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Intra-annual Variability of the Arabian Sea High Salinity Water Mass in the South-Eastern Arabian Sea during 2016-17

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ABSTRACT

Intra-annual variability of the Arabian Sea high salinity water mass (ASHSW) in the South Eastern Arabian Sea (SEAS) and Gulf of Mannar (GoM) are addressed in this paper by utilising the monthly missions carried out onboard *INS Sagardhwani* during 2016-17. Our observations revealed that the ASHSW was evident along the SEAS irrespective of seasons, whereas in the GoM the presence of ASHSW was observed during winter. The processes such as downwelling/up-welling, coastal currents, intrusion of low saline waters, stratification are clearly affect the spreading of the ASHSW. The characteristics such as core salinity value, depth and thickness of ASHSW exhibited remarkable spatio-temporal variability. Lateral mixing with the low saline waters in the region during winter reduces its core salinity. The intrusion of low saline waters was clearly seen upto 15 °N but the intrusion of low saline waters is not flowing through the GoM. The interface between the ASHSW and the prevailing low saline waters showed strong horizontal gradients of salinity. The presence of the ASHSW makes difference in the SLD and the below layer gradient which is sufficient to complicate or influence sound transmission. The spatio temporal variability of the ASHSW and its acoustic relevance are documented in this paper.

Keywords: Arabian Sea High Salinity Watermass; Intra-annual variability; Acoustic Propagation; South Eastern Arabian Sea; Gulf of Mannar

1. INTRODUCTION

An oceanographic water mass is defined as an identifiable body of water with a common formation history which has physical properties distinct from surrounding water. Most water masses are formed at the ocean surface and subducts and spreads along their unique density surfaces. Usually water-masses are named corresponds to their formation region. In the northern Arabian Sea, excess evaporation over precipitation during a relatively calm period of the winter monsoon is known to be responsible[1-2] for the convective formation of the warm and high salinity Arabian sea high salinity water mass (ASHSW). The ASHSW was first documented by Rochford[3] and subsequently by Morrison[4]. The core salinity value of ASHSW gradually decreases from the formation region and subducts and spreads towards the equator along the density surface of σ-t ~24. The characteristics of this ASHSW are[1]: T=24 °C - 28 °C; S=35.3–36.7; σ-t=22.8-24.5; Depth: 0-100 m. Formation and spreading of the ASHSW was studied by many oceanographers through the analysis of observational, climatological and model output data sets[1-15]. Most of the observational studies are limited to specific months or regions. The intra-annual variability of the ASHSW is not many addressed due to the limitation of such observations. Recently, Hareeshkumar[6] has addressed the evolution of ASHSW in the SEAS using the monthly survey. But his observation was limited to 2x2° grid domain in the South Eastern Arabian Sea (SEAS).

It is well known that waters in the SEAS modified by the exchange of fresh/salt water through the coastal currents viz., West India coast current (WICC) and East India coastal current (EICC). The branches of the WICC and EICC flows around the Lakshadweep high and low in the SEAS[16-17] link the circulations in the Arabian Sea and Bay of Bengal. During summer, WICC flows equatorward and turns around south of Sri Lanka and flows north-eastwards in to the Bay of Bengal. The WICC transports ASHSW into the Bay[18-20]. On the other hand, EICC flows equator ward in winter and flows westward south of Sri Lanka and bifurcates into two, one flowing westward into the southern Arabian Sea, the other flowing around the Lakshadweep high into the WICC[14]. The EICC brings low saline Bay of Bengal water into the SEAS, where it is entrained into the Lakshadweep high and spread along the west coast of India by the WICC[17-19]. Between these water masses (ASHSW and low saline Bay of Bengal) there is often exists a transition zone (called fronts) and these fronts show strong horizontal gradients of temperature and/or salinity, with resulting sound speed variation and current shear. The sound speed variability across these fronts should have a significant impact on anti-submarine warfare (ASW) operations[21]. Understanding of the spreading of the ASHSW in to the Gulf of Mannar (GoM) region still remains as a lacunae. In this context, *INS Sagardhwani* of NPOL had carried out regular monthly observations along

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the southwest coast of India and Gulf of Mannar region during 2016-2017. These data set has given us a unique opportunity to address the monthly variability of ASHSW and its extension towards the shore. The objective of the present paper is to study the intra-annual variability of ASHSW in the SEAS and GoM. The significance of the ASHSW on the acoustic propagation is also addressed in this paper.

