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An Analysis on Sound Speed in Seawater using CTD Data

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Abstract: Sound speed computation based on field observations of temperature, salinity and pressure in the Southern coastal waters of the Caspian Sea, off Babolsar port in Autumn 2008 was presented. The collected data showed a variation of sound speed between 1488 m sec^{-1} at the sea surface to 1460 m sec^{-1} at depth of 42 m in the study area. In the sea surface mixed layer, sound speed mainly ranged between 1487-1488 m sec^{-1}. The results showed strong vertical gradient but weak horizontal gradient of sound speed in the water column. Vertical structure of sound speed indicated a sharply decreasing trend from 1488 to 1460 m sec^{-1} across the thermocline. The sound speed variations follow the variations in temperature, indicating strong correlation between the two parameters in the study area. Therefore, sound speed was predominantly influence by temperature rather than salinity and pressure.

Key words: Caspian Sea, physical oceanography, sound speed, thermocline, vertical structure

INTRODUCTION

The sound velocity determination in seawater is one of the important factors in hydrographic surveying (Alkan *et al*., 2006). In oceanography and marine research, acoustic pulse is extensively used to investigation on ocean floor and measurement of wave and current (Stewart, 2005). Profiles of sound speed can give useful information on ocean characteristics (Carriere *et al*., 2009) and seawater properties. Recently, acoustic methods has been widely developed for under water communications, remote observations of seas and oceans (Salon *et al*., 2003) and fisheries purposes.

Owing to the special mechanical properties of seawater, the sound moves at a mean speed around 1500 m sec^{-1} in water. This average value for the sound speed in seawater is accepted for the nominal condition of the water environment (0°C temperature, 35 ppt salinity and 760 mmHg pressure) (Ingham, 1992). Sound travels faster with increasing temperature, salinity and pressure. Temperature strongly affects the speed of sound (e.g., sound travels faster in warm water than in cold water) and is very influential in some parts of the ocean (Fofonoff and Millard, 1983).

The speed of sound in seawater is variable and depends on its temperature, as well as on the salinity and hydrostatic pressure (Descamps, 2009). In the other word, in fluids the medium's compressibility and density (as function of temperature, salinity and pressure) are the important factors. For calculation of the speed of sound, Wilson's empirical formula offered in 1960 is of common use (Wilson, 1960).

An accurate description of the seawater parameters is essential for underwater acoustics applications that are based on full-field measurements (Rixen *et al*., 2009; Carriere *et al*., 2009). The investigation on sound speed structure in water column in various ranges of environmental properties represents the great interest for oceanographers and marine researchers.

Recently, physical oceanography and marine sciences were widely grown in the Southern Caspian Sea, in adjacent to Iranian coasts. The effect of the equipments application and shipboard field observations on the development of physical oceanography in the Southern coastal waters of the Caspian Sea was considerable. The aim of this research was to observe the vertical structure of sound speed in the Southern Caspian Sea waters near Babolsar port in Autumn 2008.

MATERIALS AND METHODS

Study area: This research was carried out in a rectangular area which located at latitude about N36°45′ and longitude about E52°38′ and covered a band of coastal waters with the length of 10 km and width of 9 km in adjacent to Babolsar port (Fig. 1a, b). In this area, the continental shelf has a width of about 10 km. The depth from the coast increases gently to about 45 m near the

