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Observations of internal wave oscillations in the upper thermocline based on CTD-yoyo measurements during ARMEX-I

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सार – इस शोध पत्र में संचरण के मार्ग के साथ ध्वनि गति के उतार चढ़ाव को प्रभावित करने वाले आंतरिक तरंग दोलन के विस्तार का प्रेक्षण करने के लिए आरमेक्स चरण–I की द्वितीय यात्रा के दौरान ओ. आर. वी. सागरकन्या (एस. के. – 179) में सी. टी. डी. योयो प्रयोग किया गया । सागरकन्या में उपलब्ध सी–बर्ड सीकृ टी. डी. के साथ संवेदी आँकड़ों का मिनी सी. टी. डी. लगाया गया। दोनों तंत्रों को लगातार नीचे लाया गया और गहरे पानी के एक स्थान (15° 23.12′ उ. और 72°10.55′ पू.)में जल स्तंभ के 45 से 205 मी. के बीच ऊपरी थर्मोक्लाइन में कर्षित (योयो) किया गया और पोत को संचरण के लिए छोड़ दिया गया । 2 घंटे और 10 मिनट की अवधि में कुल 36 प्रोफाइल (अधोमुखी और ऊर्ध्वमुखी) एकत्रित किए गए । मिनी सी. टी. डी. और सी–बर्ड सी. टी. डी. द्वारा लिए गए प्रेक्षणों को तुलना के लिए गहराई (1 मी. के अंतराल पर 50 से 200 मी.) और समय (3.6 मिनट – प्रत्येक कास्ट की अवधि) में अंतर्वेशित किया गया क्योंकि इनकी परिशुद्धताएँ भिन्न हैं । योयो के आरम्भ और उसके पूरे होने के दौरान एकत्रित किए गए प्रोफाइलों से सुपरिभाषित मिश्रित सतह (लगभग 43 मी.) का पता चला, और इसका तापमान व्यवहारिक रूप से समान रहा। समय श्रंखला के दौरान समताप रेखाएँ उच्चतर बारंबारताओं को छोड़कर 2 से 4 मीटर और 18 से 40 मिनट के बीच क्रमशः ऊँचाई और अवधि के आंतरिक तरंग दोलनों को स्पष्ट रुप से दर्शाती हैं । गहराई / उर्ध्वाधर के साथ 2 से 20 मी. की ऊर्ध्वमुखी और अधोमुखी गति सुपरिचित ज्वारीय आंतिरक तरंगों से संबंद्ध हैं ।

ABSTRACT. A CTD yoyo experiment was conducted onboard ORV Sagar Kanya (SK-179) during the second cruise of ARMEX Phase-I to observe the extent of internal wave oscillations which induce sound speed fluctuations along their propagation path. The Mini CTD of Sensor data was attached with the Sea-Bird CTD available onboard SK. Both the systems were continuously lowered and hauled up (yoyo) within the upper thermocline, between 45 and 205 m of the water column at a deep water location (15° 23.12′ N and 72° 10.55′ E) while the ship was allowed to drift. There were total 36 profiles (down cast and up cast) collected within a period of 2 hours and 10 minutes. The observations made by Mini CTD and Sea-Bird CTD were interpolated in depth (50 to 200 m at 1m interval) and time (3.6 minutes – duration of each cast) for comparison as they have different accuracies. The profiles collected during the start of the yoyo and on completion clearly revealed a well defined mixed layer (nearly 43 m) and its temperature remained practically same. The isotherms during the time-series clearly revealed internal wave oscillations of height and period ranging from 2 to 4 m and 18 to 40 minutes respectively excluding the higher frequencies. The upward and downward movements of 2 to 20 m along the depth/vertical were attributed to well known tidal internal waves.

Key words − ARMEX, CTD yoyo, Observations of internal waves.

1. Introduction

The oscillations of internal thermal layers (isotherms) within the ocean are called internal gravity waves. They are very common in all the oceans, both in deep as well as shallow waters. These waves significantly influence the sound transmission in the ocean causing fluctuations (Dashen *et al*., 1979) of sound speed. The shallow water internal waves are very complex and not well understood as in deep waters (Sarma *et al*., 1991; Yang and Yoo, 1999). A CTD yoyo experiment was conducted onboard ORV Sagar Kanya (SK-179) during her second cruise (17 July to 16 August 2002) of the Arabian Sea Monsoon experiment (ARMEX), Phase-I. This particular mission SK-179 belongs to one of the observational experiments under the Indian Climate Research Programme (ICRP), which aimed at gaining an insight into the processes of monsoon activities linked with the convection over the Arabian Sea. Though internal wave oscillations on high frequency scale are not part of the overall ARMEX objectives, advantage was taken of the opportunity of having two shifts SK and SD to make observational campaign on high frequency interval waves. Therefore, even though this paper does not concern with monsoon fluctuations during ARMEX, the study of internal wave oscillations using CTD yoyo data would