2. MATERIALS AND METHODS

INS Sagardhwani was carried out high resolution monthly survey off SEAS and GoM during 2016-2017. The details of the survey are as shown in the Table 1. The study region and the location of the CTD stations in each mission are marked as black dots in Fig. 1. CTD profiling has been carried out along the transects perpendicular to the coastline, each starting from 30 m depth contour near shore to offshore up to 500 m depth contour; between GoM (7 °N) and off Goa (15 °N). Stations in each transect is separated by 0.25° and each transects are separated by ~ 1° interval.

All CTD data have been quality controlled and interpolated as per the standard procedures to make all profiles at 1m intervals. The salinity maxima and the corresponding depth of salinity maxima are extracted from each salinity profile. If the salinity maxima is fall within the thermo-haline index of the ASHSW (T=24 °C- 28 °C, S = 35.3–36.7, σ-t = 23-24, Depth: 0-100 m), salinity maxima is considered as the core of the ASHSW of that station.

Table 1. Details of *INS Sagardhwani* missions carried out during 2016-2017

Mission No	Period
189	17 – 27 Nov 2016
192	21 – 28 Dec 2016
194	26 Feb – 5 Mar 2017
197	17 – 27 Apr 2017
200	19 – 29 May 2017
202	15 – 25 Jun 2017
203	18 – 24 Jul 2017
204	24 – 30 Aug 017
207	6 – 12 Oct 2017

3. RESULTS AND DISCUSSIONS

Salinity maxima and the depth of the salinity maxima derived from the individual profiles are as presented in the Figs. 1 and 2, respectively. Core value of salinity greater than

