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Investigation of the Effect of Persian Gulf Outflow Intrusion into the Oman Sea on the Acoustic Signal Fluctuations

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Abstract

Outflow intrusions are often detected in the vertical profiles of temperature and salinity in the ocean (for example, the Red Sea and Persian Gulf outflow into the India Ocean and Oman Sea, respectively). They are being visible by large fluctuations or inversions within the profiles and as zig-zag patterns in the temperature-salinity plots. In this study, first, using the collected salinity and temperature data in the region of the Oman Sea during spring 1996, the sound speed is calculated via Makenzie formula. Then, by plotting the sound speed profile, it was seen that the vertical structure meet anomaly at depth 200 to 400 meter of the profile. Moreover, the effects of presence and absence of the temperature inversion have been examined on the acoustic signal fluctuations with similar boundary conditions using SPARC model at frequency of 100 Hz. The results show that, when the acoustic source is installed below the inversion layer, receivers that are located in the low temperature inversion layer, receive the signal with time delay, and amplitude is greater than that with the absent inversion temperature. Thereby, the present achievements indicate that the outflow intrusion may affect the shapes and delay times of the received signals.

Keywords: Outflow intrusion, Acoustic signal fluctuations, SPARC model, Persian Gulf, Temperature inversion.

1. Introduction

The ocean is a random medium having both deterministic and nondeterministic characteristics. This behavior often leads to the difficulty in performing underwater applications such as telemetry and tomography.

The sound speed profile as a function of ocean depth is perturbed by spatial-temporal variations produced by internal gravity waves (Apel et al., 2007; Tang et al, 2007; Zhang and Swinney, 2014) and eddies (Baer, 1980; Jian et al., 2009) and fronts (Holbrook et al., 2003; Lin and Lynch, 2012).

The propagation of acoustic rays in the ocean depends on temperature, salinity, and density (Mackenzie, 1981). While pressure is primarily controlled by depth, temperature and salinity vary in the ocean due to the currents, surface mixed layer, eddies, internal waves and other oceanographic features. These features affect the structure of the temperature and salinity fields, which in turn determines the sound velocity fields. Furthermore, these features change both in time and space, modifying the temperature, salinity and sound velocity fields both spatially and temporally. Another oceanographic feature that affects the acoustic propagation is temperature inversion such as in China seas (Hao et al., 2010), Huanghai Sea (Yuan et al., 2013) and Persian Gulf. Thus, a sudden change in the sound speed with depth within an intrusion flow can greatly affect the sound propagation. The ocean environment that includes water column, surface and bottom boundaries, plays a vital role in the operation of sonar system. In fact, the ocean environment models constitute the basis for sonar performance ones and acoustic propagation models serve as a link between them. Unlike the sea bottom characteristics, which are considered time-invariant for sonar applications, the water column properties like temperature, salinity, density and currents are highly variable both in time and space (Kurian and Vinayachandran, 2006). Thermohaline intrusions are often observed in vertical profiles of temperature and salinity in the ocean. They are observable in terms of

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large fluctuations or inversions in the profiles and as zig-zag patterns in the vertical temperature-salinity profiles. These features typically have vertical scales of 10–100 m and horizontal ones of 1–100 km (Stojanovic and Preisig, 2009). In the seas and oceans, the temperature decreases in the lower latitudes from the surface to the depths. However, at some points, this phenomenon does not occur normally, so that the temperature rises again with increasing depth from a specific amount and began to fall again after a few tens of meters. This increase in temperature is called the temperature inversion. Temperature inversion in the seas around Japan has been studied using topographic data. The obtained results indicated that temperature inversion occurs in many parts of the region, which are mixed with Oyasho and Korshyo water. Akbarinasab et al. (2012) investigated the sound propagation in the presence and absence of vertical fine-structure fluctuations in the Oman Sea. Their results indicated that the shadow zones increase (the sound ray does not penetrate in these locations) in the absence of vertical inhomogenities, while in the presence of them, which cause the sound energy scattering in the environment, the energy can leak in to the sound channel (Akbarinasab et al., 2012). Akbarinasab (2015) also, investigated the influence of Plume outflow intrusion on the acoustical signal fluctuations in the laboratory. Results show that the outflow intrusion could be important in changing the shapes of the received signals (Akbarinasab, 2015).

The objective of the present research is to investigate the effect of the presence or absence of temperature inversion on the acoustic signal fluctuations in the Oman Sea.