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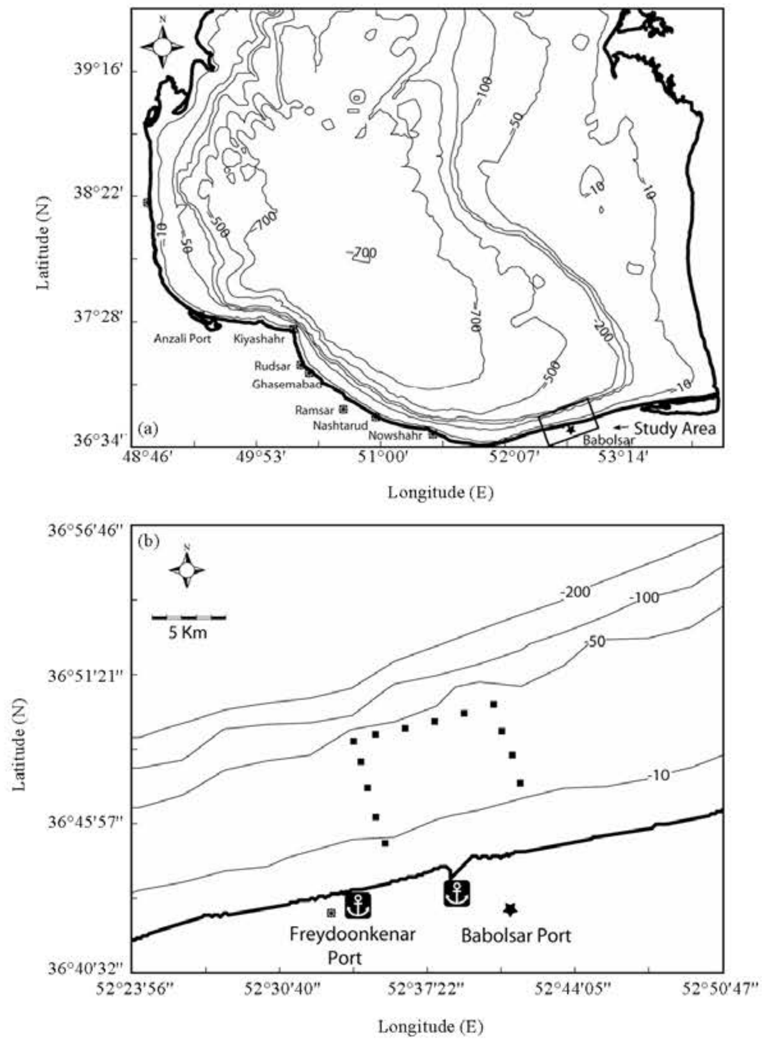

Fig. 1: (a) The Southern Caspian Sea, (b) positions of stations in the study area

shelf break, after that the width sharply increases to 400 m about 18 km from the coast line (Zaker *et al*., 2007).

The Southern coast of the Caspian Sea has a warm and humid subtropical climate. The maximum and minimum air temperatures are in the August and January, respectively. In the winter, the air temperature ranges between 8-12°C and in Summer the mean monthly air temperature over the entire sea equals 24-26°C. In the South Caspian, the mean annual wind speed is 3-4 m sec^{-1} and the recurrence rate of weak winds here reaches 90%. In the Southern part of the sea, the number of days with storms (wind speed greater than 15 m sec^{-1}) is not more than 20-30 year^{-1}. The salinity in the Southern basin of the Caspian Sea ranges between 12 and 13 psu (Kosarev, 2005).

Due to the isolation of the Caspian Sea from the World Oceans, the formation of thermohaline is under effect of atmospheric conditions over the sea and its vast drainage area. In addition, large-scale features of the thermohaline structure and its temporal variability are controlled with river runoff, the fluxes of heat and freshwater across the sea surface (Tuzhilkin and Kosarev, 2005).

Seawater properties: In a previous study, Zaker *et al*. (2007) were made a seasonal study on physical properties of coastal waters of the Southern Caspian Sea in Summer and Autumn 2003. Basis on their research, temperature at the sea surface water over the east part of the Southern continental shelf of the Caspian Sea, off Babolsar port reached a maximum of 29°C in Summer. Then in accordance to the reduction of air temperature due to seasonal changes, seawater temperature reduced to 20°C in late Autumn. They reported existence a sharp thermocline between 20-50 m depth with 15°C temperature decrease across it in Summer (Zaker *et al*., 2007).

In the time of measurements, vertical variations of temperature were between 17.9 to 9.2°C from sea surface to 42 m depth, with the maximal levels at the surface. Surface mixed layer had a thickness about 30 m and temperature through it ranged between 17.9 to 17.6°C from surface to above thermocline. A seasonal thermocline located below 30 m depths with more than 8°C temperature gradient across it. Variations of the salinity were found to vary between 12.06-12.67 psu. Density variations were between 1008.6 kg and 1010.4 kg m^{-3}. Due to small salinity values of the Caspian Sea water, the density changes highly correlated with variations of water temperature (Jamshidi and Abu Bakar, 2009).