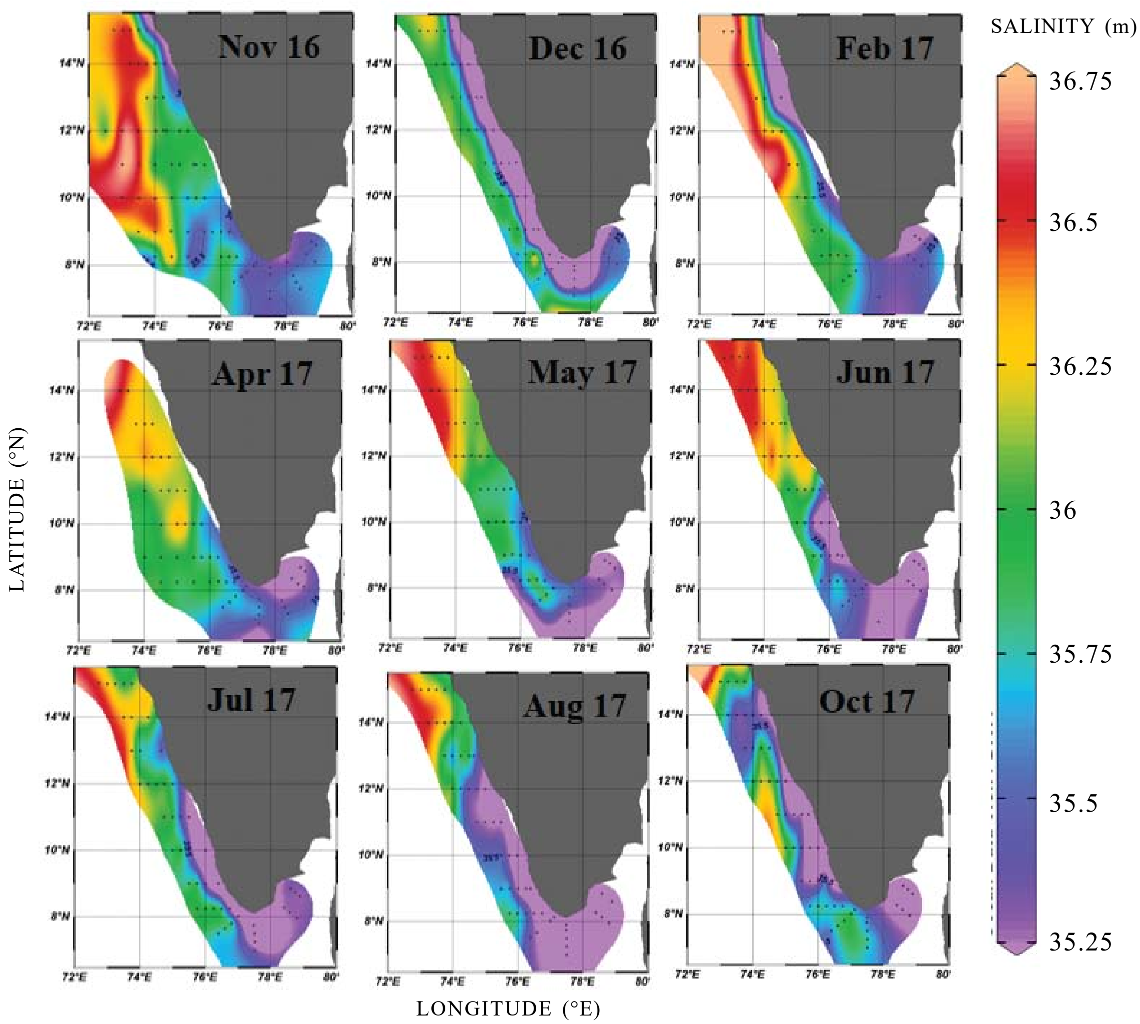

Figure 1. Monthly distribution of salinity maxima in the South Eastern Arabian Sea and Gulf of Mannar.

35.5 psu in the SEAS can be considered as the presence of ASHSW[4] and the core value decreases as it enters into the GoM. In order to demarcate the spatial extent of the ASHSW, the contour of 35.5 psu provided in all the plots can be considered as the reference of lower limit of the ASHSW. In general, the core of the ASHSW showed a gradual decrease from north to south and towards the shore in all months. During November, presence of ASHSW was evident most of the study region. But its presence is not evident alongshore region north of 13 °N and off Kanyakumari. Interestingly, ASHSW was present in the offshore waters in the GoM. But in December, the presence of ASHSW is not evident in the entire alongshore region, possibly limited by the northward-flowing WICC. Whereas ASHSW was present in all other region including the GoM. Lateral mixing of the low saline waters intruded from the Bay of Bengal possibly reduced the core salinity values during this period. As the inflow of low saline waters decreases, the core value of ASHSW increases, which can be seen from February on wards. The traces of ASHSW can be seen in the GoM region until April. During April and May ASHSW was present along the entire south-west coast of India. During summer monsoon (May-Aug), ASHSW starts retreating from southern tip and as the season progresses the disappearing trend of ASHSW gradually extends northward coastal regions of SEAS. Usually, West India Coastal Current (WICC) carries the ASHSW formed in the northern Arabian Sea in winter towards the SEAS[1]. But the quasi permanent cyclonic eddy during the southwest monsoon often meanders the WICC along the south west coast of India, in fact in this region WICC often flows northward[17]. This is well discernible in the salinity maxima plots of May to Aug. But in Oct, ASHSW starts appearing in the southern tip of SEAS. The ASHSW was also not evident in the Gulf of Mannar region during the southwest monsoon and post monsoon period.

