections from the sea surface. If the sea surface is smooth, these rays remain in the surface layer regardless of the distance from the source. SLD has immense operational implications in the underwater research.

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At deeper levels, the sound speed increases with depth, as the hydrostatic pressure increases and temperature variation is not significant. This "channeling" of sound occurs because of the presence of a minimum in the vertical sound speed profile. The axis of the channel is defined as the depth where the minimum sound speed occurs in the profile. The subsurface duct centered on the axis of the channel is known as the SOFAR channel. Critical (limiting) depth is that depth where the sound velocity is equal to the maximum sound velocity at the surface or in the surface mixed layer. Sound from a source within the channel gets trapped by refraction and travels over long ranges with little loss. Since sound absorption in sea water is very small at low frequencies, the energy propagates to very long ranges. In majority of the observational programmes, the temperature and salinity measurements are limited to the upper 1000 m the water column, as there is as the variability is less below this depth. A major problem that hinders the acoustic studies in the ocean is the non availability of sound speed profiles upto the bottom. The availability of CTD data upto the bottom with closely sampled stations on the western side of the Andaman Nicobar islands prompted to study the variability in the surface and deep channel characteristics of this region. In spite of the strategic and scientific importance of sound speed, only few investigators [1]-[-6] explained the acoustic behavior of the BoB. Therefore, any study in this regard will enhance the understanding of the physical and dynamical nature of the BoB, and hence to the acoustic community.

The paper is oriented as follows. In the first section, the temperature and salinity data are utilized to document the sound speed characteristics in the BoB between the equator and central BoB. The departure between the mixed layer based on the temperature (MLD) and sonic layer (SLD) is discussed. Finally, the latitudinal variation in the surface and deep sound channel characteristics and the lower cut-off frequency for the near surface sound channel is discussed.

II. RESULTS AND DISCUSSION

Temperature and salinity data were collected upto the bottom using a CTD system onboard RV Knorr in February, 1995 between 2.9ºN and 12.7ºN along ~91.5ºE (stations at 30 nautical mile intervals); west of Andaman Nicobar Islands (Fig. 1). Utilizing this data, the sound speed is estimated following the equation of Chen and Mellero [7]. In this study, mixed layer, hereinafter referred to as isothermal layer (MLD), is defined as the depth at which a drop of 1ºC from the surface temperature occurs in the individual temperature profiles.

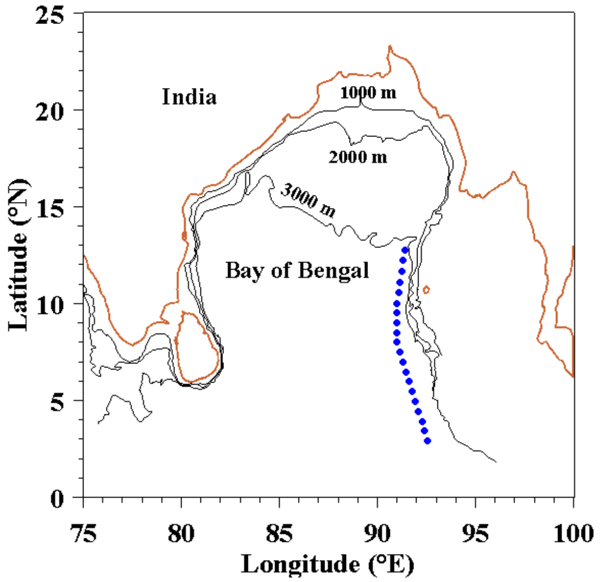

Fig. 1 Blue dots indicate station locations. Twenty stations, each separated by 55 km, were covered during the survey.