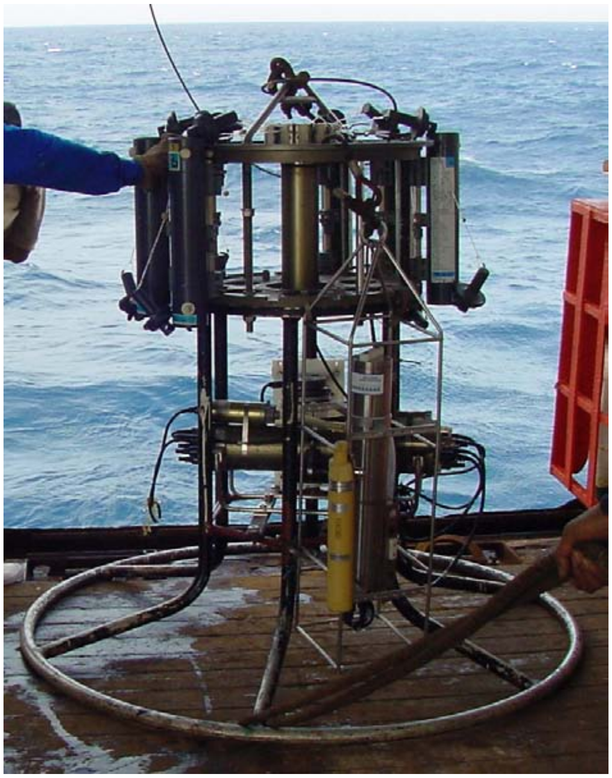


Fig. 1. Sea-Bird CTD and Mini CTD of Sensor data are attached together for yoyo experiment during mission SK-179

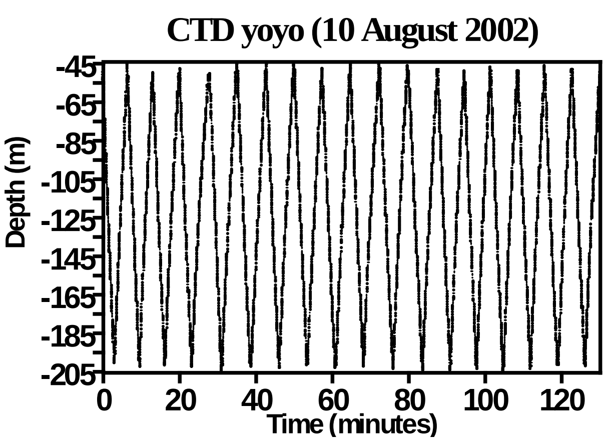
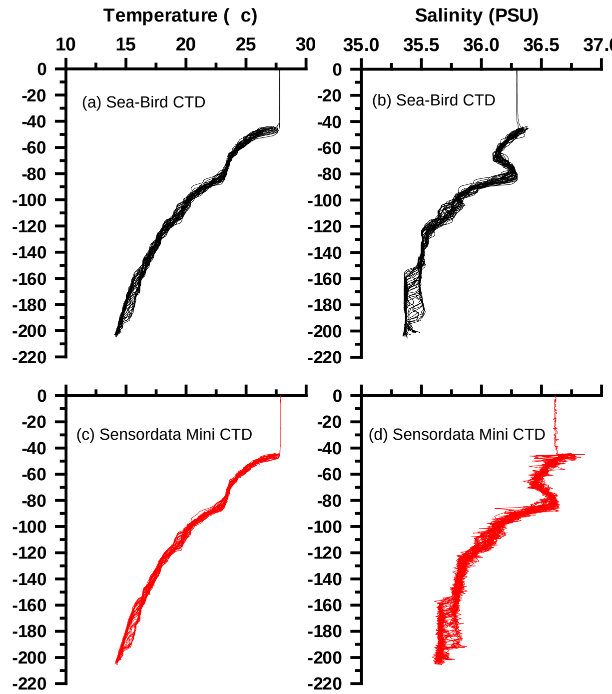