To address the spreading of ASHSW in the SEAS, salinity sections along 14 °N, 10 °N, 8 °N and along 77.5 °E from Nov 16 to Oct 17 are presented in the Fig. 3. During November, ASHSW was evident along 14 °N and is seen upto the shore. ASHSW starts appearing below 20 m depth and the core was observed between 30-40m.. ASHSW was

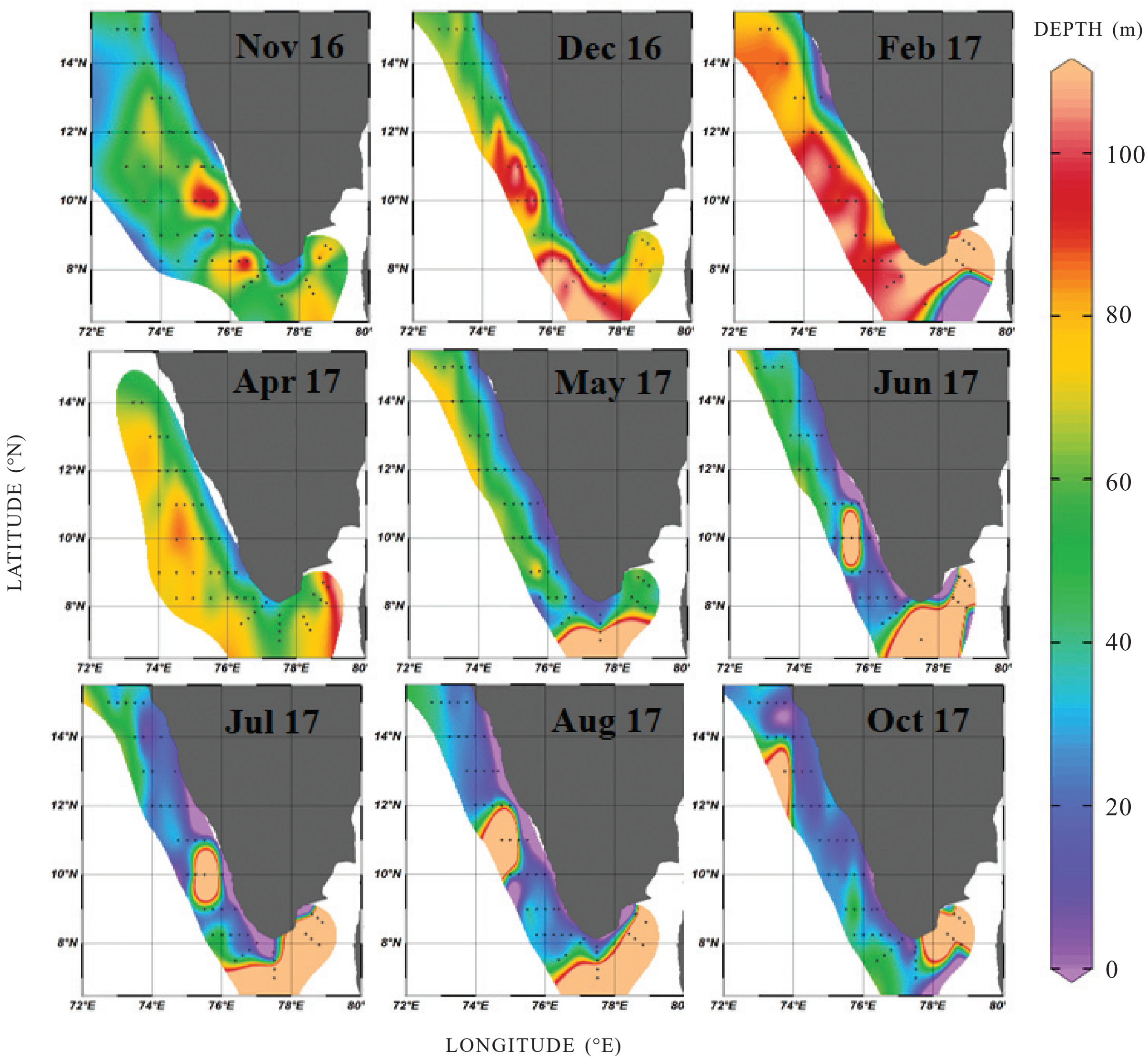

Figure 2. Monthly distribution of depth of salinity maxima in the South Eastern Arabian Sea and Gulf of Mannar. X axis longitude and Y axis is latitude.