A. Composite profiles of temperature, salinity and sound speed

The composite profiles of temperature (Fig. 2a) show an isothermal layer (MLD) of 40-80 m thickness with temperature 27° - 30°C. Within the MLD, salinity increase upto 75 m depth (from 32.3 psu at the surface to 35.5 psu at 75 m) resulting in a highly stratified (0.043 psu/m) surface layers (Fig. 2b). Figure 2 also shows marked difference between the isothermal layer and isohaline layer that leads to the formation of a barrier layer. The isothermal layer is capped by a seasonal thermocline with gradient in excess of 0.9°C/m (17°C between 50 m and 250 m). Below the seasonal thermocline, the gradient is <0.005°C/m below upto 2000 m, which further reduces to <0.001°C/m below 2000 m. The marked variability in the water characteristics in the surface layers between the equator and northern BoB [8], results in a spread of ~3°C in temperature and 2.5 psu in salinity. In the temperature field, the spread increases to 5.5°C towards the upper thermocline and reduces thereafter. Similar observations are also reported in [8], where they attributed the salinity variations to freshwater influx. The temperature and salinity profiles together suggest that the study region is highly stratified and can be visualized as a two layer system. Figure 2c shows a permanent upper sound velocity maximum (around 75m) at velocities less than 1545 m/sec and an intermediate minimum (between 1350 m and 1750 m) at velocities between 1492 and 1493 m/sec. Within the SLD, the sound speed increases by 1-2 m/s. In the present case, the critical depth is found to be around 95m. As the sound speed at the bottom (~1527 m/s) is less than the value at the top of the SOFAR channel (1544 m/s), its bottom depth and hence the channel thickness could not be defined. Prasannakumar [1] also reported similar situation in the BoB. This situation is referred to as the depth limited SOFAR channel.

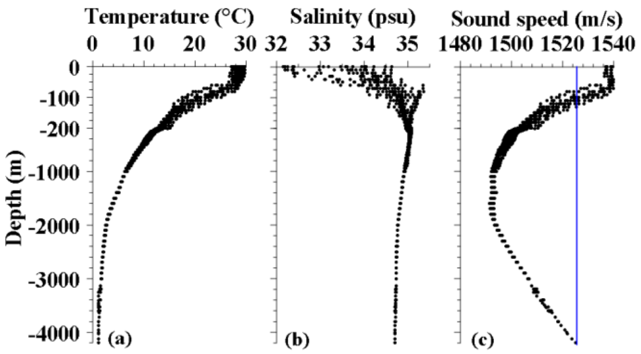

Fig. 2 Composite profiles of (a) temperature, (b) salinity and (c) sound speed upto the ocean bottom. Blue line is drawn to show the depth limited SOFAR channel. As the variability is more in the surface layers, surface to 200 m depth is enlarged in the figure.

In the surface layers (Figs. 2, 3), two different watermasses exists, the Eastern Dilute Water (EDW) of Indo-Pacific origin [8] and the Bay of Bengal Watermass [9] (BBW). The EDW occupies the upper 10 m at 10°N and extends upto a depth of 30 m at 12.77°N. This water is present in the salinity and temperature indices of <31 psu and 27°C respectively and sigma-t level less than 21. The BBW occupies the upper 50 m of the southern Bay (south of 10°N) with thermohaline indices of 25-29°C and 32.0-34.5 psu respectively and sigma-t of 21.0-22.0. The two watermasses, EDW and BBW are confined within the SLD. The subsurface salinity maximum (35.3 psu) noticed below 75 m is associated with the Arabian Sea Watermass [10]-[12] with sigma-t of 23-24. The sound speed maximum coincides with the top of the subsurface salinity maximum associated with the ASW.

B. Vertical sections of temperature, salinity and sound speed

To further investigate the depth-space variability in the temperature, salinity and sound speed between the equator and central BoB, their vertical sections are presented in Figure 3. A noticeable observation from Figure 3 is the gradual ascending of isolines from equator towards the central BoB. This causes progressive cooling towards the central BoB, but with different magnitudes; cooling of ~2°C between 2.9°N and 6.47°N, weak cooling (0.05°C) between 7.5°N and 10.55°N and cooling of 1.12°C between 10.55°N and 11.68°N (Fig. 3a, d). In the thermocline also, similar ascending nature of the isolines is evident. For example, the 10°C isotherm (Fig. 3d) shoals by 130 m within a distance of ~1075 km in the south-north direction (from 560 m at 2.9°N to 430 m at 12.77°N). Moreover, thickness of the seasonal thermocline reduces from 120 m at 2.9°N to 100 m at 12.77°N, but the vertical gradient increases from 0.1°C/m to 0.12°C/m. In the salinity field, the vertical gradient is ~0.025 psu/m in the upper 50 m near the equator and 90 m at 12.77°N follow by near homogeneous water towards the deeper depths (Fig. 2b, 3e).