Fig. 2. Depth-time distributions of CTD data

produce information in the acoustic transmission experiment by Naval Physical and Oceanographic Laboratory (NPOL) onboard INS Sagardhwani (INSS) while SK carried out her ARMEX measurements. INSS was the transmitting ship and the received acoustic signals were recorded onboard SK during the time-series and at selected ranges. The objective of the acoustic transmission experiment was to study the effect of high-frequency (>1 cph) and low (0.04 to 0.16 cph) frequency internal waves, which cause acoustic intensity fluctuations



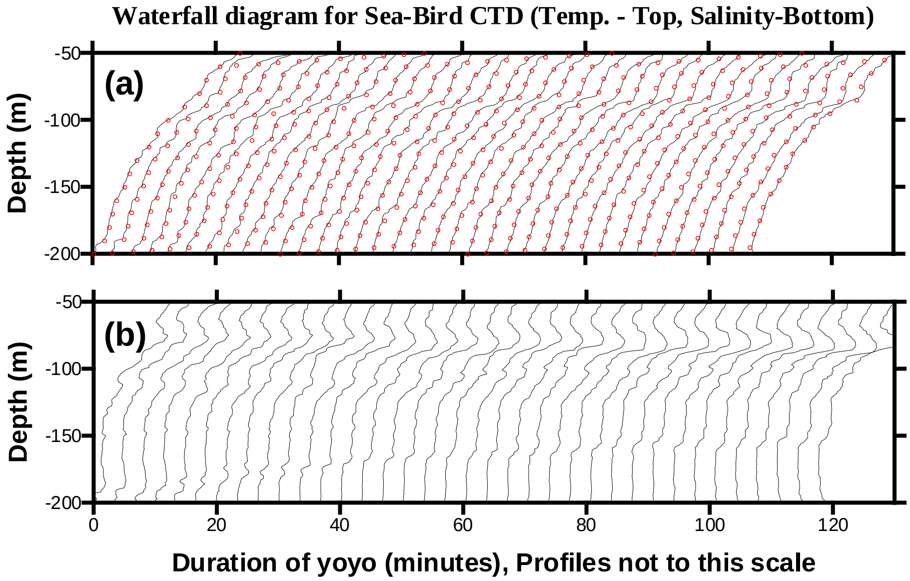
Figs. 3(a-d). Composite plots of observed temperature and salinity by both CTDs

during its transmission in the deep waters and prevailing rough weather conditions during south-west monsoon. Prasada Rao *et al*. (2005) in this volume at page 281-286. The observed acoustic fluctuations in the surface duct can be due to wind, waves, internal waves and the prevailing current at the time-series station of SK (15° 23.07′ N and 72° 10.23′ E). This paper only deals with the observed high frequency internal wave oscillations within the upper thermocline region based on CTD yoyo data. There is another article in this issue where the observed (CTD yoyo data) and simulated internal waves have been compared [Krishna Kumar and Swain (2005) in this volume at page 269-274].

Before we proceed further, it may be noted that, the CTD yoyo data collected during (SK-179) experiment was only for a limited period. Secondly, the frequency of operation (lowering and hauling) was also limited to the speed at which the Sea-Bird CTD winch could be operated. In spite of these limitations, the available CTD profiles have been optimally used to assess the observed internal wave oscillations.

2. Data and methods

ORV Sagar Kanya was stopped on 10 August 2002 at 0730 hr (IST) and allowed to drift from a location (15° 23.12′ N and 72° 10.55′ E, station depth 1950 m) closer to the time-series position. The Mini CTD of Sensordata was attached with the Sea-Bird CTD onboard



Figs. 4(a&b). Observed profiles of (a) temperature and (b) salinity using Sea-Bird CTD (continuous lines). Circles on the top diagram are Mini STD temperature values in steps of 1 in 10 data points

SK (Fig. 1) and both the systems were continuously lowered and hauled up (yoyo) within the upper thermocline region between 45 and 205 m of the water column. The depth-time distribution of recorded CTD data is shown in Fig. 2. There were total 36 profiles (down cast and up cast) collected within a period of 2 hours and 10 minutes during which SK drifted for about 2 knots. It may be seen from Fig. 2 that, the lowering and hauling rates of CTD winch was fairly steady and each operation (down and up) took about 7.2 minutes approximately.