further deepens from November and it deepens towards coast. The deepening of the ASHSW can be attributed to the downwelling processes usually observed in winter along the southwest coast of India. By February, the low saline waters spreads offshore along 14 °N, below which ASHSW was observed and the core occurs around 80 m. The freshening of surface waters can be seen until April. During the pre-monsoon season, the increased solar radiation, weak winds and currents reduces the mixing in the region, consequently ASHSW was further moves upwards. During May, the ASHSW intensified and exhibited the maximum core value among the other seasons. Unlike winter season, the ASHSW during summer monsoon was appeared as narrow band and its core values showed an upsloping trend towards the coast. This may be attributed to the prevailing upwelling processes. But during post monsoon, the waters along 14 °N showed an entirely different salinity characteristics and the signatures of ASHSW was very weak. Presence of ASHSW along 10 °N was observed similar to 14 °N but at different intensities. The down sloping of ASHSW in December and the upsloping towards coast during summer is clearly seen along 10 °N. However, the onshore spreading of ASHSW during summer is possibly prevented by the prevailing WICC. Along 10 °N, the ASHSW was more prominent in the offshore side during November and April. The intrusion of low saline waters are dominant in this transect during Dec – Feb. Similarly along 8.25 °N showed the presence of low saline waters during Dec-Feb. Along 8.25 °N, observed deepening of ASHSW during Nov-Feb and shoaling of ASHSW towards the coast during Apr-Aug can be associated with the downwelling/upwelling processes respectively. In general, the ASHSW was present in the entire transect along 8.25 °N except monsoon season. During Nov and May, the signature of ASHSW are very vague in offshore region possibly due to the presence of eddies. Transect along 77.5 °E represent the southern tip of India (off Kanyakumari) where the Arabian Sea and Bay of Bengal meets. Unlike the other transects, it is well evident that the low saline waters are present offshore rather than coastal region. Below the low saline waters, the ASHSW was observed. Though the signatures of ASHSW was very weak, its signatures are almost present in all seasons except Feb. In this transect, ASHSW was most dominant in October, which is dissimilar to other transects. Transect along 8.85 °N in the Gulf of Mannar clearly delineates the protrusion of ASHSW in the region. ASHSW was more prominent during Nov- Dec, but the weak traces are continues until the southwest monsoon. Very low saline waters intruded from the Bay of Bengal is clearly seen during the winter and pre-monsoon season and maximum intrusion was appeared during Dec. Hence the monthly analysis of salinity data clearly delineated the intrusion of low saline waters from the BoB in to the SEAS