Along the track, two bands of saline water (>34 psu) sandwiched between fresher water (<34 psu) on either side forms (Fig. 3b, e). The SSS increases by 1.25 psu between 2.9°N and 6°N and 0.93 psu between 8°N and 9.5°N.

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The surface layers are cooler in the region of saline water and warmer in the fresh water region. To the north of 9.5ºN, there is a sharp decline of 1.85 psu in the salinity (34 to 32.15 psu) and ~1ºC in temperature upto 10.55ºN. The low salinity water in this region during winter is attributed to the runoff from the river Irrawaddy [8]. In spite of this regional variation, the SST and SSS increase by 2.9ºC and 1 psu respectively between the equator (30.4ºC and 33.2 psu at 2.9ºN, 92.57ºE) and central BoB (12.77ºN, 91.38ºE). This suggests that the equatorial region is warmer and saline compared to the central BoB.

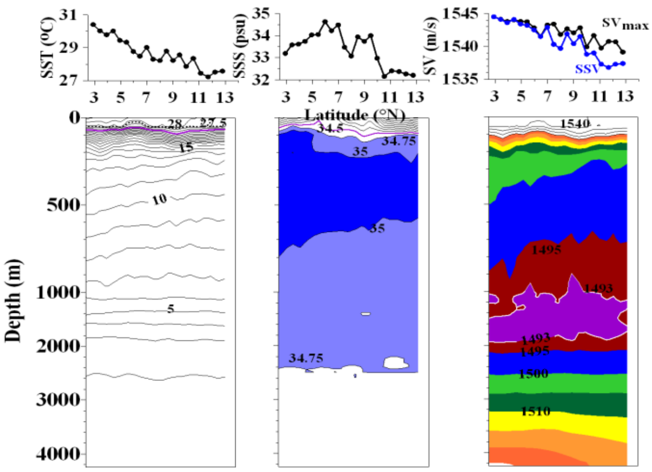

Fig. 3 South to north variation in (a) sea surface temperature, (b) sea surface salinity, (c) surface sound speed, subsurface sound speed maximum and vertical sections of (d) temperature, (e) salinity and (f) sound speed. Dashed line indicates 27.5oC isotherm. Maroon line represents 25oC isotherm in the temperature and 34.5 psu in the salinity fields.

The noticeable observation in the salinity field (Fig. 3e) is the subsurface maximum with core salinity (Smax) in excess of 35 psu, present between 50 - 800 m near the equator (2.9oN) and 220 - 580 m in the central BoB (12.77oN). South of 5oN, Smax is more than 35.2 psu at its core depth (DSmax) of 100 m. To the north of this latitude, Smax drops to less than 35.05 and DSmax deepens to 250 m. Varkey et al. [8] reported a slightly deeper core, i.e. 350 m in the nearby region. The opposing movement of isolines (35 psu) in the upper and lower halocline reduces the thickness of the subsurface core by more than a double fold towards the central BoB (750 m to 360 m). In February, two bands of cold (<28oC) and saline water (34 psu) centered at 6.47oN and 9.5oN sandwiched between warm and fresh water on either side forms (Fig. 3). The upheaval of isolines is more discernable in the salinity field and increases the surface salinity in those regions. Utilizing the hydrographic data collected during the northeast monsoon, Rao and Murty [13] attributed the doming of isolines to the cyclonic eddy form west of the Andaman Islands. This cyclonic eddy shoals the 28oC isotherm from a depth of 62 m at 5.44oN to 40 m at 6.47oN, i.e. a vertical displacement of about 22 m. In the thermocline, the corresponding upwards displacement, as indicted by the 20oC isotherm, is 30 m (110 m at 5.44oN to 80 m at 6.47oN). Towards deeper depths, signature of the eddy is not discernible as doming tapers off below 200 m depth. The eddy drops the ambient temperature at 100 m by more than 3.5oC and increases salinity by 0.2 psu. In between the cyclonic eddies; salinity varies by 0.25 psu, i.e. between 34.25 and 34.5 psu in the former case and 33.75 to 34 psu in the latter.