All the 36 temperature and salinity profiles of both CTDs are plotted as clusters in Figs. 3(a-d) from surface to the maximum depths of yoyo operation. The observations made using Mini CTD and Sea-Bird CTD were available for depths less than 0.5 m which are interpolated to 1.0 m intervals between 50 & 200 m. Further the data are interpolated in time (3.6 minutes) for inter-comparison and as they have different accuracies as shown in Table 1. All the temperature and salinity profiles of Sea-Bird CTD are plotted in the form of waterfall diagrams showing the depth in *y*-axis and total duration of the yoyo operation in *x*-axis [Figs. 4(a&b)]. However, the profiles are plotted with a constant increment of temperature/salinity in *x*-axis. The temperature recorded by Mini CTD are superimposed over the Sea-Bird profiles in Fig. 4(a) with circles in steps of 1 in 10 data points for comparison. The contour plots of temperature using 18 profiles (only down cast) and 36 profiles (both down cast and up cast), salinity and estimated sound velocity (Mackenzie, 1981) using all 36 profiles are plotted

TABLE 1

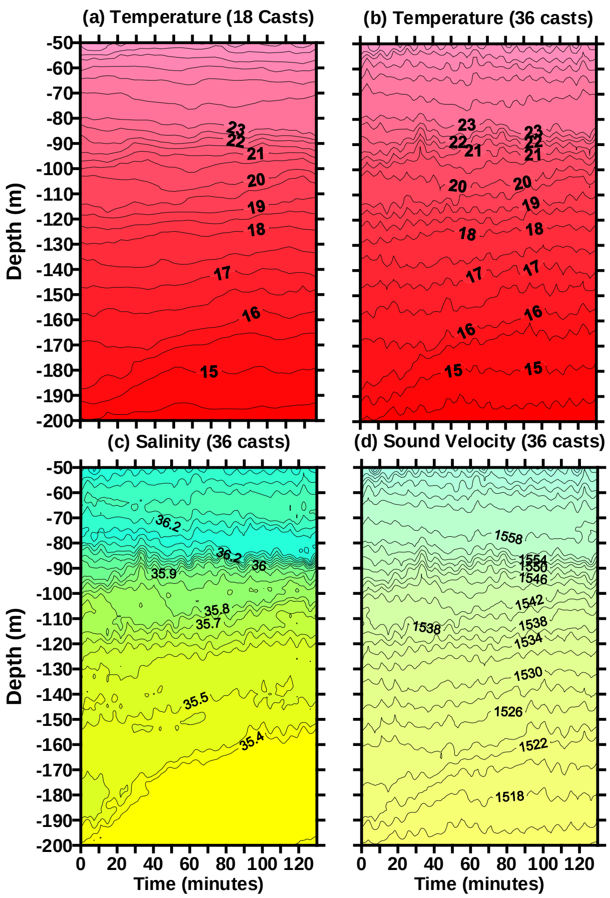
Temperature and salinity sensor specifications

S. No.	Sensor	Sea-Bird CTD		Sensor data Mini CTD	
		Resolution	Accuracy	Resolution	Accuracy
1	Depth	0.065 m	± 0.325 m	0.1 m	± 0.2 m
2	Temperature	0.0002 °C	± 0.001° C	0.005° C	± 0.01° C
3	Salinity	0.0004 PSU	± 0.003 PSU	0.01 PPT	± 0.02 PPT

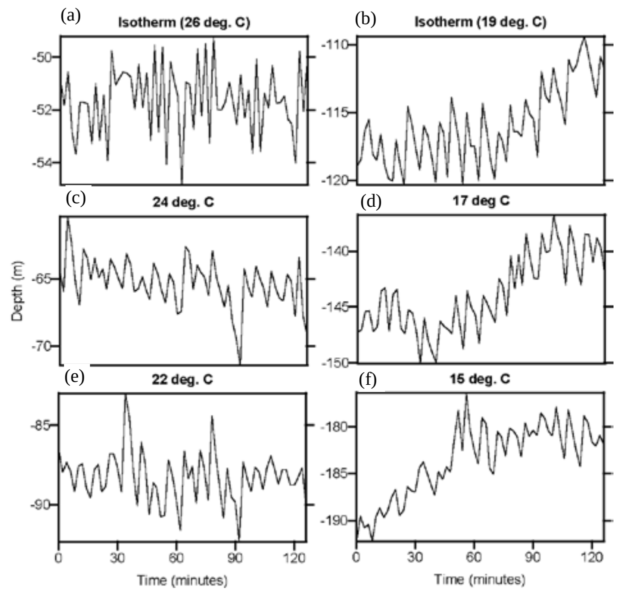
in Figs. 5(a-d). The fluctuations of the selected isotherms (26° C, 24° C, 22° C, 19° C, 17° C and 15° C) are interpolated from observed time-series Figs. 6(a-f) obtained after processing of the raw data and subjected to FFT (Bendat and Piersol, 1971) after removing their trends. The frequency spectra for each of the isotherm are plotted in Figs. 7(a-f) neglecting the higher frequencies beyond 12 cycles/hr.