Field measurements: The presented data were collected during a marine cruise on the Southern coastal waters of the Caspian Sea that were organized by the Iranian National Center for Oceanography (INCO), in November 2008. Study area and CTD stations were shown in Fig. 1. Sound speed data were measured by using a portable CTD probe (Ocean Seven 316) developed by IDRONAUT. Profiling was conducted at 13 CTD stations along three survey lines in the coastal waters of Babolsar port. Two of transects were perpendicular to the coast and one transect was parallel to the coastline. The CTD probe was set in Timed Data Acquisition mode for profiling. For sound speed measuring, the profiler was released into the seawater column below to 42 m depth with a speed of 1 m sec^{-1}. Vertical structure of sound speed data was presented in three plots related to the Western, Eastern and alongshore transects. The distances between sampling stations were 2 km in the area. The GPS (Global Positioning System) was used for recording the position of the sampling stations. Positions of the CTD stations were shown in the Table 1.

Computation of sound speed: The sound velocity might be varied from place to place over the survey area and this changing might happen during the surveying intervals (Ingham, 1992). Minimum and maximum values of sound velocity might vary between 1387 and 1529 m sec^{-1} intervals depending on the seawater characteristics (Alkan *et al*., 2006). The value of sound speed could be determined by means of empirical formula using the temperature T, pressure P (or depth D) and salinity S which measured by CTD sensors.

There are several different instruments and methods to determine the sound speed (Alkan *et al*., 2006). Some of important formulas, which are available to calculate the speed of sound in water presented by Wilson (1960),

Table 1: Position of CTD stations in the study area

Stations	Latitude	Longitude
St01	N36 45.123	E52 42.453
St02	N36 46.174	E52 42.084
St03	N36 47.198	E52 41.747
St04	N36 48.222	E52 41.411
St05	N36 48.087	E52 40.066
St06	N36 47.899	E52 38.720
St07	N36 47.710	E52 37.409
St08	N36 47.495	E52 36.131
St09	N36 47.171	E52 34.786
St10	N36 46.155	E52 35.138
St11	N36 45.099	E52 35.542
St12	N36 44.053	E52 35.905
St13	N36 43.008	E52 36.174

Table 2: Coefficients in the formula for computing speed of sound

Coefficients	Numerical values	Coefficients	Numerical values
C_{00}	1402.388	A_{02}	7.166E-5
C_{01}	5.03830	A_{03}	2.008E-6
C_{02}	-5.81090E-2	A_{04}	-3.21E-8
C_{03}	3.3432E-4	A_{10}	9.4742E-5
C_{04}	-1.47797E-6	A_{11}	-1.2583E-5
C_{05}	3.1419E-9	A_{12}	-6.4928E-8
C_{10}	0.153563	A_{13}	1.0515E-8
C_{11}	6.8999E-4	A_{14}	-2.0142E-10
C_{12}	-8.1829E-6	A_{20}	-3.9064E-7
C_{13}	1.3632E-7	A_{21}	9.1061E-9
C_{14}	-6.1260E-10	A_{22}	-1.6009E-10
C_{20}	3.1260E-5	A_{23}	7.994E-12
C_{21}	-1.7111E-6	A_{30}	1.100E-10
C_{22}	2.5986E-8	A_{31}	6.651E-12
C_{23}	-2.5353E-10	A_{32}	-3.391E-13
C_{24}	1.0415E-12	B_{00}	-1.922E-2
C_{30}	-9.7729E-9	B_{01}	-4.42E-5
C_{31}	3.8513E-10	B_{10}	7.3637E-5
C_{32}	-2.3654E-12	B_{11}	1.7950E-7
A_{00}	1.389	D_{00}	1.727E-3
A_{01}	-1.262E-2	D_{10}	-7.9836E-6

Del-Grosso (1974), Medwin (1975), Chen and Millero (1977), Mackenzie (1981). In this study, pressure, temperature, salinity and sound speed in seawater were sensed and were computed by the CTD probe, using the standard processes of UNESCO formulas (UNESCO, 1981a, b). The international standard algorithm, often known as the UNESCO algorithm, is due to Chen and Millero (1977) and has a more complicated form than other simple equations.