The changes in SSS and SST causes a variation of ~7.1 m/s in the sound speed at the surface between the equator and central BoB (Fig.3c,f), with equatorial water having high sound speed (1544 m/s at 2.9oN to 1537 m/s 12.77oN). Interestingly, south of 6.47oN, the difference between the surface sound speed (SSS) and sound speed maximum (SVmax) is very minimum. Probably, the decrease in sound speed due to temperature decrease may be compensated by the increase in sound speed as the surface layer becomes saltier. Thereafter, there is a difference of 1-3 m/s between the SSS and SVmax, with surface layers having lower sound speed.

The sound speed sections (Fig. 3f) exhibits a relatively stable deep sound channel at approximately 1700 meters extending northward towards central Bay of Bengal. The figure shows a deep axial depths and speed less than 1492 m/s near the equator that shoals to depths less than 1600m at the central Bay of Bengal. Probably, the reduction in temperature due to the ascending motion of the isolines towards north might have resulted the shoaling of the iso-velocity lines towards north. The upward tendency of the isolines in the upper above 2000 m and the downward tendency below this depth results in the broadening of the channel between equator and central BoB. The surface sound speed and the subsurface sound speed maximum also exhibits two bands associated with the cyclonic eddy. In the depth range of 300-2000 m, the magnitude of sound speed is lesser in the central BoB (by about 1-3 m/s) compared to the equatorial regions. The low values are due to the effect of cooler water in the Andaman Sea than the BoB water.

C. Sound speed variation in relation to temperature and salinity

It is known that the sound speed in the ocean is a function of depth, temperature and salinity; however in majority of the cases, temperature dominates over salinity. In order to highlight the dependence of sound speed on temperature and salinity, the scatter diagrams are presented (Fig. 4). The scatter diagram shows five different zones of sound speed variability (Fig. 4a-b), i.e. zones I to zone 5 (Table 1). The first zones (Zone I) lies well within the SLD (~0-60 m), where the temperature is uniform (29.5ºC near the equator to 27.6 ºC at the central BoB), but the salinity increases from 32.2 to 33.7 psu. Within the SLD, the increase of 2.3 m/s in sound speed (1537 to 1539.3) suggests a variation of 1.54 m/s per 1 psu change in salinity. This value is well within the reported sound speed variation with salinity (1.4 m/s per psu). However, increase in sound speed per 100 m depth is 3.8 m/s, which is much higher than the reported values (~1.7 m/s per 100 m). This highlight the role of salinity in the sound speed in the surface layers of the BoB. In the upper thermocline of the central BoB (Zone II), corresponding to a drop of 21ºC (from 27.6 to 6.6ºC between70 and 1000 m depths), the sound speed decreases by 41 m/s (1503 to 1544 m/s), i.e. at a rate of 2.4 m/s. Between 1000 and 2000 m depths (Zone III) a prominent sound channel is present. Here, both temperature (6.6 to 2.6ºC) and salinity (34.8-34.9 psu) variations are very weak resulting in only marginal changes in the sound speed (drop of 1.5 m/s, i.e. from 1493.5 to 1492 m/s). Below Zone III, there is gradual increase in the sound speed with depth (7 m/s) upto 2600 m

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(Zone IV) and followed by a zone of (Zone V) rapid increase in sound speed upto the bottom (26 m/s). At deeper depths (2000-4280 m), there is no significant variation in salinity (0.1 psu) and temperature (1.5°C), but the sound speed increases from 1492 to 1526 m/s, i.e. at a rate of 1.4 m/s per 100 m depth. Here, pressure (depth) is the prime factor that contributes to the sound speed variation. In the case of salinity, below the SLD (Zone II-V), the salinity variation is not very significant to cause significant changes in the sound speed.

In acoustic propagation studies, more stress is given on the vertical gradient in the sound speed rather than the actual values. Figures 4c-d depicts the relationship between the vertical sound speed gradient with the temperature (Fig. 4c) and salinity gradients (Fig. 4d). The figure shows that there exists a very good relation between temperature and sound speed gradients (correlation coefficient of 0.87), where it is very weak between the sound speed and salinity gradient.