2. Materials and methods

2-1. Data collection

A site map for simulating the acoustic signal fluctuations is depicted in Figure 1. The data used in this work were provided by the International Project Joint Global Ocean Flux Study (JGOFS) during the spring 1996 (http://usjgofs.whoi.edu/jg/dir/jgofs/). In this analysis, temperature, salinity, and sound speed (calculated by Wilson formula (Robert, 1983)) are used. The propagation site is located between the southern and middle parts of the Oman Gulf or Oman Sea. Station 12 (longitude of 59°.29'02" and latitude of 24°.47'19" in case of temperature inversion presence) is nearly located at the Strait of Hormuz and station 29 (longitude of 57°.62'58" and latitude of 25°.03'86" in the case of temperature inversion absence) is nearly located at the middle of Oman Sea.

Figure 1. Positions of stations 12 and 29 in the study area.

2-2. Physical properties of the intrusion outflow

In order to study the temperature inversion layer on the sound propagation, the variations of field data such as sound speed, temperature and salinity in the vertical profile of the Oman Sea were analyzed using MATLAB software. Figures 2 (station 12) and 3 (station 29) show the variations of temperature and salinity vertical profiles at different depths within the spring season. As can be seen from these plots, the thickness of temperature inversion associated with station 12 is more than that of station 29. This phenomenon is due to the Persian Gulf outflow intrusion in to the Oman Sea. Among the parameters affecting the sound propagation, water temperature and pressure dynamically change with depth and have more impacts on the sound speed variation, compared to the salinity. In this season, the outflow is more evident at a depth of 209 m and absent at that of 236 m.

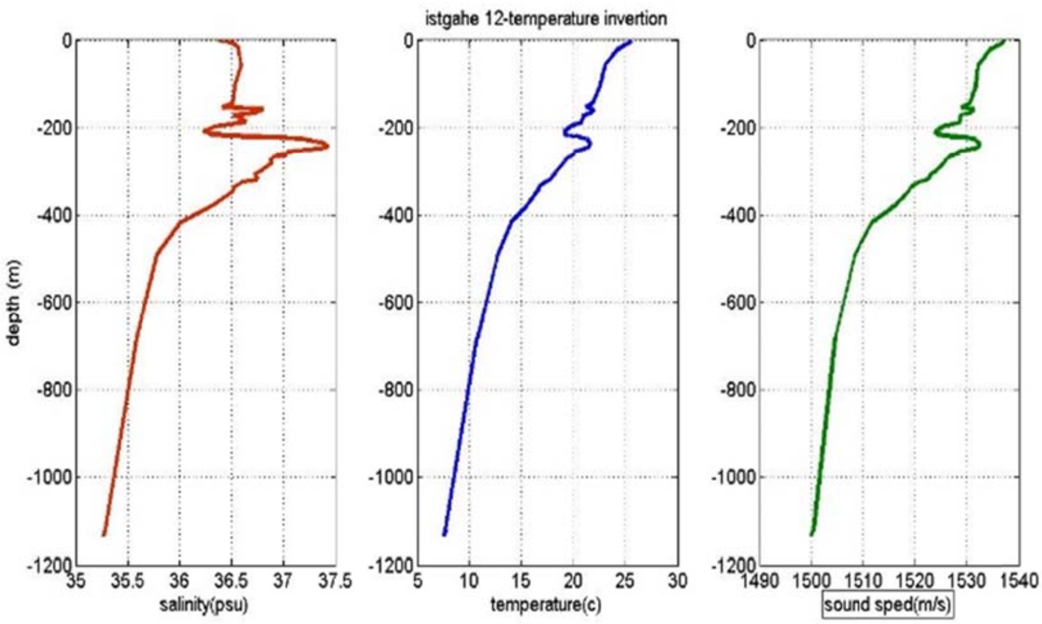

Figure 2. From left to right, the vertical profiles of salinity, temperature and sound speed corresponding to 29 station.

