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Changes of Physical Parameters of the Water Column from the Indian Ocean to the Persian Gulf

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ABSTRACT

A comprehensive and complete understanding of how physical parameters and sound wave propagation change in different places and times is essential and inevitable. The present study examined and evaluated vertical and horizontal changes in temperature, salinity, and sound velocity parameters in the seas surrounding the country's south, including the Persian Gulf, the Strait of Hormuz, the Sea of Oman, and the northern Indian Ocean. The physical parameters of the water column in the two cold and warm seasons of the region have been monitored and analyzed at selected stations in the aforementioned seas from the surface to the bed using the international data of the World Ocean Atlas 2018. The results of the studies indicate the existence of a permanent thermocline layer in the deep regions of the Oman Sea and the northern Indian Ocean, due to which the propagation of sound waves is reduced by more than 30 units. In the Persian Gulf and the Strait of Hormuz, due to the shallowness of the region, the thermocline layer is created only in the warm season of the region, and as a result, a weak sound channel is formed at depths near the bed. It should be noted that in all the studied regions, the propagation speed of sound waves is strongly dependent on the temperature parameter and its resulting changes in the water column are similar to vertical temperature changes. Also, two-dimensional sections indicate the penetration of salty waters of the Persian Gulf into the Oman Sea in layers near the bed throughout the year.

1. Introduction

As it is known, on average, 72% of the Earth's surface is covered by water, of which more than 97% is made up of seas and oceans. There are huge mineral resources and oil in these areas, which are now being used by humans for extraction and exploitation with the advancements in science and technology [4]. The science of sound wave propagation, or sonar for short, has numerous and abundant applications in marine activities. Among its applications are remote control systems in exploration equipment, collection and reception of information obtained by autonomous submarines, establishing voice communication between divers, studies and measurements of physical and chemical parameters of water, mapping of sea and ocean beds, tracking and navigation of subsurface floating systems, and real-time notification of some natural disasters such as tsunamis [4]. Therefore, accurate modeling of sound wave propagation and investigation of environmental effects is the first step in designing and building advanced industrial and military marine systems and estimating the efficiency of equipment used at sea.

Radio waves are highly attenuated in water and have a short effective range. Therefore, to send and receive information via radio waves over long distances, carriers with very low operating frequencies are required, which in turn requires very large antennas with very high transmission power [13]. This leads to the use of wireless communications underwater based on the use of sound waves in subsurface sound channels. Sound waves have received more attention and use than other common methods of communication due to their sufficient transmission and coverage of data transfer rates in the subsurface. Therefore, sound wave communications in the subsurface have made it possible to establish highly reliable communication over distances on the scale of several hundred kilometers [4]. The use and application of sound waves in marine topics and sciences is very effective and fruitful. However, the use of acoustic equipment in water bodies has several limitations and technical bottlenecks, including the following:

1. Information loss in the propagation path of sound waves;
2. Limitations in bandwidth selection;
3. Fading due to multipath propagation, due to multiple collisions with the surface and seabed;
4. Dependence of propagation and transmission of information on the frequency of sound waves;
5. Unknowingness' of sound channels at different times and places;
6. Delay in the propagation of sound waves due to the low speed of sound propagation compared to radio waves.

The underwater sound channel is one of the most challenging communication interfaces. Among the challenges of this environment are the low speed of sound propagation, distance and frequency dependent attenuation, noise caused by sea state and wind speed, reflection from the surface and seabed, and Doppler effects. These phenomena vary depending on the geographical conditions of the underwater environment, such as temperature, salinity, depth, etc. [10].

Many phenomena affect the propagation of sound waves underwater. The wave sent from the transmitter in this environment is subject to more severe attenuation, which depends not only on the distance but also on the frequency, and increases with increasing frequency. Part of this attenuation is due to the conversion of sound energy into heat and the other part is due to the absorption of sound energy by water molecules. On the other hand, sound waves sent underwater are combined with a lot of noise. Among these noises, we can mention noise caused by ship traffic, noise caused by sea surface turbulence, noise caused by marine organisms, and thermal noise. The effect of these phenomena is different at different frequencies. Another very important phenomenon, especially in shallow waters, is the reflection of sound waves from the surface and seabed, which causes wave multipathing. The amount of wave reflection from the seabed depends on the frequency and type of sediment. The amount of wave reflection from the sea surface also depends on atmospheric conditions, including wind speed and sea turbulence. In addition to the above, due to the low speed of sound underwater, the Doppler effect also has a significant effect on sound propagation [10].

The theory of sound wave propagation in an elastic medium can be described by solving the wave equation with respect to boundary conditions, and these waves can be evaluated as plane and spherical sound waves according to the propagation of waves in the medium. A plane wave does not exist in practice because it requires an infinite source to produce it. However, if we move far enough away from the source, the wave front (constant phase surface) becomes almost spherical, and a very small part of the surface of a large sphere is very close to a plane. The characteristics of plane waves have a certain simplicity and their study is important from a theoretical and practical point of view. Cartesian coordinates are used to study plane waves, and spherical coordinates are used for spherical sound waves [11]. The spatial and temporal characteristics of hydrophysical parameters in Dabob Bay were evaluated by Jinshan et al. (2008) using measured data. In this study, the effects of tides, temporal changes in sound velocity, and substrate material on sound transmission loss have been investigated and analyzed by presenting the MITgcm hydrophysical model [8]. Hareesh et al. (2010) studied the sound transmission loss caused by the effects of supereruption and suberuption on the southern coast of India using the parabolic method. The first step of this study included identifying and investigating the way supereruption and suberuption are created, and then modeling sound propagation using the parabolic wave equation at a frequency of 3 KHz in the presence of these phenomena has been studied [3]. Sridevi et al. (2010) also evaluated the effect of internal waves on sound propagation on the eastern coast of India using the beam method by placing the sound source at different depths in two modes: range-independent and range-dependent. According to their research results, the presence of internal waves causes a change in the transmission loss in the range of 2.86 dB and 15.59 dB in the water column [14]. In another study conducted by Hareesh et al. (2007), the effects of the cold and warm cores of the Arabian Sea in the range of 67.5 degrees East to 75 degrees East on the propagation of sound waves with a frequency of 100 kHz were investigated [6]. In this study, the cold and warm cores of the Arabian Sea were identified and the propagation of sound waves dependent on the presence of these cores was evaluated. The results of this study indicate that the sound transmission loss changes almost significantly in the presence of these cores [6].

Xun et al. (1999), in a project affiliated with the Institute of Acoustic Studies of the Chinese University of Sciences, studied the dispersion and scattering of signals in places with underwater turbulence and fast ocean currents [18]. A study on sound propagation and detection of targets and obstacles in shallow and deep basins was conducted by Clary and Medwin in 1977. In this study, it was determined through sampling and measurements of sound speed, sound signals and the formation of sound channels that sound channels with the sea surface and seabed as their boundaries are formed in shallow places [3].