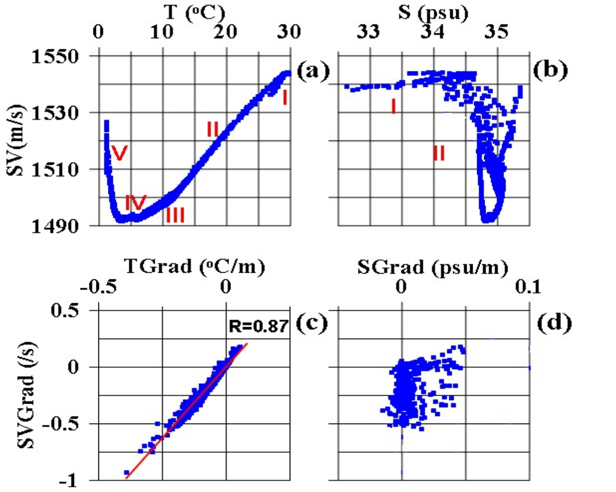

Fig. 4 Scatter diagrams of (a) sound speed vs temperature, (b) sound speed vs salinity, (c) sound speed gradient vs temperature gradient and (d) sound speed gradient vs salinity gradient.

Table I: Typical zones of sound speed variability with corresponding temperature and salinity in the central BoB

	Zone I	Zone II	Zone III	Zone IV	Zone V
D (m)	0-60	60-1000	1000-2000	2000-2600	2600-4280
T (°C)	27.4-27.6	27.6-6.6	6.6-2.6	2.6-2.0	2.0-1.1
S (psu)	32.2-33.7	33.7-34.9	34.9-34.8	34.8-34.7	34.8-34.7
SV (m/s	1537-1539	1539-1493	1493.5-1492	1493-1500	1500-1526

D. Sound channel characteristics

If the sound speed is determined primarily by temperature, the SLD may coincide with the MLD. In the present case, the SLD (MLD) increases from 30 m (40 m) near the equator to over 60 m at the central BoB; with occasional deep SLD's (>60m) centered at 8.5°N and 10.5°N (Fig. 5a). The sound speed maxima generally occur at the approximate depth of the ASW. Between the MLD and SLD, there is noticeable departure (>10 m), with SLD always shallower than the MLD. In the upper layers, the water column is homogeneous with respect to temperature; but the increase in salinity with depth (~1.5 psu in the central BoB) resulting in a sound speed variation of 2-3 m/s psu (Fig. 2). In the central BoB, it is found that the rate of increase in sound speed within the SLD is 1.4 m/s per unit psu change in salinity. This suggests the importance of salinity in the sound speed variability, especially in the upper layers of the BoB.

In the ocean, a phenomenon called sound channel frequently occurs. Changes in sound propagation due to temperature and pressure will form these sound channels at varying depths and with varying thickness. Both these factors influence transmission of signals through sound channels. Sound channels act like ducts that tend to focus the sound energy, and attenuation in these ducts can be significantly less than normal spherical spreading. Through this mechanism sound can travel over considerable distances. Surface sound channel will not transmit all frequencies in the same manner. Depending on its thickness, there will be a cut-off frequency; sound energy with a lower frequency will not be affected by the channel. The lower cut-off frequency (f_{min}) for a near surface sound channel can be estimated following $f_{min} = 1.76x10^5xH^{-3/2}$ Hz. In the present case, for a surface layer of thickness (SLD) of 50m, the estimated cut-off frequency is ~500 Hz (Fig. 5b). In other words, frequency of 500 Hz is required to for the signal to be transmitted through a channel of 50 m thickness. With the decrease in SLD, f_{min} increases. For example, for a layer of 20 m, the critical frequency increases to ~1 kHz. Figure 3 shows that there is large variation in the f_{min}, i.e. between 0.25 to 1.25 kHz along the track; with minimum f_{min} coinciding with the deep layer and vice versa.