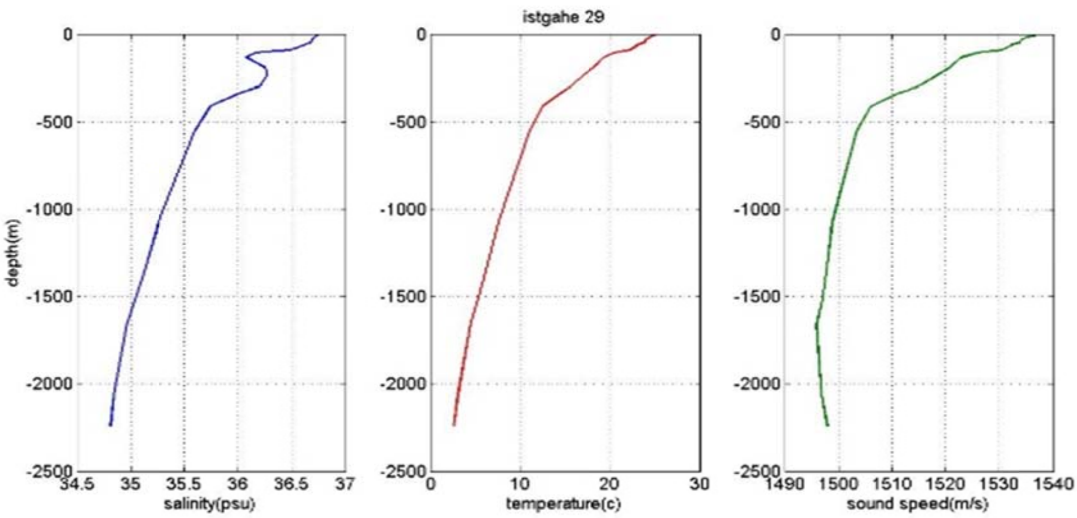

Figure 3. From left to right, the vertical profiles of salinity, temperature and sound speed corresponding to 12 station.

Using these figures, it is clear that temperature is the main factor affecting the sound speed in the Oman Sea during this season.

2-3. Investigation of the sound propagation in the study area

As mentioned earlier, the temperature inversion is due to the outflow of the Persian Gulf in to the Oman Sea. Today, there are several acoustic models which can be used to predict the sound propagation changes, but all of them have limitations as they use approximations in calculating the acoustic intensity. In this study, SPARC (SACLANTCEN Pulse Acoustic Research Code) model (Porter, 1990; Jensen et al., 2011) has been implemented for investigating the effect of Persian Gulf outflow intrusion in to the Oman Sea on the acoustic signal fluctuations. SPARC is an experimental time-marched FFP. Here, different scenarios of the acoustic signal fluctuations at the two stations were simulated. In addition, to prevent the backscattered effects from the boundaries in the acoustic signals, the characteristics of the boundaries at surface and bottom in all scenarios were considered as vacuum. For all scenarios, the sending signal is a pseudo-

Gaussian pulse with amplitude of 1.2982 cm and frequency of 100 Hz, whose bandwidth rannge from 1 to 300 Hz. The program was run to compute the received acoustic pulse structure for the following different environmental conditions in two stations :(a) Case 1: The transmitter is at the depth of 200 m (into the inversion layer) and receivers are at depths of 50, 266, 483 and 700 m, respectively with an interval of 500 m. (b) Case 2: The transmitter is at a depth of 700 m (below the inversion layer) and receivers are placed at the depths the same as in case 1. The received multi-path pulses structure is shown in Figures 4, 5 and 6. The pulse amplitude is a relative value and the horizontal axis is the propagation time from the transmitter to the receiver. The arrangement of the acoustic sensors is exhibited in Figures 4, 6, 8 and 9. Meanwhile, in all presented figures and tables, the received signals are normalized to their maximum magnitudes.

2-4. Simulation scenario of the acoustic signal fluctuations in the presence of temperature inversion at the depth of 200 m

In the first scenario, the computer simulation (SPARC model) was performed for the case with temperature inversion as described above. The depth of acoustic source is 200 m and vertical array of receivers is installed within the depths of 50, 266, 483, and 700 m with a distance of 500 m. The schematic of this set up is shown on the left panel of Figure 4. In the right panel of this figure, the output fluctuations of the acoustic signal are shown in the above-mentioned depths. Meanwhile, the amplitudes shown are normalized with the maximum amplitude of the corresponding signals. As would be observed, the received signal consists of two distinct wave packets. The modes that have been affected by the stratification of the water layers are evidence for the shape and scope changes. Further to these, the delay time between the two modes is increasing from the surface to the depth. The delays are caused by the sound speed reduction from the surface to the bed. The peak amplitude also changes, which its origin is from stratified layers and range of signal fluctuations reduce from the surface to the seabed. In general, the signal amplitude in the received second mode meet higher reduction from the surface to the depth compared to the first one.