$$c(S,T,P) = C_W(T,P) + A(T,P)S + B(T,P)S^{3/2} + D(T,P)S^2 \quad (1)$$

$$\begin{aligned} C_W(T,P) = {} & (C_{00} + C_{01}T + C_{02}T^2 + C_{03}T^3 + C_{04}T^4 + C_{05}T^5) \\ & + (C_{10} + C_{11}T + C_{12}T^2 + C_{13}T^3 + C_{14}T^4)P + (C_{20} + C_{21}T + \\ & C_{22}T^2 + C_{23}T^3 + C_{24}T^4)P^2 + (C_{30} + C_{31}T + C_{32}T^2)P^3 \end{aligned} \quad (2)$$

$$\begin{aligned} A(T,P) = {} & (A_{00} + A_{01}T + A_{02}T^2 + A_{03}T^3 + A_{04}T^4) + \\ & (A_{10} + A_{11}T + A_{12}T^2 + A_{13}T^3 + A_{14}T^4)P + \\ & (A_{20} + A_{21}T + A_{22}T^2 + A_{23}T^3)P^2 + (A_{30} + A_{31}T + A_{32}T^2)P^3 \end{aligned} \quad (3)$$

$$B(T,P) = B_{00} + B_{01}T + (B_{10} + B_{11}T)P \quad (4)$$

$$D(T,P) = D_{00} + D_{10}P \qquad (5)$$

where, T is temperature in degrees Celsius, S is salinity in PSU and P is pressure in bar. Coefficients and numerical values were shown in Table 2 (Chen and Millero, 1977).

RESULTS AND DISCUSSION

Vertical structure of sound speed in the seawater and its variations over the Southern continental shelf of the Caspian Sea in adjacent to Babolsar port, Iran were presented basis on CTD collected data in Autumn 2008.

In the Western transect, depth from 9 m depth reached to 42 m at the end of transect. The water body over the continental shelf was mainly located in the surface mixed layer and thermocline. The section was included of five sampling stations. Here, vertical structure of sound velocity showed a variation from 1488 to 1460 m sec^{-1} (Fig. 2). At the surface mixed layer, (0-30 m depth) range of sound speed variations was not great (between 1787 and 1488 m sec^{-1}). Vertical difference in sound speed below 30 m depth was more than upper layer. At the end of transect sound velocity variations in water column were sharp (between 1488-1460 m sec^{-1}).

Field observations in the Eastern transect were done in four sampling stations. Values of sound speed at the surface layers were around 1488 m sec^{-1} (Fig. 3). With increase the depth, amounts of sound speed in the deeper part of transect, were rapidly reduced.

The vertical structure of sound speed along section parallel to the coastline in Northern part of the study area and located 10 km away from the coast was indicated in Fig. 4. Vertical and horizontal variations of sound speed were clearly shown in the Fig. 4. The contours of the sound speed are parallel to the sea surface level, across the thermocline. Sound speed variations were from 1488 m sec^{-1} at the surface to 1460 m sec^{-1} near the bottom at the 42 m depth. At the surface mixed layer (upper 30 m depth), the sound speed was about 1488 m sec^{-1}. Below 30 m depth, vertical gradient of the sound speed was considerable. Horizontal gradients of sound speed along transect were slight. Variation of sound speed was from 1487 to 1460 m sec^{-1} with reduce the depth. In the surface mixed layer, low changes of temperature were observed. Due to existence of high agreement between temperature and sound speed, vertical variations of sound velocity were slight in mixed layer. At the time of measurements, most changes of sound velocity were across the thermocline layer.

Vertical profiles of seawater properties consist of temperature, salinity, pressure and sound speed were illustrated in Fig. 5. Range of the variations of sound

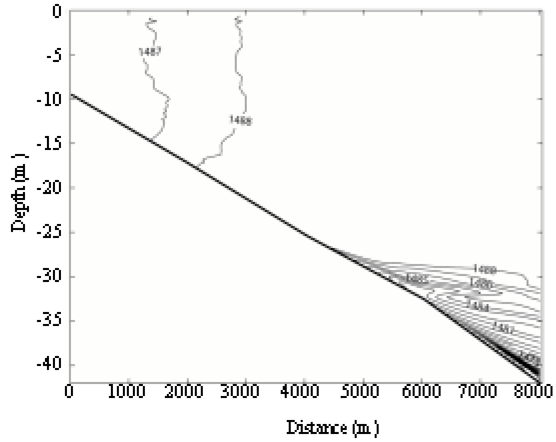

Fig. 2: Vertical structure of sound speed along Western transect, the left side of the plot is to the South