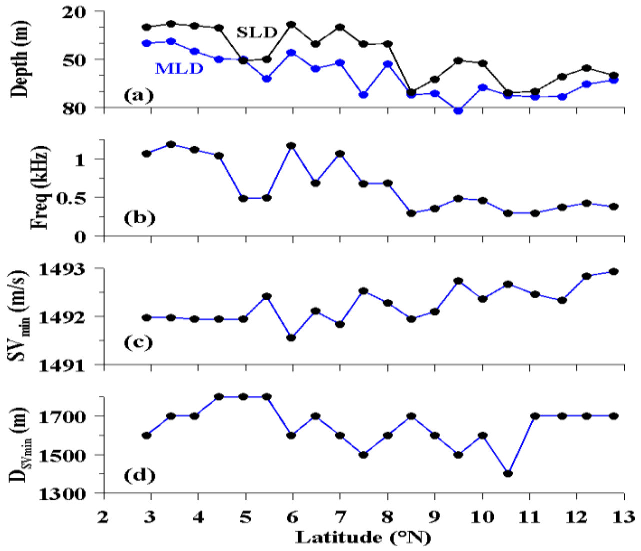

Fig. 5 Latitudinal (2.9°N to 12.77°N) variation of (a) sonic layer depth (SLD), mixed layer depth (MLD), (b) critical frequency, (c) sound speed minimum (SV_{min}) and (d) depth of sound speed minimum (D_{SVmin})

Another important observation is the presence of a subsurface duct, known as the deep sound channel or SOFAR channel. The upper boundary of the channel is observed at a shallower depth at the southern latitude and it deepens to nearly 75 m towards north (Fig. 3f). The axis of the channel (D_{SVmin}), where the sound speed minimum occurs (1492 m/s), shoals from ~1700 m near the equator to 1350 m around 10°N (Fig. 5c, d). The shallower axial depth (1350 m) between 7.5°N and 10.5°N coincides with the region of cyclonic eddy.

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Near the equator, deep axial depth (~1700 m) and sound speed around 1492 m/s are consistently seen. North of this latitude, the axis is noticed abound 1700 m. The deep axial sound speed increases from less than 1492 m/sec in the equatorial region to over 1493 m/sec towards the central BoB, indicating a variation of ~1 m/s along the track. The depth below the channel axis, i.e. D_{SVmin}, where the sound speed is same as the surface maximum is called the critical depth. In all the profiles, the thickness of the channel could not be defined because the sound speed at the bottom is less than the value at the top of the channel.

III. SUMMARY AND CONCLUSION

The research vessel, RV Knorr carried out a spatial survey along ~91.5ºE longitude between the latitudes 2.9ºN and 12.7ºN on the western side of the Andaman Nicobar Islands during February, 1995. Temperature profiles consist of an isothermal layer of 40-80 m thickness within which salinity increases by 3.2 psu, resulting in a highly stratified surface layers. Presence of cyclonic eddy along the track results in the formation of bands of saline water (>34 psu) sandwiched between fresher water (<34 psu). In the surface layers, the increase in sound speed is mainly due to the salinity variation (@1.54 m/s per 1 psu change in salinity). In the thermocline, sound speed decreases by 1.95 m/s per one degree drop in temperature. At the axial depth, temperature, salinity and sound speed variations are very weak, whereas the temperature and salinity does not vary significantly at deeper depths. Here, the increase in sound speed is mainly due to the pressure effect (@ 1.4 m/s per 100 m depth). The sound speed gradients show good relationship with temperature gradient (correlation coefficient of 0.87) than salinity gradient.

The sound speed profiles show a permanent upper sound velocity maximum (~1545 m/sec) around 75 m and an intermediate minimum (~1493 m/sec) between 1350 m and 1750 m. The sonic layer increases from 30 m near the equator to over 60 m at the central BoB; with occasional deeper values centered at 8.5ºN and 10.5ºN. A critical frequency of 500 Hz is required for the signal to be transmitted through a channel of 50 m thickness and it increases to over 1 kHz for a layer of 20 m. Between the MLD and SLD, there is a departure of more than 10 m, with SLD always shallower than the MLD. Within the sonic layer, Eastern Dilute Water of Indo-Pacific origin and Bay of Bengal Watermass are noticed. The bottom of SLD coincides with the top of the Arabian Sea Watermass. In the present case, thickness of the subsurface channel could not be defined as the sound speed at the bottom (~1527 m/s) is less than the value at the top of the SOFAR channel (1544 m/s). The upper boundary of the SOFAR channel is observed at a shallower depth near the equator compared to the central BoB, whereas its axis is consistently seen around 1700 m depth near the equator than around 10ºN. The shallower axial depth between 7.5ºN and 10.5ºN coincides with the region of cyclonic eddy. In all the profiles, the sound speed at the bottom is less than the value at the top of the channel and hence the channel thickness could not be defined.

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