The variability of the mixed layer in the North Arabian Sea was investigated using measurements taken by the Argo floats in 2007 by Bhaskar et al. In line with the international Argo project, more than 5000 unmanned surface and subsurface vessels of various types are active in waters around the world to create a complete archive of observations of physical and chemical parameters since 2000 [2]. Ohno et al. (2004), also investigated and analyzed the depth of the mixed layer in the winter season using data from the Argo float in the North Pacific Ocean. They also continued their studies in 2006 to investigate the distribution of mixed layer characteristics in the Pacific Ocean [19]. The depth of acoustic channels and their relationship with other physical parameters and the depth of the surface mixed layer in different oceans was evaluated by Helber et al. in 2007. According to their results, the depth of the acoustic layer and the depth of the surface mixed layer often coincide [7].

Ross and Lavery conducted experiments on the scattering behavior of sound waves in the presence of dual-scattering microstructures in 2007. After creating a dual-scattering structure in a laboratory glass tank, they investigated the scattering of sound signals through these structures at two frequencies, 250 kHz and 500 kHz.

2. Materials and methods

2.1 Methodology

The physical parameters studied in the present study include temperature, salinity, and sound velocity. Changes in the aforementioned physical parameters in the water column are variable and depend on factors such as the location of the region, latitude, season, water depth, time of day, and so on. Therefore, in the present study, the changes in the mentioned parameters in the cold and warm seasons of the northern Indian Ocean, the Sea of Oman, the Strait of Hormuz and the Persian Gulf in different layers of the water column have been investigated and evaluated. This study aims to determine the changes in each of the parameters in the water column for different marine areas in the cold and warm seasons of the region to comprehensively and completely understand the physical parameters, especially the speed of sound propagation in different layers of the water column. The vertical structure of the water column can be divided as follows [15].

1. Surface layer: The waters located at the sea surface are referred to as the surface layer and the changes in the speed of sound in this layer change with daily changes in water level, temperature and atmospheric conditions. Due to relatively high-speed winds, the waters in this layer mix with the underlying layers and create a mixed layer.

2. Seasonal thermal layer: By passing through the mixed layer, we will face a sharp drop in temperature. This layer is formed in shallow areas and mid-latitudes in the warm season and weakens in the cold season. In this layer, the speed of sound usually decreases with a relatively steep slope.

3. Main layer: In this layer, which is also known as the main thermocline layer, the temperature of the water layers always decreases with increasing depth. As a result of this decrease, the speed of sound propagation in this layer also decreases with increasing depth.

4. Deep isothermal layer: This layer, which is usually formed at depths of more than 1000 meters, has the same temperature and temperature changes do not occur with increasing depth. In this layer, the speed of sound propagation usually increases with increasing depth due to the increase in the density of the water layers.

Among the factors affecting the propagation of sound waves in marine environments is the change in the sound velocity profile. According to ray theory, if the change in the sound velocity is negative, the rays bend in the direction where the sound velocity is reduced; but if the change in the sound velocity is positive, the rays bend upward. The areas of the sea where sound waves do not penetrate are called the dark zone (Figure 1).

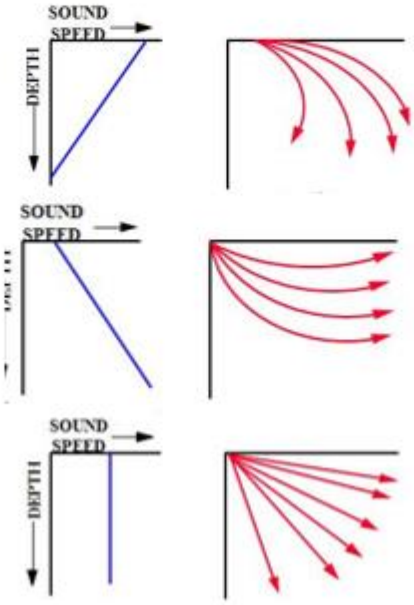


Figure 1. How sound propagates based on the sound velocity profile [15]

2.2 Data collection

In this project, monthly averaged data from the international World Ocean Atlas 2018 project in the northern Indian Ocean, the Sea of Oman, the Strait of Hormuz, and the Persian Gulf with a spatial accuracy of 0.25 degrees have been used to obtain vertical profiles of temperature, salinity, and sound velocity parameters. The World Ocean Atlas is a collection of averages of temperature, salinity, oxygen, phosphate, silicate, and nitrate that have been obtained through measurement data and analyzed after accurate and reliable quality control based on the World Ocean Database data. These data can be used to establish boundaries and initial conditions for various ocean models, or to validate and verify the results of numerical modeling, as well as to confirm the accuracy and precision of satellite data [16]. It is worth noting that WOA2018 used the latest seasonal data updates for the aforementioned parameters. Figure 3 shows the areas studied in terms of vertical profiles of temperature, salinity, and sound speed in the northern Indian Ocean, the Sea of Oman, the Strait of Hormuz, and the Persian Gulf. The evaluated stations are indicated in this figure by black dotted dots.