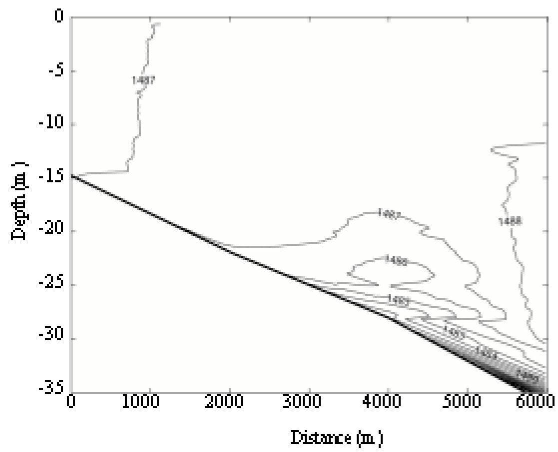

Fig. 3: Vertical structure of sound speed along Eastern transect, the left side of the plot is to the South

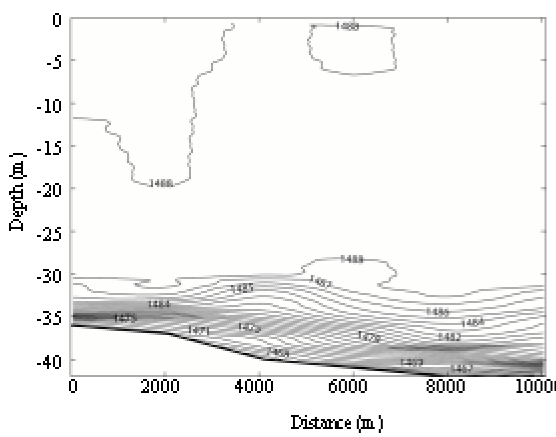

Fig. 4: Vertical structure of sound speed in an alongshore transect about 10 km away from the coastline; the left side of the plot is to the East

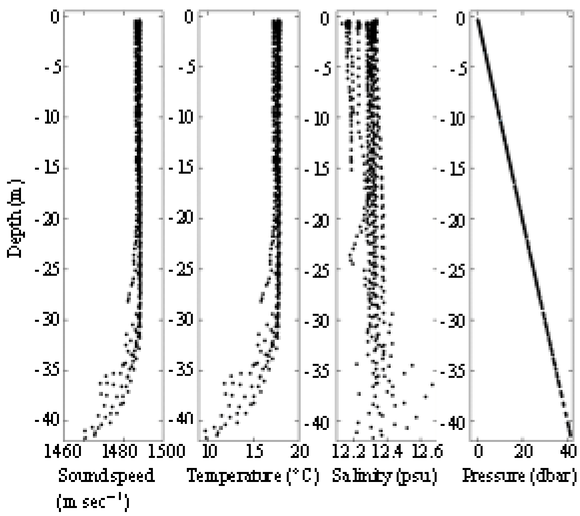

Fig. 5: Profiles of seawater properties in the study area

speed was between 1488 and 1460 m sec^{-1} from sea surface to depth of 42 m. Vertical gradient of sound velocity at the surface layer was high. Basis on the analysis of the collected data, there is a good coordination between variations of sound speed in the study area with the temperature changes. Furthermore, the effect of the salinity on sound velocity changes was low (Fig. 5).

Diagram of temperature-salinity-sound speed over whole data was illustrated in the Fig. 6. As it can be seen, the data was divided to main part at the top and down of the graph. The great part of data with high values of temperature and sound speed was located in the top levels of diagram. This data was related to the surface mixed layer and upper levels of the thermocline. Another part of collected data with temperature less than 16°C, various salinity and low levels of sound speed was seen in the lower part of the diagram. This set of scattered data was recorded from the near bottom.

To characterize the relation of sound speed with temperature and salinity, plots of sound speed versus temperature and salinity referred to all observed data, were presented. Scatter plots of sound speed-temperature- and sound speed-salinity were indicated in Fig. 7. Figure 7a showed the high coherency of sound speed and temperature data, which located on a line. Figure 7b shows a data of sound speed-salinity, which subdivided to two parts.