The received signals have delay times at different hydrophones. The delays are clearly seen in Figure 5. According to this figure, the signals are received earlier at the depths of 50, 266, 483 and 700 m, respectively.

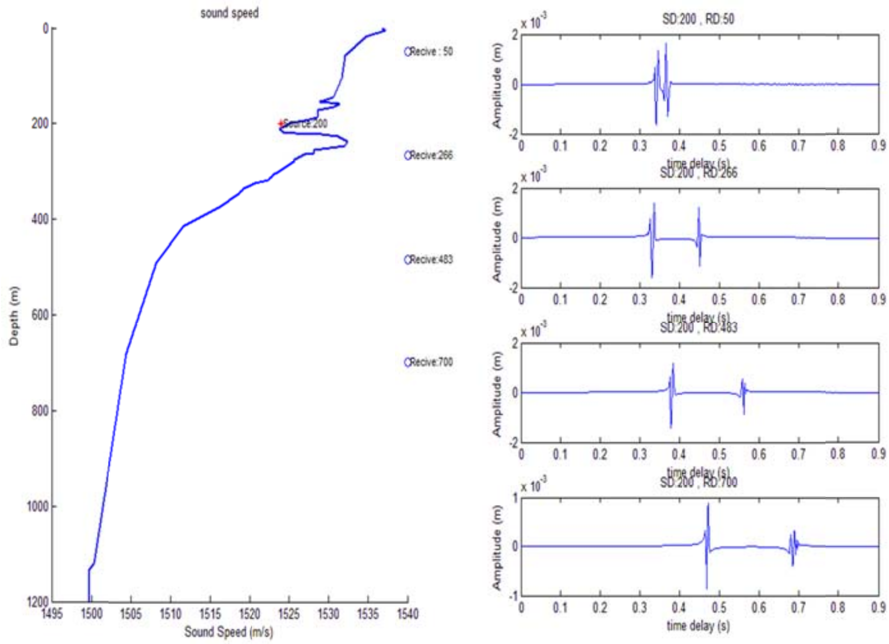

Figure 4. left panel shows the vertical profile of sound speed at station 12, location of the acoustic source and vertical array of the receivers. Right panel shows the time series of the acoustic signal fluctuations versus time at different depths.

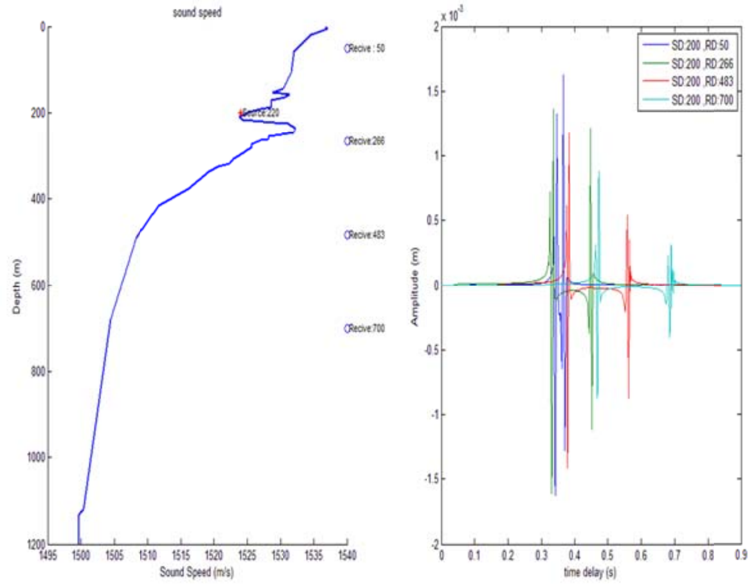

Figure 5. (left panel) shows the vertical profile of sound speed at station 12, location of acoustic source (200 m) and vertical array of the receivers. Right panel shows the delay time series of the acoustic signal fluctuations versus time at different depths (50, 266, 483 and 700 m) (the corresponding graph of the receiver depth of 433 m is highlighted as red signal).