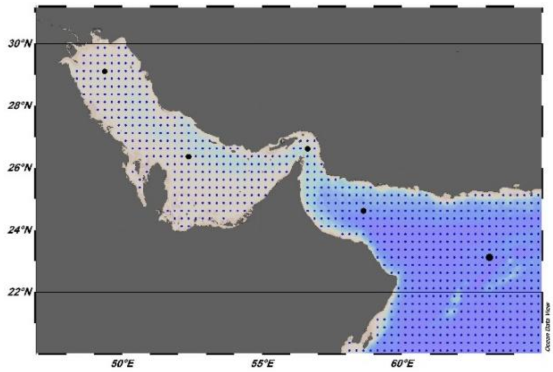
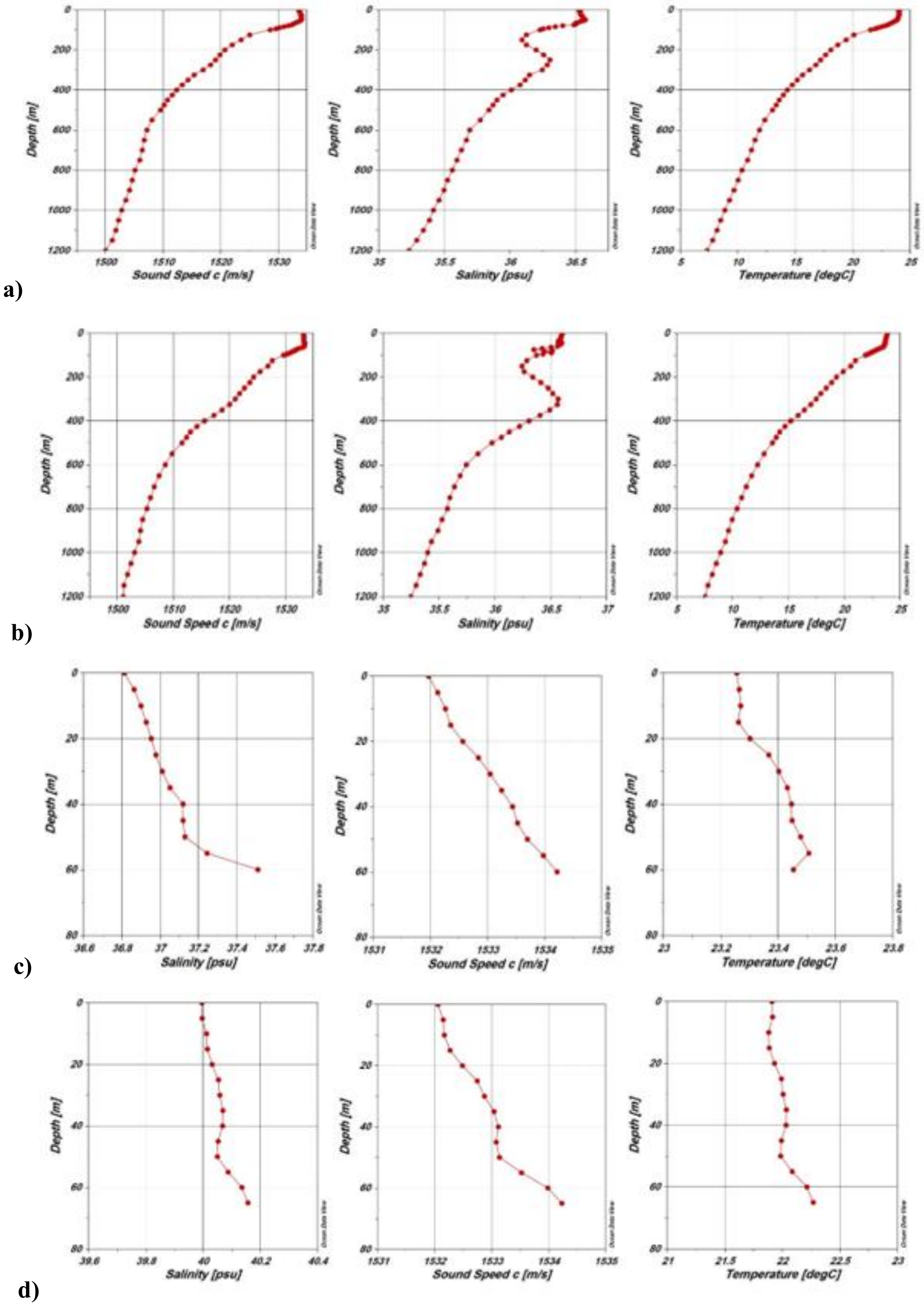


Figure 2. Surveyed stations in target areas [17]

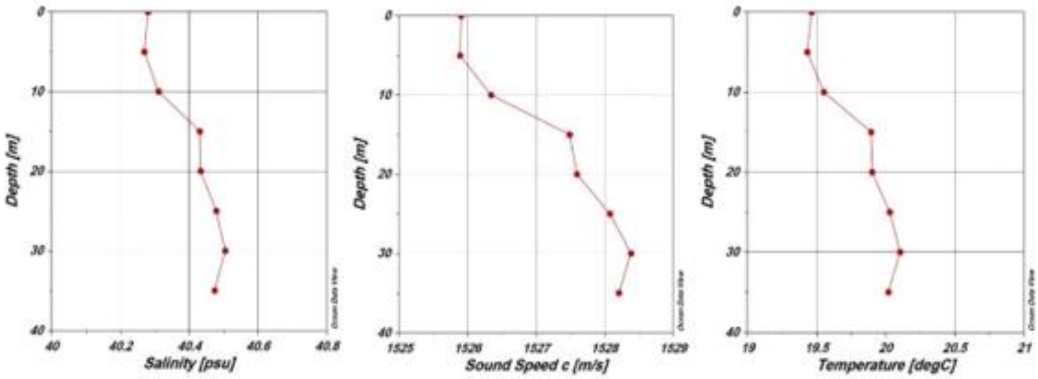
Considering the climate of the region and the location of the studied areas at latitudes of 20 to 30 degrees north, the mentioned areas have only two cold and hot seasons throughout the year. Accordingly, in the present project, the physical parameters of the water column in the two cold and hot seasons of the region, in January and July, respectively, have been investigated. The data at the same depths from the surface to the bed and averaged in January and July have been used to determine the different layers of the column and the way the vertical profiles of the physical parameters change.

3. Results and Discussion

In this section, the vertical profiles of the physical parameters of temperature, salinity and sound speed of the studied stations are shown (Figure 3). In the following figures, the vertical changes of the physical parameters of the stations of the northern Indian Ocean, the central Oman Sea, the central Strait of Hormuz, the central Persian Gulf and the northwestern Persian Gulf are presented in the cold season and then in the warm season of the region. Considering the bathymetric conditions and the presence of shallow areas in the Persian Gulf and the Strait of Hormuz and deep oceanic areas in the Oman Sea and the Indian Ocean; the vertical changes in the stations have been evaluated in proportion to the depth of the station in question.



Depth [m]
Sound Speed c [m/s]
Salinity [psu]
Temperature [degC]
a)
Depth [m]
Sound Speed c [m/s]
Salinity [psu]
Temperature [degC]
b)
Depth [m]
Salinity [psu]
Sound Speed c [m/s]
Temperature [degC]
c)
Depth [m]
Salinity [psu]
Sound Speed c [m/s]
Temperature [degC]
d)



e)

Figure 4. Right profile (temperature), middle profile (salinity), left profile (speed of sound) (January) in cold season: a) North Indian Ocean, b) Central Sea of Oman, c) Central Strait of Hormuz, d) Central Persian Gulf, e) Northwestern Persian Gulf

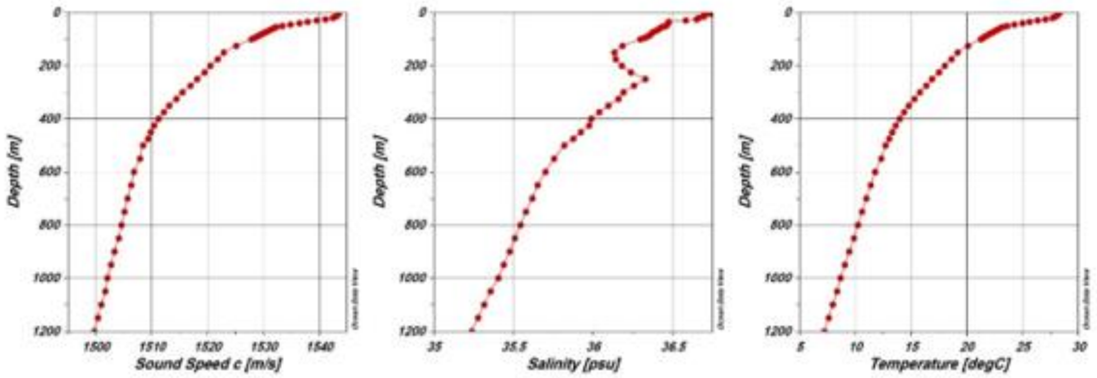
Given the presence of depths of more than 1000 m in the northern Indian Ocean and the central regions of the Sea of Oman, vertical changes in physical parameters indicate the presence of a permanent thermocline layer (slope) in these areas. Accordingly, in the first 100 m of the depth of the aforementioned areas, a homogeneous layer is formed and changes in temperature, salinity and sound speed at these depths are very insignificant. Due to the presence of winter monsoon winds (left diagram of Figure 4) in the northern parts of the Indian Ocean, which blow from the northeast and move parallel to the eastern coast of Africa towards the southwest, the surface homogeneous layer has a relatively large depth compared to the warm months of the region.