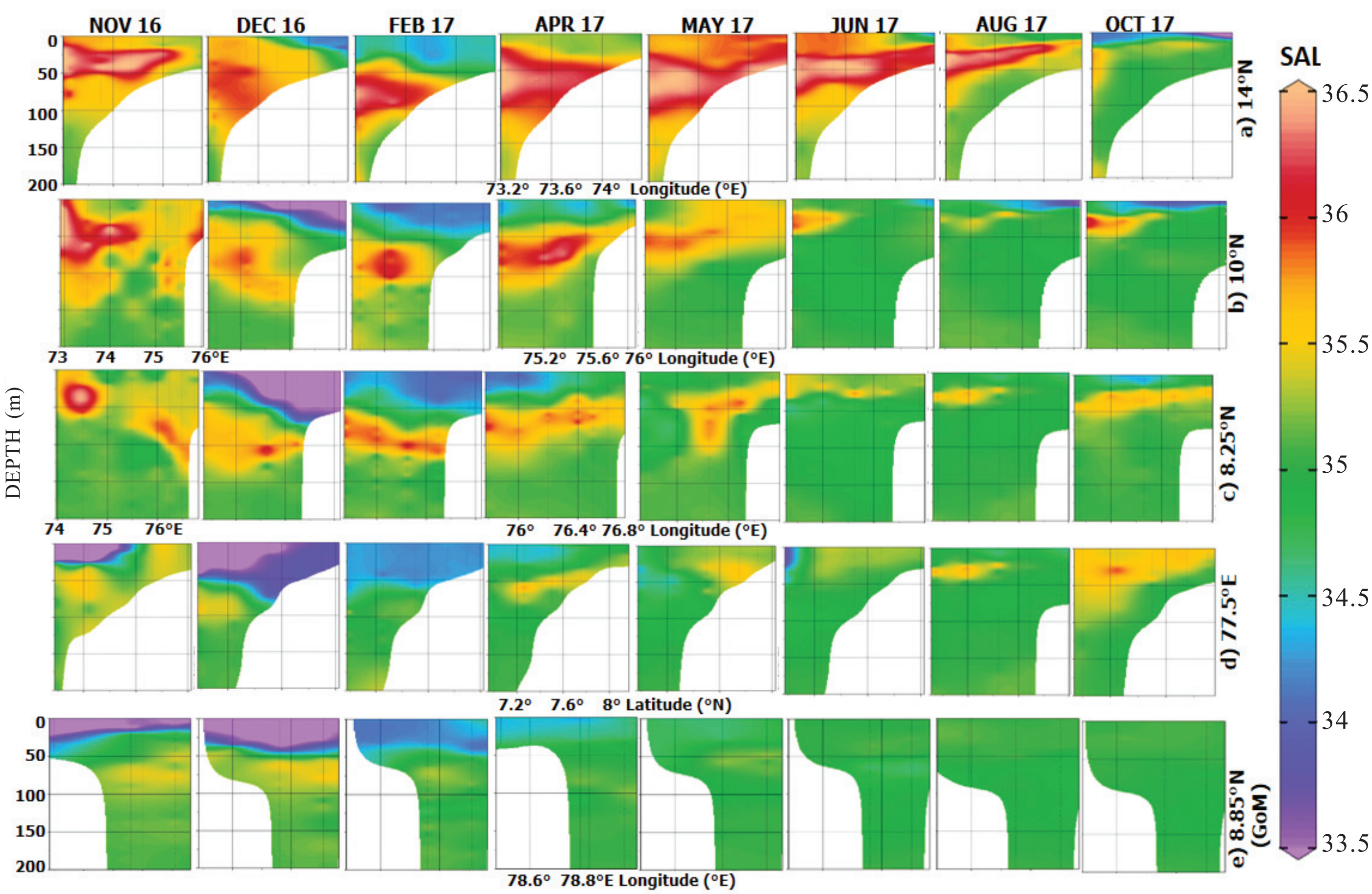

Figure 3. Monthly variation of vertical section of salinity along (a) 14 °N, (b) 10 °N, (c) 8.25 °N, (d) along 77.5 °E, and (e) 8.85 °N (along GoM). Please note the X-axis of 10 °N and 8.25 °N during Nov 2016 as it extended offshore to incorporate additional stations occupied

and GoM. We could clearly trace the intrusion of low saline waters upto 15 °N. This contradicts the earlier findings of Hareeshkumar and Basil[11], they reported that the maximum of the northward extension of the low saline waters is about 12 °N. The surface salinity during winter in the GoM region is about 0.5 psu - 0.8 psu saltier than that of Kanyakumari which clearly suggests the intrusion of low saline waters in the GoM. The intrusion of low saline waters are entering to the southern tip via East India coastal current (EICC) which might turns around Sri Lanka and continue to flow as the WICC along the eastern Arabian Sea. During this course, current in the southern tip bifurcates towards GoM region hence the region possibly received the low saline waters.

To decipher the temporal variability of ASHSW vertical profiles of salinity at 10 °N: 75 °E during the period from June 2016 to Oct 2017 are presented in Fig. 4. For this, three additional cruise data collected onboard *INS Sagardhwani* between June 2016 and Sept 2016 were also utilised. In general, sound speed exhibited the pattern of temperature profile. ASHSW was usually occurs immediately below the mixed layer. The thickness and the core value of ASHSW showed significant temporal variability. The presence of ASHSW also showed some noticeable impact on temperature and sound speed profiles. For example, during July 2016, the occurrence of ASHSW can be seen from 20 m and the core was centered at 40 m depth. Consequent to this, temperature and sound speed profile showed small scale inversion up to the core of ASHSW. But in Nov 2016, the presence of ASHSW was very weak, therefore its impact on temperature and sound peed profile is negligible. During winter ASHSW was so strong but it occurred immediately below the mixed layer. This clearly affects the below layer gradients of temperature and sound speed profile. But during April, the MLD was very shallow due to the high stratification, below which ASHSW was observed. But its core was observed relatively deeper (~100 m) as a result the ASHSW could not make any positive sound speed gradients at these depth. As the season progress, the vertical profiles showed a gradual decrease of the thickness and core value of ASHSW from May 2017 to Aug 2017. But in October the vertical profiles showed relatively higher core values and appeared from the 40 m depth.