3. Results and discussion

A moored thermistar chain with depth sensors is the most suitable means of data acquisition for the study of internal waves. Several other methods of measurements are also utilised to study the internal wave characteristics. CTD yoyo is one of such methods that one can adopt for such investigations. It has one important advantage that, the entire water column is sampled at very close depth



Figs. 5(a-d). Contour plots for temperature, salinity and sound speed using the time-series observation of CTD yoyo

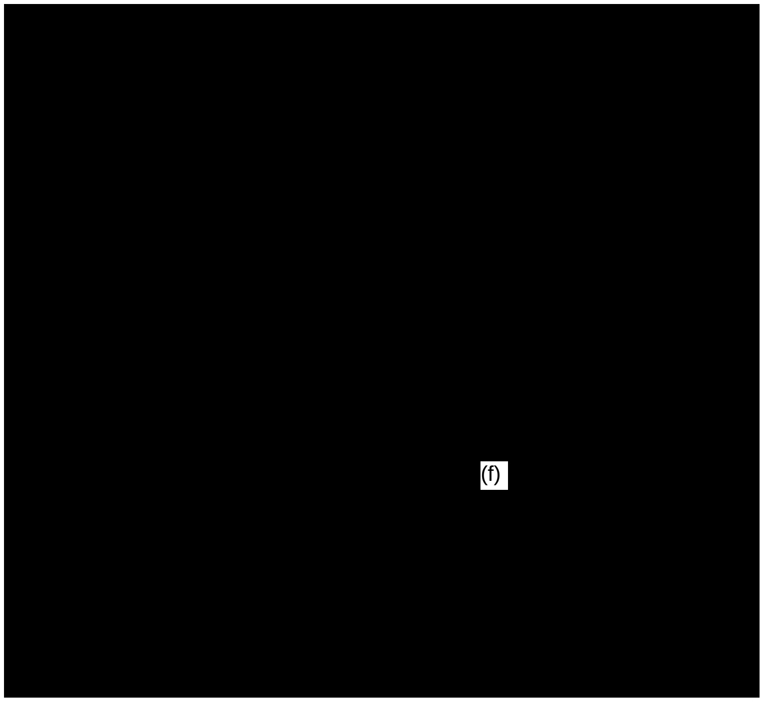


Figs. 6(a-f). Fluctuation of selected isotherms plotted as time-series

intervals (Yang and Yoo, 1999) which is only limited to the response time of the sensors. The disadvantage of yoyo operation is the time requirement for lowering and hauling up of the equipment. Secondly, the upper and lower depths are sampled at closure intervals during successive operations of heaving-lowering and lowering-heaving respectively. Only the middle depth is sampled at equal time intervals if the lowering and heaving rates are kept uniform with constant time-gap or preferably without any time gap between two successive casts.

The temperature profiles collected during the start of the yoyo and on completion clearly revealed a well defined mixed layer (nearly 43 m) and its temperature remained practically same within 2 hours and 10 minutes duration. During the period of yoyo ship's drift could be one of the limitations but it helps the sensors to move to the undisturbed water which is considered as a practical advantage. Temperature clusters for both CTDs Figs. 3(a&b) include first as well as last profiles from surface to 205 m. The spread in both temperature and salinity clusters reveal their variations during the yoyo period. The thickness of Sea-Bird temperature cluster indicated a higher spread in the data although the accuracy of the sensor is almost ten times the Mini STD of Sensordata (Table 1). The comparison between the Sea-Bird CTD and Mini STD temperature as shown in Figs. 4(a&b) revealed mean deviation of 0.11° C. The Mini CTD salinity cluster as shown in Figs. 3(c&d) has large fluctuations/spikes as the sensor does not have any control over the flow of sea water through the conductivity cell. Moreover, the average salinity recorded by Mini CTD is almost 0.3 PSU higher than Sea-Bird CTD. Therefore, the temperature as well as salinity data of Sea-Bird CTD are considered reliable and more accurate compared to Mini CTD data. Hence, the Sea-Bird CTD data was preferred for further processing/ analysis in this investigation. The comparison between both the sensors could provide an opportunity for an assessment of the reliability of yoyo measurement.