Upon passing through the surface homogeneous layer, the thermocline layer begins with a relatively steep slope and continues to depths of more than 1000 m and a temperature of 6 degrees Celsius. This sharp decrease in temperature also affected the speed of sound waves, causing a decrease of more than 30 m/s in the thermocline layer. Vertical changes in the speed of sound in the vertical direction indicate the existence of a deep sound channel in the northern Indian Ocean and the Sea of Oman. Accordingly, if there is a sound source at depths of more than 100 meters, sound waves will be able to travel long distances without colliding with the surface layer of water with minimal loss.

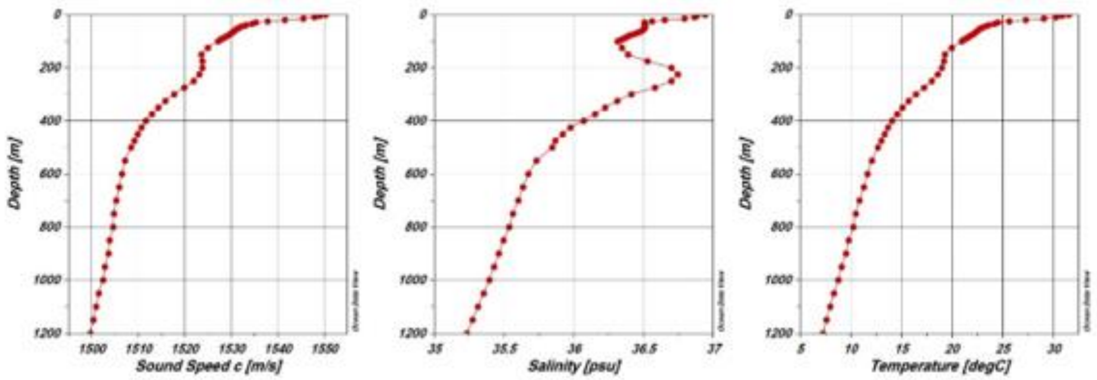
Salinity changes in the deep regions of the Indian Ocean and the Sea of Oman are such that the depth range of 200 to 400 meters has an increase of 0.5 psu. This increase in the aforementioned depths in the middle of the Sea of Oman and the northern Indian Ocean can be attributed to the penetration of dense outflow currents (with relatively high salinity) deep subsurface of the Persian Gulf. This is also clearly evident in the vertical salinity profile in the center of the Strait of Hormuz. Salinity changes in the Strait of Hormuz indicate an increase of more than 1 unit of salinity from the surface to the bed of this region, which indicates a subsurface flow near the bed in this region.

Temperature changes in this cold season of the region from the surface to the bed are very insignificant and the entire water column can be considered almost isothermal. This is due to the increase in surface wind speed in the region and especially the prevailing atmospheric conditions in the cold season, which causes the water mass to become thermally homogeneous. Due to the insignificant temperature changes, changes in the speed of sound are not a function of temperature, and therefore, due to the increase in salinity with depth and the increase in water column pressure, we witness a 2-unit increase in the speed of sound from the surface to the bed in this region.

Due to depths of less than 100 in most of the Persian Gulf, and especially in the shallow areas of the northwest Persian Gulf; this water body has almost homogeneous waters from the surface to the bed in the cold season, and we witness very limited vertical changes in the parameters of temperature, salinity, and sound speed. This has caused the changes in the speed of sound from the surface to the bed to be more a function of the water column pressure than temperature changes. Hence, a 2-unit increase in the speed of sound has been recorded in the water column of the central and northwest Persian Gulf. This slight increase in the speed of sound relative to the water surface has created a relatively weak surface sound channel, and due to this, sound waves will have successive collisions with the water surface in their propagation path.



a)



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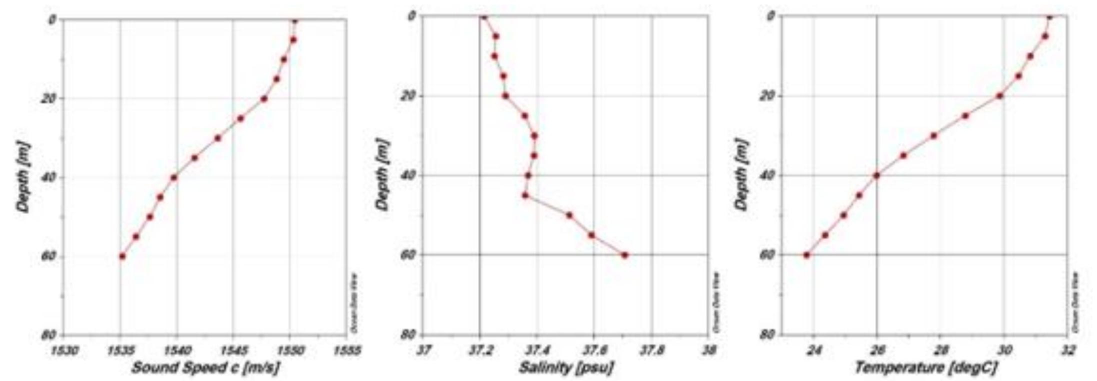
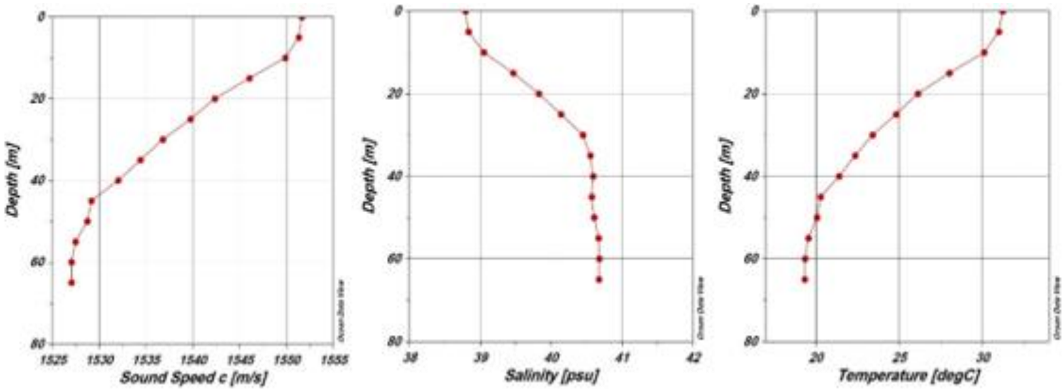


c)