To understand the significance of the ASHSW on acoustic propagation, transmission loss modelling[22] (Kraken RQ) has been done for all the profiles described in the Fig. 4. The model was run for the frequency of 1500 Hz, source and receiver depths at 10m and the results are as presented in the Fig. 5. Among all the profiles, the profiles during June 2016, July 2016, Feb 2017 and Dec 2017 showed better surface duct propagation. For example, all these profiles showed the transmission loss between 65 db - 75 db, for a receiver at 10 m depth and 20 km range. Whereas the profiles of Sep 2016, Oct 2017 and May 2017 showed the transmission loss between of 90 db – 95 db at 20 km range. Similarly the profiles during Nov 2016, Jun 2017 and Aug 2017 showed relatively short surface detection. From this analysis it has been very clear that the presence of ASHSW showed remarkable influence on acoustic propagation.

4. SUMMARY AND CONCLUSIONS

Intra-annual variability of ASHSW in the SEAS and GoM are addressed in this paper by utilising the monthly missions carried out onboard *INS Sagardhwani* during 2016-17. In general, the ASHSW was evident along the SEAS irrespective of seasons, whereas in the Gulf of Mannar region the presence of ASHSW was observed during winter. The characteristics of ASHSW such as core salinity value, depth and thickness showed remarkable spatio-temporal variability. Lateral mixing with the low saline waters in the region during winter reduces its core salinity. The intrusion of low saline waters was clearly seen in the Gulf Mannar region and in the South Eastern Arabian Sea up to 15 °N. The waters along the southern tip of India (Off Kanyakumari) is relatively less saltier than that in