2-5. Simulation scenario of the acoustic signal fluctuations in the absence of temperature inversion at the depth of 200 m

In the second scenario, the computer simulation (SPARC model) was performed in the absence of temperature inversion for station 29 (Porter, 1992). The working method and simulation set-up is similar to the first scenario. The schematic of this set up is shown in the left panel of Figure 6. In this figure, we see that the received signal consists of two distinct wave packets similar to the previous scenario. The acoustic signal amplitude decreases from the surface to the depths. In a same manner as above, the delay time in this case will increase between the two modes from the surface to the depth. Besides, the energy intensity reduction in the second mode is more than the first one.

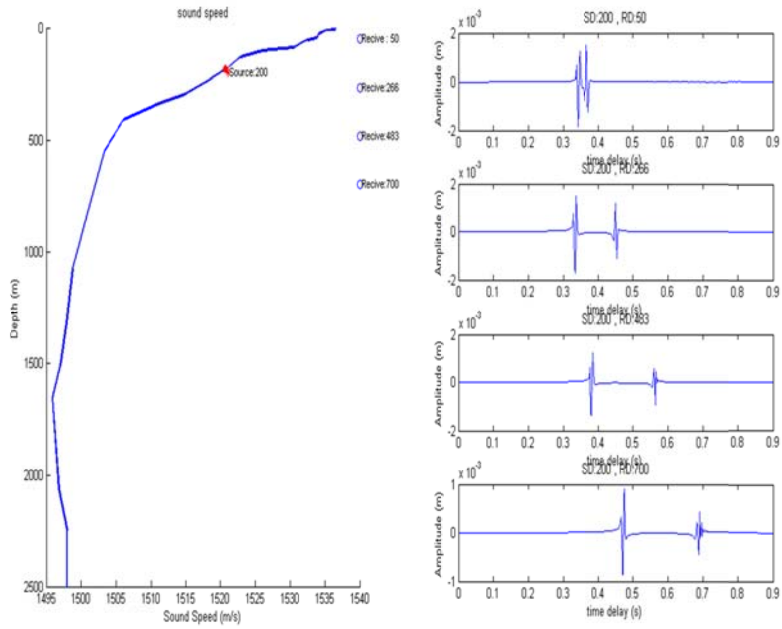

Figure 6. (left panel) shows the vertical profile of sound speed at station 29, location of the acoustic source (200 m) and vertical array of the receivers. Right panel shows the time series of acoustic signal fluctuations versus time at different depths.

Table 1. peak to peak comparison of the signals in the presence and absence of inversion within the range of 500 m (transmitter depth is 200 m and all signals are normalized).

Transmitter and receiver depths		**temperature inversion Present is (normalized)**		**temperature inversion is Absent**	
SD	RD	peak to peak (normalized)	time delay	peak to peak (normalized)	time delay
200	50	0.92	0.009	0.96	0.0099
200	266	0.93	-0.0027	1	0
200	483	0.81	0.0459	0.81	0.0486
200	700	0.54	0.1359	0.55	0.1377

2-6. Simulation scenario of the acoustic signal fluctuations in the presence of temperature inversion at the depth of 700 m

In this section, the simulation is presented similar to the previous cases in the presence of inversion, but the acoustic source is placed at a depth of 700 m. In this simulation, as shown in Figure 7, the signal is received by the source at the depth of 700 m. Then, the receiver sensors at depths of 483, 266 and 50 m receive the acoustic signal. It is observed that the transmitted signal in this situation is received with two modes as well. Since the transmitted signal in this case from a depth of 700 m where there is the lowest temperature changes, the second received mode becomes the high amplitude one from bottom to top. The fluctuations amount in the received signal intensity is low in the lower depths, but increases as it passes and reach the upper layers, due to the higher temperature profile changes.

In order to investigate the delay time of the signals received at different depths of the simulation, the whole received signals are plotted in one figure. The time delays can be clearly seen in Figure 8. As can be observed, the signals are received sooner at the depths of 483, 266 and 50 m, respectively. The second mode of signals will appear due to the acoustic signals passing through water layers with temperature and salinity fluctuations, which all affect the vertical profile of sound speed.