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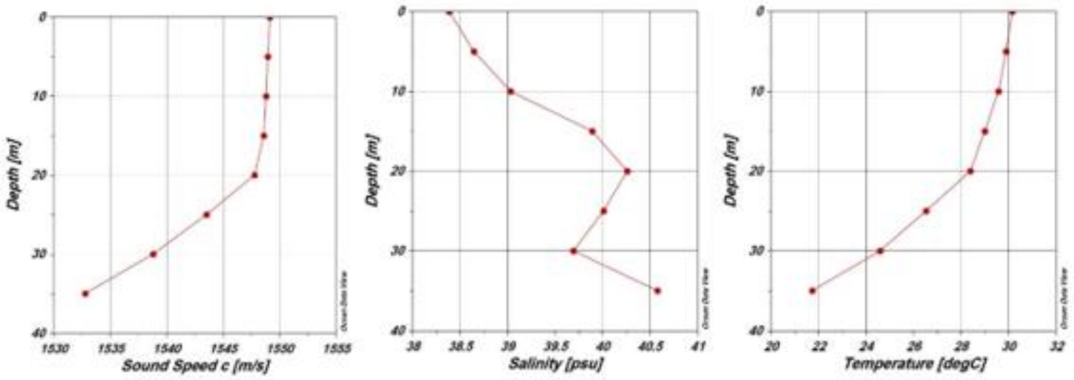

e)

Figure 5. Right profile (temperature), middle profile (salinity), left profile (speed of sound) in warm season (July): a) North Indian Ocean, b) Central Sea of Oman, c) Central Strait of Hormuz, d) Central Persian Gulf, e) Northwestern Persian Gulf

As mentioned earlier, the summer monsoon is the dominant weather system in the warm months of the year in the northern Indian Ocean and the Sea of Oman. During monsoon times (right-hand diagram in Figure 6), relatively strong winds blow from the southwest along the east coast of Africa to the north of the Indian Ocean in a northeasterly direction. This creates surface currents and waves towards the northern Indian Ocean and, in some cases, the central Sea of Oman.

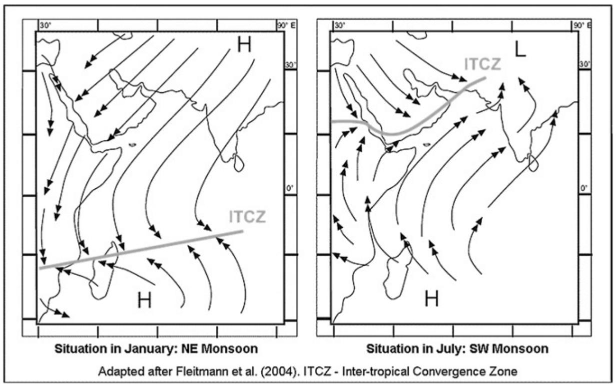

Figure 6. The path of the winter (left) and summer (right) monsoon atmospheric system in the North Indian Ocean [12]

The homogeneous surface layer in the warm months of the region is shallower than in the cold season due to the decrease in surface wind speed and is limited to a few tens of meters at the beginning of the water column in the northern Indian Ocean and the Sea of Oman stations. In this season, a strong permanent thermocline layer is still visible in the deep waters of these regions with a decrease of 20 units in water temperature and 50 units in the speed of sound propagation. This has created a stable water mass in terms of density in these regions, to the extent that even the penetration of salty waters of the Persian Gulf at depths of 200 to 250 meters is not able to destabilize the water column of these regions. By passing through the deep regions of the Sea of Oman and reaching the shallow parts of the Strait of Hormuz and the Persian Gulf, due to the decrease in wind speed in the warm season and the increase in air temperature at a height of 2 m above sea level, we witness the creation of seasonal thermoclines in these regions. There is a relatively weak homogeneous layer in the first few meters of the surface layer, and immediately after passing the first few meters, the thermocline layer begins and continues to the bed. In this layer, the temperature of the water column has decreased by more than 10 units, and due to this, the speed of sound propagation also shows a decrease of 15 units.

Vertical changes in salinity in the Strait of Hormuz have continued to witness an increase in depths near the bed; this increase in salinity, like the cold season, indicates the outflow of dense currents with high salinity compared to the surface layer from this region. This outflow exists at all times of the year and only has increases and decreases in the salinity of the outflow during different seasons. Shallow waters along the southern coasts of the Persian Gulf, between Qatar and the Emirates, which have depths of less than 30 m, among the areas forming waters with salinity exceeding 40 psu are the Persian Gulf.

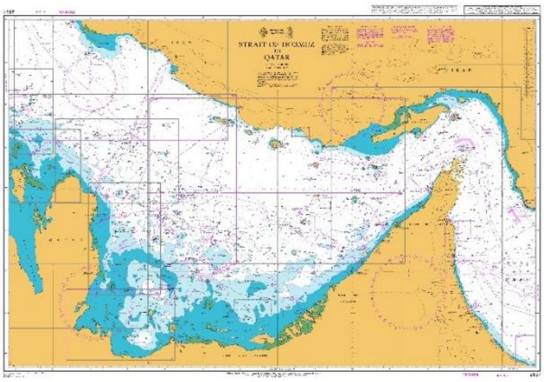

Figure 6. Nautical chart 2837, southern coast of the Persian Gulf [16]

Vertical changes in the speed of sound in shallow areas of the Persian Gulf indicate a decrease in the speed of sound with increasing depth in these areas. Therefore, if there is a sound source at depths of more than 20 m, it causes sound propagation in these areas to encounter multiple collisions with the bed and, as a result, high transmission loss. The 20-unit decrease in the speed of sound observed has created a sound channel near the bed in the warm season of the region, which, due to the shallowness of the region, causes sound waves to interact more with the bed. The changes in the physical parameters of the water column have been analyzed and investigated in the form of two-dimensional profiles over a length of more than 2000 km from the northern Indian Ocean to the northwest of the Persian Gulf. In this regard, the characteristics of the physical parameters of the water column along the center of the target areas from the surface to the bed are presented in the figures below. It is necessary to explain that, considering the shallowness of the Persian Gulf and the Strait of Hormuz regions, as well as the depth of the central parts of the Sea of Oman and the northern Indian Ocean, two-dimensional profiles have been evaluated in two sections: the Persian Gulf to the Sea of Oman and then the Sea of Oman to the northern Indian Ocean.