The data presented in the waterfall diagram Figs. 4(a&b) are the individual processed profiles obtained during the successive down cast and up cast of Sea-Bird CTD. Inspection of these temperature and salinity profiles obtained from both the casts reveal that they do not have bias and can be together used for analysis. The separate contour plots of temperature in Figs. 5 (a&b) using all the 18 down cast profiles and 36 down and up cast included clearly reveal the oscillations of internal thermal layers. However, the plot containing 36 profiles reveal high frequency oscillations due to higher sampling rate. Therefore, the salinity and sound velocity contours were also plotted using all the 36 profiles. All these plots of temperature, salinity and sound speed shows mixed wave like fluctuations of higher and lower frequencies due to the presence of internal waves.



Figs. 7(a-f). Frequency spectra for six selected isotherms

TABLE 2

Estimated depth, height and period parameters of observed internal oscillations for selected isotherms using Sea-Bird CTD yoyo data

S. No.	Isotherm (°C)	Mean depth (m)	Depth range (m)	Standard deviation (m)	Average internal wave height (m)	Estimated peak periods (minutes)
1	26	52	5.6	1.3	3.2	19, 8
2	24	65	11.0	1.8	3.9	38, 18, 11, 7
3	22	88	9.3	1.6	3.7	40, 11, 8
4	19	116	10.9	2.9	4.4	18, 7
5	17	144	13.3	3.4	4.2	33, 18, 8
6	15	184	15.8	3.9	4.3	21, 8

For a better understanding on the oscillations of internal waves observed in the CTD yoyo data, the depth variations of some typical isotherms were plotted Figs. 6(a-f). These plots indicate internal wave periods ranging from 15 minutes to less than an hour (excluding higher frequencies) and their upward and downward movements (2 to 20 m) along the depth were due to tidal internal waves. The sound velocity computed using the processed temperature and salinity values of both sensors will also reveal similar fluctuations for the yoyo period due to the presence of oscillations caused by internal waves. These oscillations are likely to influence the sound propagation (Stefanick, 1984) which is evident from the visually observed internal wave magnitudes Figs 6(a-f) showing variations predominantly from 2 to 5 m within a short span of 2 hours.

The frequency spectra as shown in Figs. 7(a-f) shows predominant peaks around 8 minutes with maximum energy for all the cases except the top 26° C isotherm. In case of 26° C isotherm [Fig. 7(a)], high frequencies oscillations are predominant which may be clearly seen from Figs. 6(a-f). This is also evident from top few isotherms shown in the contour map [Fig. 5(b)]. Therefore, the energy levels are significantly lower below 12 cycles/hr compared to other isotherms. Table 2 shows the mean depth, depth range and standard deviation for all the six isotherms considered along with spectrally estimated (Emery and Thomson, 1997) average wave height and the peak periods. The average wave height and the peak periods for the spectra shown in Figs. 7(a-f) varied from 3.2 to 4.4 m and 7 to 40 minutes although the energy levels are low for higher wave periods. If we neglect the higher periods around the sampling frequency considering only the down casts (7.2 minutes), then also we have peaks from 11 to 40 minutes whose corresponding wave heights shall be lower as the length of the data set is insufficient to obtain a better statistical estimates. However, the study clearly reveal the presence of high frequency internal oscillations of intermediate periods between the sampling frequency and the total length of the time-series (CTD yoyo).

4. Conclusions

The CTD yoyo experiment conducted onboard ORV Sagar Kanya (SK-179) during the ARMEX-I program for a period of 2 hours 10 minutes using the Sea-Bird and Sensor data CTD systems was an observational evidence on the prevailing internal gravity waves causing significant oscillations within the upper thermocline. The experiment could reveal internal wave periods ranging from 10 to 40 minutes excluding higher frequencies and the upward and downward movements of isotherms (2 to 20 m) were due to tidal internal waves. Salinity values obtained by the Mini CTD of Sensor data had large spikes as the sensor does not have any control over the flow of sea water through the conductivity cell. The sound velocity computed from temperature and salinity data of both sensors also reveal fluctuations during the period of yoyo due to the presence of oscillations caused by internal waves. These oscillations are likely to influence the transmission of sound in the sea. However, the length of the data set is insufficient to bring out statistically significant results on the internal wave characteristics. Hopefully, a longer time-series of such a CTD yoyo in the deep waters may be very useful to study the high frequency internal waves in future.

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