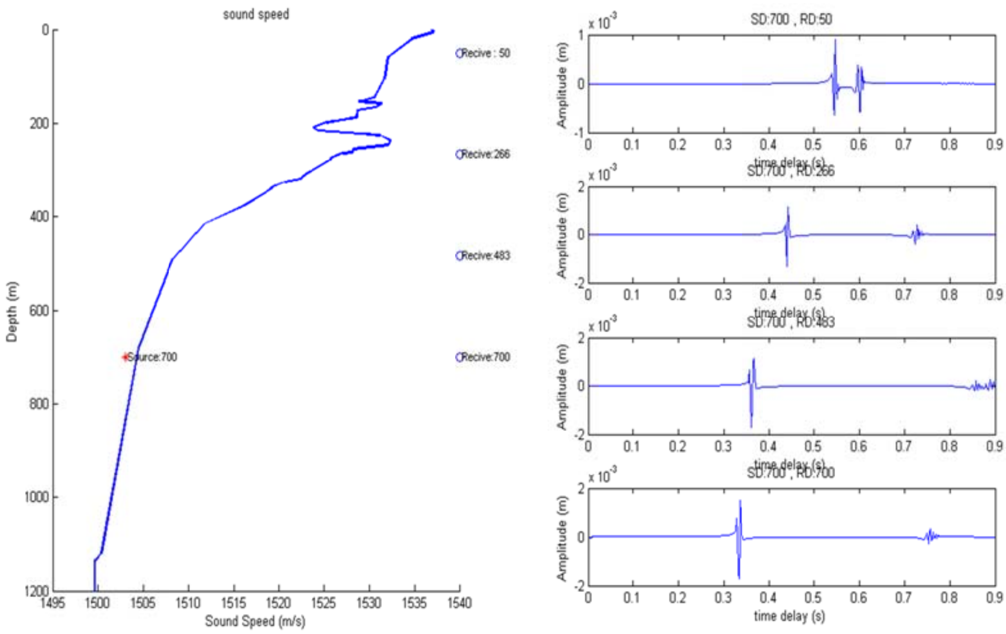

Figure 7. Left panel shows the vertical profile of sound speed at station 12, location of the acoustic source (700 m) and vertical array of the receivers. Right panel shows the time series of acoustic signal fluctuations versus time at different depths.

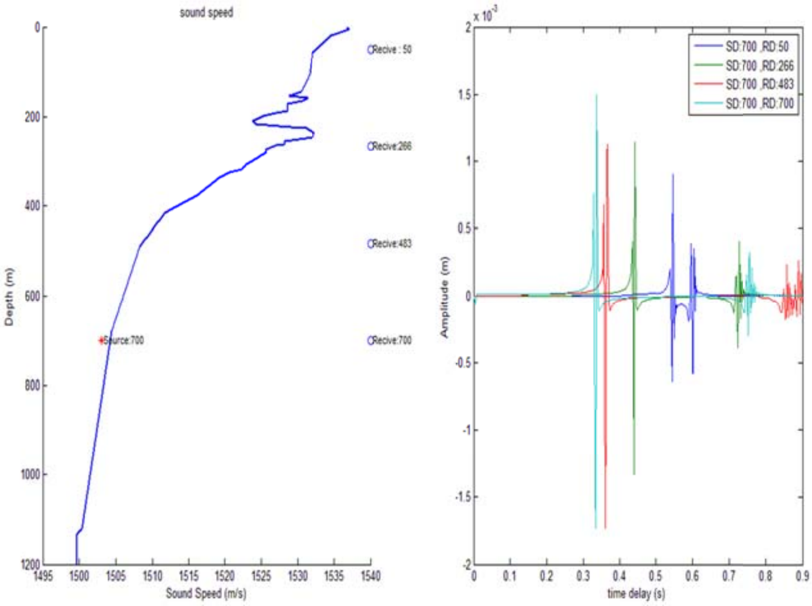

Figure 8. The received time signals by four sensors (station 12).

2-7. Simulation scenario of the acoustic signal fluctuations in the absence of temperature inversion at the depth of 700 m

In this section, the simulation process is similar to the previous cases in the absence of inversion and the acoustic source is installed at a depth of 700 m. The simulation results are illustrated in Figure 9. As can be seen in this figure, when the receiver sensor is installed at a depth of 700 m, the second mode is not observed because there is no environmental inhomogeneities and the sound speed profile is nearly smooth. It is shown that the second mode is received after the first one at the depths of 483, 266, 50 m. The first mode is received between 0.3 s and 0.4 s by the sensors placed at the depths of 700 and 483 m. However, this mode is received between 0.4 s and 0.5 s, and between 0.5 s and 0.6 s by the sensors located at the depths of 266 and 50 m, respectively.