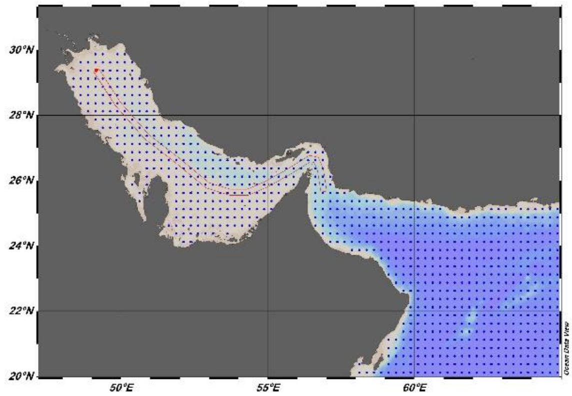

Figure 7. Assessed section of the Persian Gulf to the Sea of Oman

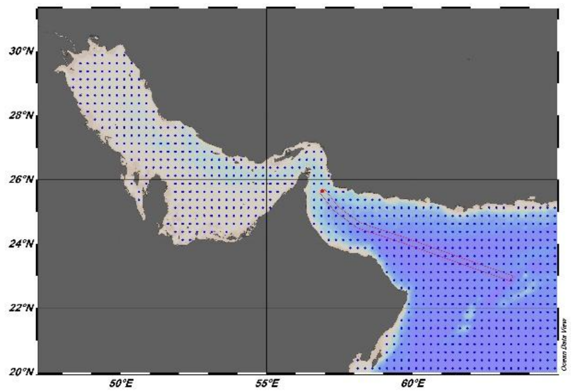

Figure 8. Assessed section of the Sea of Oman to the northern Indian Ocean

Figures 9, 10, and 11 respectively show two-dimensional cross-sections of temperature, salinity, and sound velocity parameters from the northwestern parts of the Persian Gulf to the west of the Strait of Hormuz (corresponding to the cross-section in Figure

6) in the cold season of the region. Considering the vertical changes in the aforementioned parameters, it is possible to observe the homogeneity of temperature and salinity of water from the surface to the bed in most areas. This issue, which was also observed in the cold season temperature and salinity indexes of the Persian Gulf and the Strait of Hormuz, is due to the increase in local wind speed, especially the north wind, in the cold season of the year and the creation of vertical mixing of the water column, resulting in the homogenization of temperature and salinity parameters.

Only in the areas close to the Strait of Hormuz (800 to 1000 km in the figures below) do we witness an increase in salinity at depths near the bed, which indicates the penetration of permanent subsurface currents of Persian Gulf salt into the Sea of Oman in these areas. Moving from the northwestern parts of the Persian Gulf towards the Strait of Hormuz; the water temperature in the same depth layers has increased and the salinity in these layers shows a significant decrease.

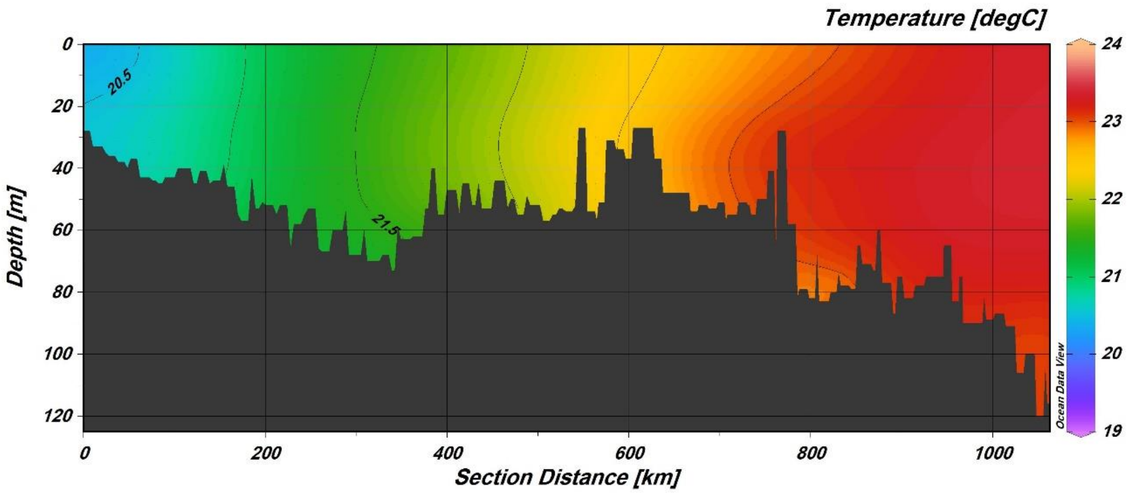

Figure 9. Two-dimensional cross-section of temperature changes from the northwest of the Persian Gulf to the Sea of Oman (along the cross-section path of Figure 6) in the cold season (January)

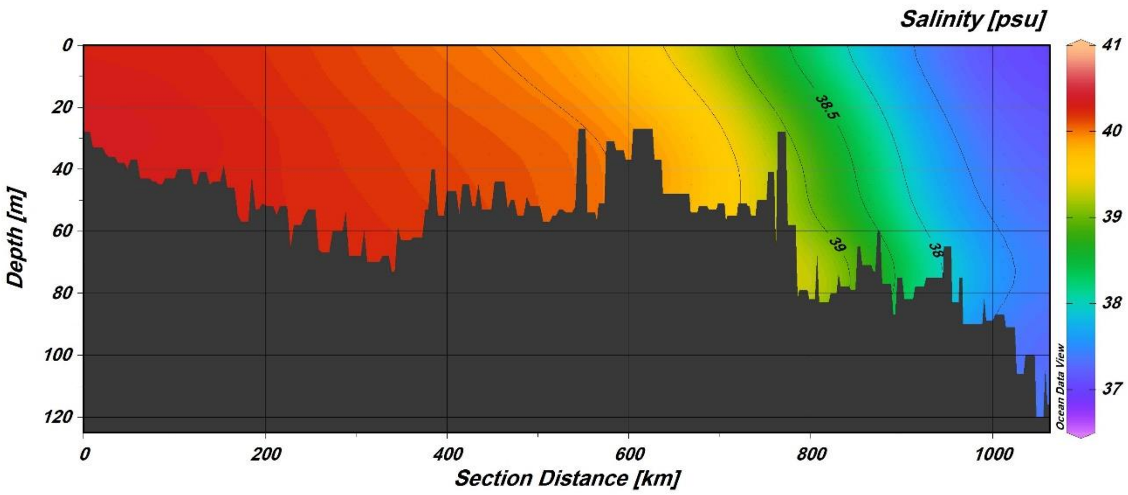

Figure 10. Two-dimensional cross-section of salinity changes from the northwest of the Persian Gulf to the Sea of Oman (along the cross-section path of Figure 6) in the cold season (January)