Totally, in the time of the measurements, vertical variations of sound velocity were in agreement with temperature changes. Range of variations of sound speed was great due to high gradient in the temperature from

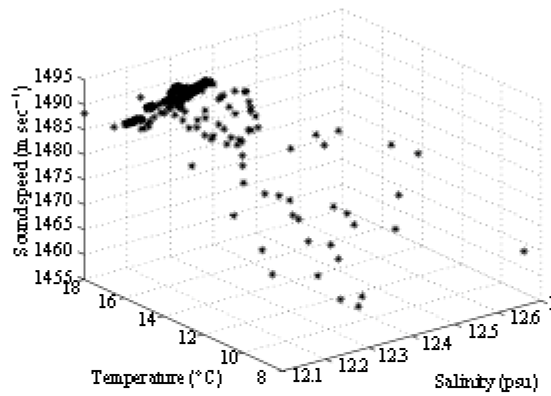

Fig. 6: Temperature-salinity-sound speed diagram

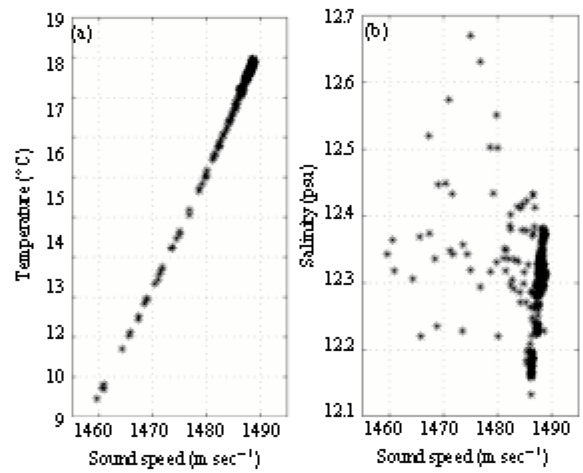

Fig. 7: Scatter plot of (a) sound speed (m sec^{-1}) and temperature (°C), (b) sound speed (m sec^{-1}) and salinity (psu)

surface to bottom. The sound speed varied between 1488-1460 m sec^{-1} at the sea surface and depths of 42 m, respectively. In the surface mixed layer, sound speed ranged between 1488-1487 m sec^{-1} between surface and depth of 30 m. Vertical structure of sound speed indicated a sharply decreasing from 1487 to 1460 m sec^{-1} across the thermocline. Changes of temperature affecting on variations of sound velocity were major. Due to sharply decreasing in temperature in the thermocline, contours of sound speed are very compact across the thermocline. Due to existence the coherency between sound speed and temperature and similarity of their variations, stratification of upper mixed layer (0-30 m), thermocline (below 30 m depth) can be clearly seen in vertical profiles. Vertical variations of sound velocity across the surface mixed layer were slight and less than thermocline layer.

In comparison between field measurements of the present study and observations which were done by Zaker *et al*. (2007) in the region, difference of temperature between sea surface and deeper layer in the study area in warm months is greater than its gradient in cool months. Therefore, according to the structure of temperature in various seasons in the Southern coastal waters of the Caspian Sea, it is expected that, vertical gradients of sound speed in warm months are more than its vertical gradient in cool months. The vertical gradients of sound velocity in Winter and Summer are minimal and maximal, respectively.

Based on our search, important and accurate studies on vertical structure of sound speed in the Southern coastal waters of the Caspian Sea are not available. Therefore, results of a similar study in Mediterranean Sea were presented for comparison. It should be noted that, due to existence difference between seawater properties of Mediterranean and Caspian Seas, there are some changes in range and structure of sound speed in them. Salon *et al*. (2003) conducted an analysis on sound speed variations in the Mediterranean Sea based on climatological temperature and salinity data. Basis on their measurements, the minimum values of sound speed observations were at the base of the thermocline at about 120 m depth (1508 m sec^{-1}) in Western part of the sea. While the profile from the Eastern part of Mediterranean Sea showed a minimum value of 1515.3 m sec^{-1} from 150 to 280 m depths. In mid Winter, sound velocity was observed from values lower than 1498 m sec^{-1}, up to 1520 m sec^{-1} at depth about 50 m. In Summer, at 50 m depth, sound speed ranged from 1506 m sec^{-1} up to the maximum velocity of 1530 m sec^{-1} in Eastern coasts of Mediterranean Sea (Salon *et al*., 2003).

CONCLUSION

Vertical structure of sound speed in the Southern coastal waters of the Caspian Sea, off Babolsar in Autumn 2008 was presented. The results of the study give useful preliminary information on vertical and horizontal variations of sound speed in the region in Autumn. The collected data showed variation of sound speed between 1488 m sec^{-1} at the sea surface to 1460 m sec^{-1} at depth of 42 m. Vertical structure of sound speed indicated a sharply decreasing trend from 1488 to 1460 m sec^{-1} across the thermocline. The sound speed variations follow the variations in temperature, indicating strong correlation between the two parameters in the study area.

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