Table 2 gives a comparison between peak-to-peak variations of signal in different circumstances and for two cases of present and absent temperature inversion.

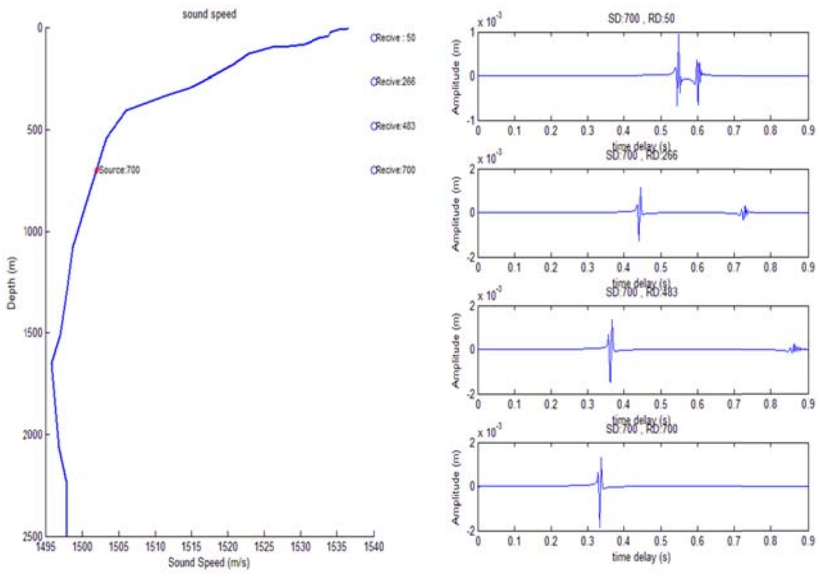

Figure 9. Left panel shows vertical profile of sound speed at station 29, location of the acoustic source (700 m) and vertical array of the receivers. Right panel shows the delay time series of the acoustic signal fluctuations versus time at different depths (50, 266, 483 and 700 m) (the corresponding graph of the receiver depth of 433 m is highlighted as red signal).

Table 2. peak-to-peak comparison of the signals in the presence and absence of inversion within the range of 500 m (transmitter depth is 700 m and all signals are normalized).

Transmitter and receiver depths		**Present temperature inversion (normalized)**		**Absent inversion temperature**	
SD	RD	peak-to-peak (normalized)	time delay	peak-to-peak (normalized)	time delay
700	50	0.47	0.2106	0.50	0.2124
700	266	0.76	0.1062	0.74	0.108
700	483	0.88	0.0297	0.87	0.0306
700	700	1	0	0.98	0

Tao and Xu (2007) investigated the propagation of acoustic pulse in the Taiwan straits using a fast field program. They showed that parameters such as propagation distance, water depth and sound speed profile have significant effects on the multi-path of the shallow water channel. The results of this research are very consistent with the results of present research.

3. Conclusion

Temperature inversion due to the Persian Gulf outflow to the Oman Sea has been investigated in the current study. This inversion leads to the sound speed inversion at the depths between 200 and 400 m and sound channel creation in these depths. The aim was to simulate the received signals at the frequency of 100 Hz by a linear array over time in order to investigate the impacts of the presence and absence of temperature inversions on the acoustic signal fluctuations in the Oman Sea.

The main findings of the present simulation are listed as below:

- If the transmitter is located at a depth of 200 m (the outflow intrusion) and receiver at 266 m, the received signal in the case of presence temperature inversion is earlier rather than the absence one but the signal amplitude decreases.
- When the transmitter is located at a depth of 700 m (the outflow intrusion) and receiver at the same depth, the received signal delays are similar for both cases, but the signal amplitude in the case of presence temperature inversion is higher than that associated with the absence temperature inversion.
- Table 1 gives a comparison between peak-to-peak variations of signal in different circumstances and two cases of presence and absence temperature inversion. As can be seen from this table, the received signal in the presence of an inversion can be observed by the receiver sooner but with an amplitude less than that when there is no temperature inversion.
- According to Table 2, it is revealed that the time delay of the received signal in both conditions is the same when both transmitter and receiver are at the depth of 700 m. This is due to the absence of temperature and salinity inhomogenities.

The acoustic signal fluctuations should be investigated by laboratory and filed experiment; this is strongly recommended that for improve improvement of the performance of undersea acoustic wireless communication.

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