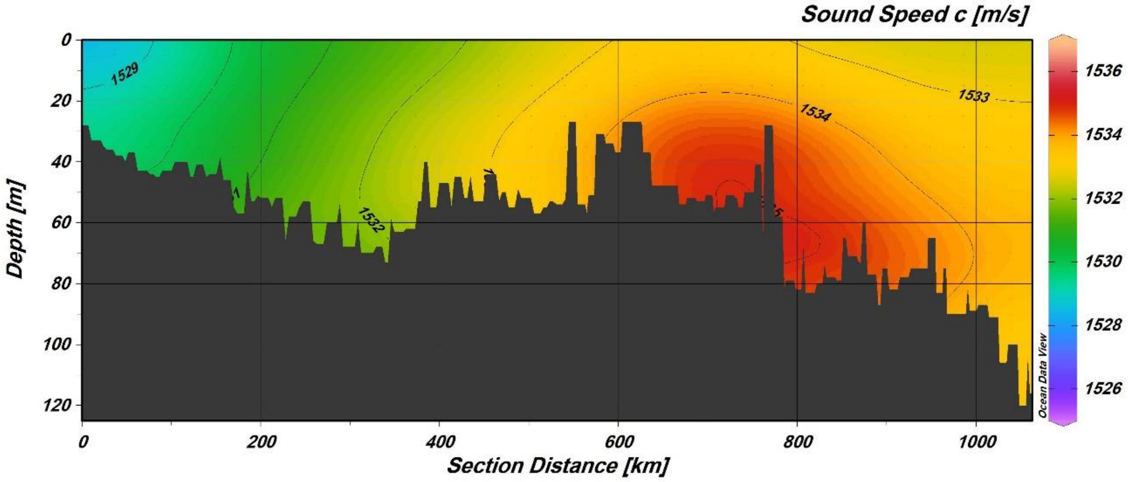

Figure 11. Two-dimensional cross-section of sound velocity changes from the northwest of the Persian Gulf to the Sea of Oman (along the cross-section path of Figure 13) in the cold season (January)

The two-dimensional changes in the cross-section of the Sea of Oman to the northern Indian Ocean are presented in Figures 12, 13 and 14, respectively, for the temperature, salinity and speed of sound parameters. In these areas, due to the great depth, a permanent thermocline has formed in all areas. This causes the surface homogeneous layer to be separated from the deep homogeneous layer by the thermocline layer. It is worth noting that in these areas there is a relatively strong sound channel at depths of more than 500 m due to the reduction in the speed of propagation of sound waves from the surface to the bed during the cold season of the region.

The penetration of dense (high salinity) waters from the layers near the bed of the Strait of Hormuz into the Sea of Oman can be clearly seen up to the first 200 km in Figure 13. Due to their high density, these water masses penetrate up to 100 km into the Sea of Oman until they gradually mix with the adjacent waters and overflow into the Indian Ocean. Also, when moving from the central parts of the Oman Sea towards the northern Indian Ocean in layers of the same depth, no significant changes occur in any of the physical parameters.

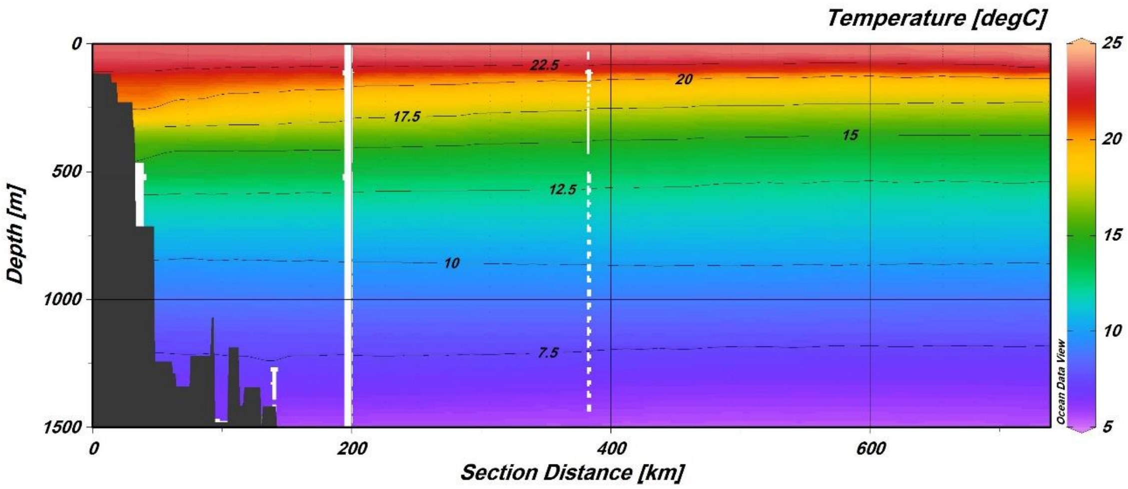

Figure 12. Two-dimensional cross-section of temperature changes from the center of the Oman Sea to the northern Indian Ocean (along the cross-section path of Figure 8) in the cold season (January)

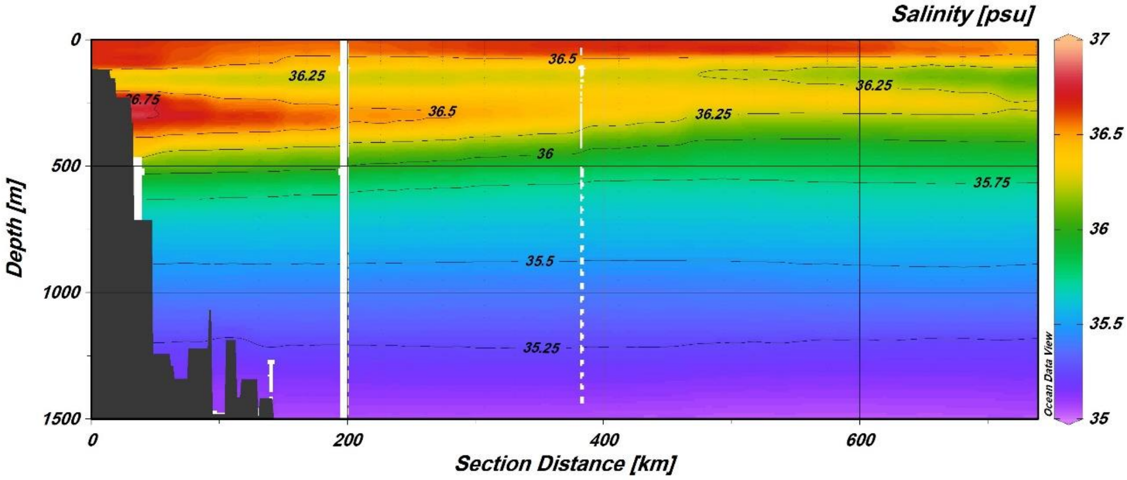

Figure 13. Two-dimensional cross-section of salinity changes from the center of the Oman Sea to the northern Indian Ocean (along the cross-section path of Figure 8) in the cold season (January)