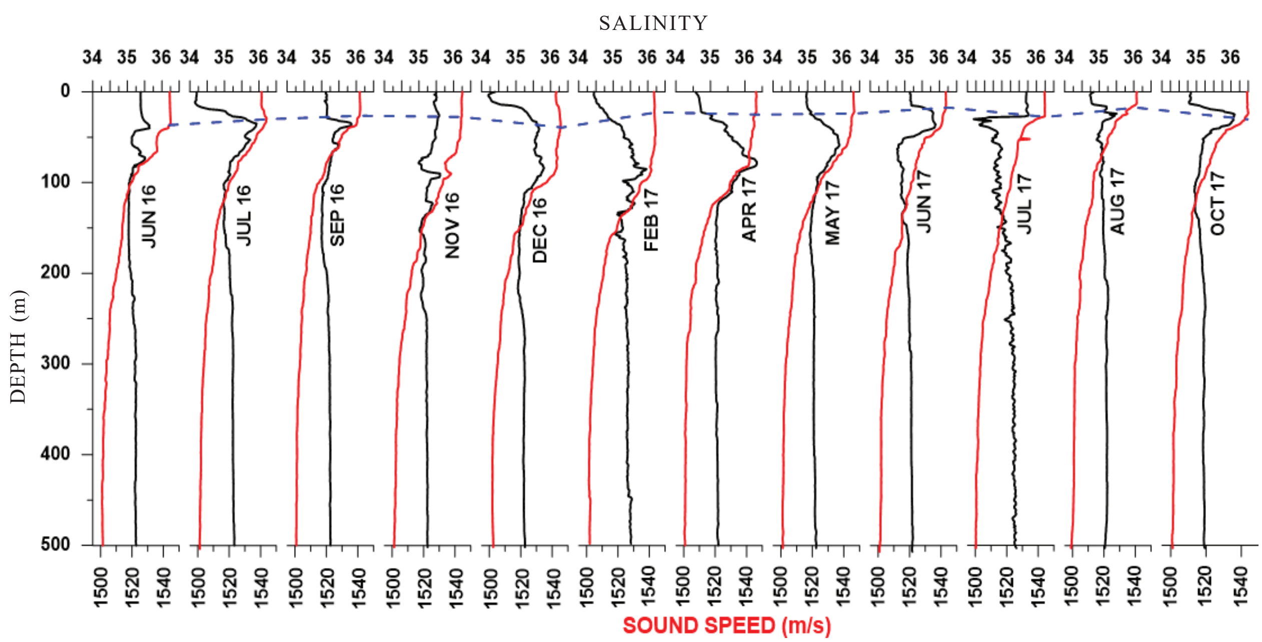

Figure 4. Monthly variability of vertical profiles of salinity and sound speed at an offshore station (10 °N : 75 °E) in the SEAS. The dashed horizontal line represents the variability of sonic layer depth (SLD).

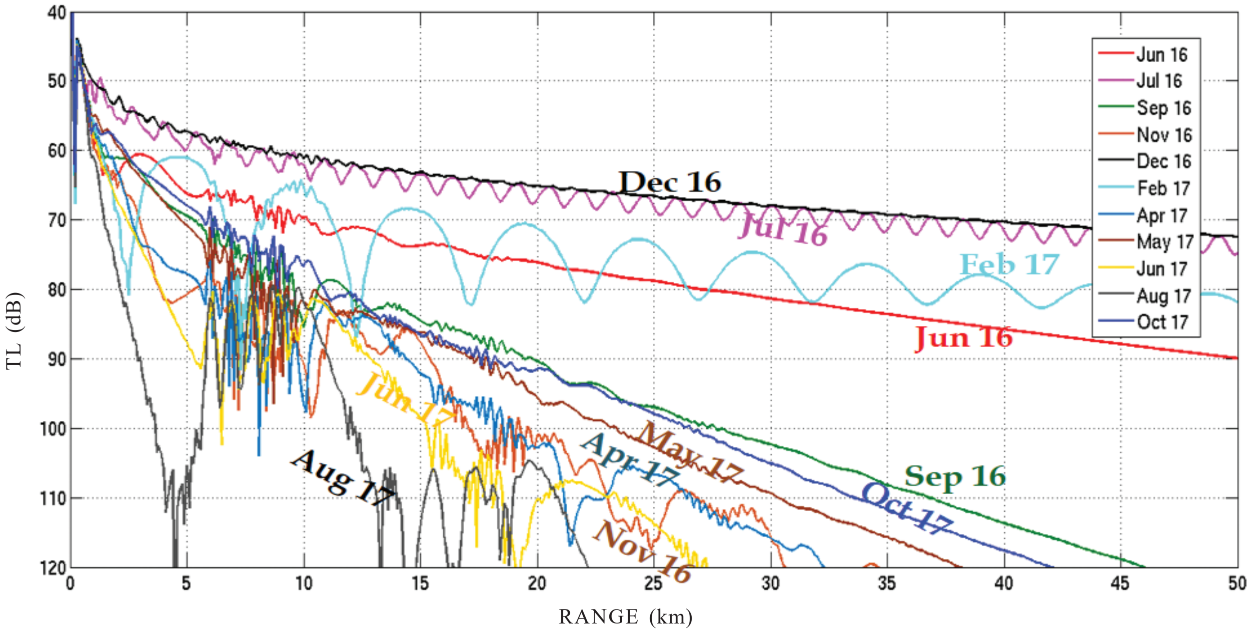

Figure 5. Model output of the normal mode (Kraken RQ) for the profiles at 10 °N: 75 °E for various periods.

the Gulf of Mannar region which gave an insight to the pattern of the intrusion of low saline waters through the EICC. The interface between the ASHSW and the prevailing low saline waters showed strong horizontal gradients of salinity. The presence of the ASHSW makes difference in the SLD and the below layer gradient which is sufficient to complicate or influence sound transmission.

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