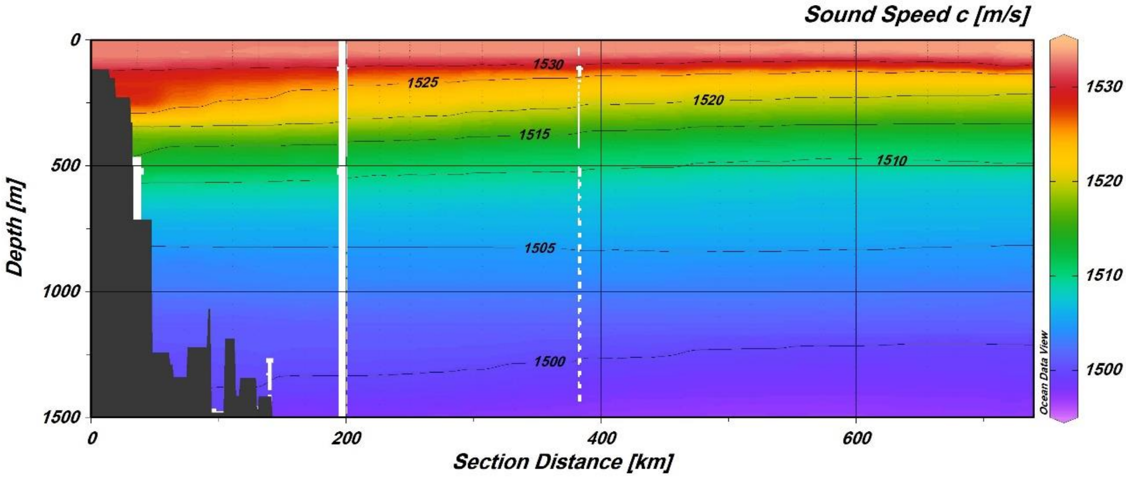

Figure 14. Two-dimensional cross-section of sound velocity changes from the center of the Oman Sea to the northern Indian Ocean (along the cross-section path of Figure 8) in the cold season (January)

Two-dimensional cross-sections of changes in physical parameters in the warm season are shown in Figures 15, 16, and 17 of the cross-sections of Figure 8. The results of the study indicate the formation of a seasonal thermocline layer in most areas, especially in the deeper areas of the Persian Gulf. Accordingly, temperature changes of more than 15 units have been recorded in some areas, which indicates the formation of a relatively strong thermocline layer at depths of less than 100 meters in the Persian Gulf. In this season, we also observe the highest salinity values (more than 40 units) in the shallow northwestern parts. The northwestern regions along with the shallow southern parts of the Persian Gulf have always had higher salinities than other regions of the Persian Gulf and are considered to be the main factors in creating dense subsurface currents from the Persian Gulf to the Sea of Oman. A relatively weak sound channel has formed in the deep parts and near the bed of the Persian Gulf and the Strait of Hormuz due to a reduction of more than 20 units in the speed of sound from the surface to the bed in the deep areas of the Persian Gulf and the Strait of Hormuz. This causes sound rays to have multiple collisions with the bed in their propagation path and increases the loss due to transmission.

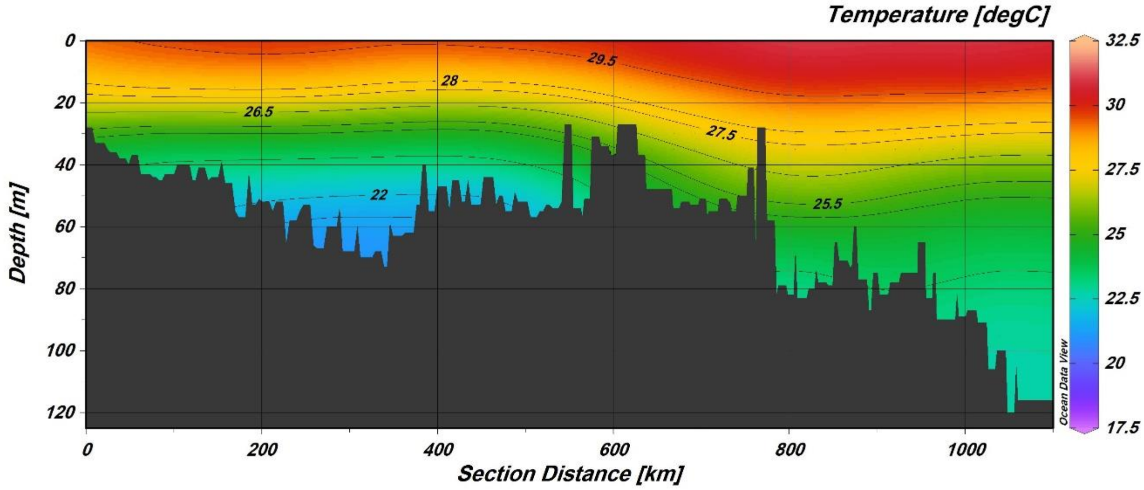

Figure 15. Two-dimensional cross-section of temperature changes from the northwest of the Persian Gulf to the Sea of Oman (along the cross-section path of Figure 8) in the warm season (July)

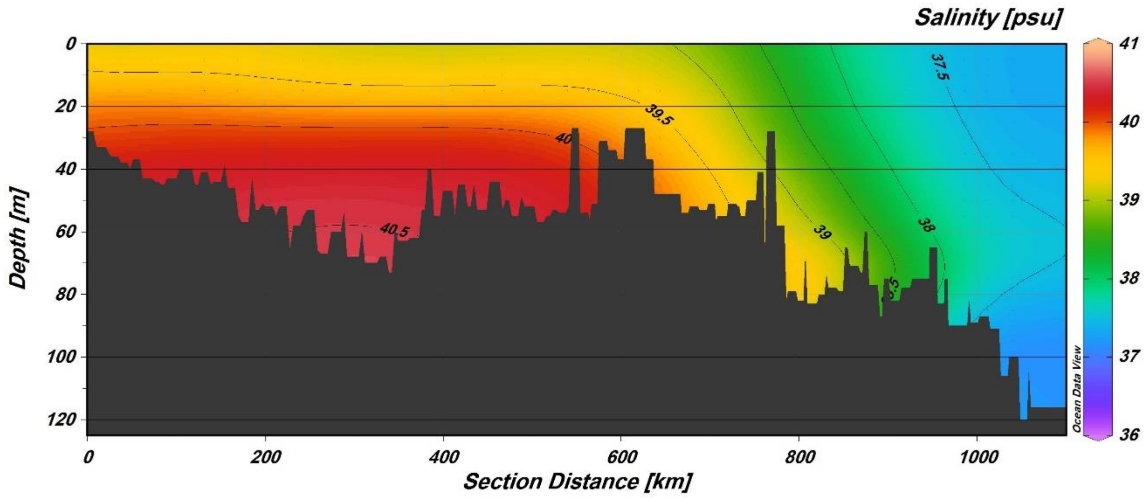

Figure 16. Two-dimensional cross-section of salinity changes from the northwest of the Persian Gulf to the Sea of Oman (along the cross-section path of Figure 8) in the warm season (July)

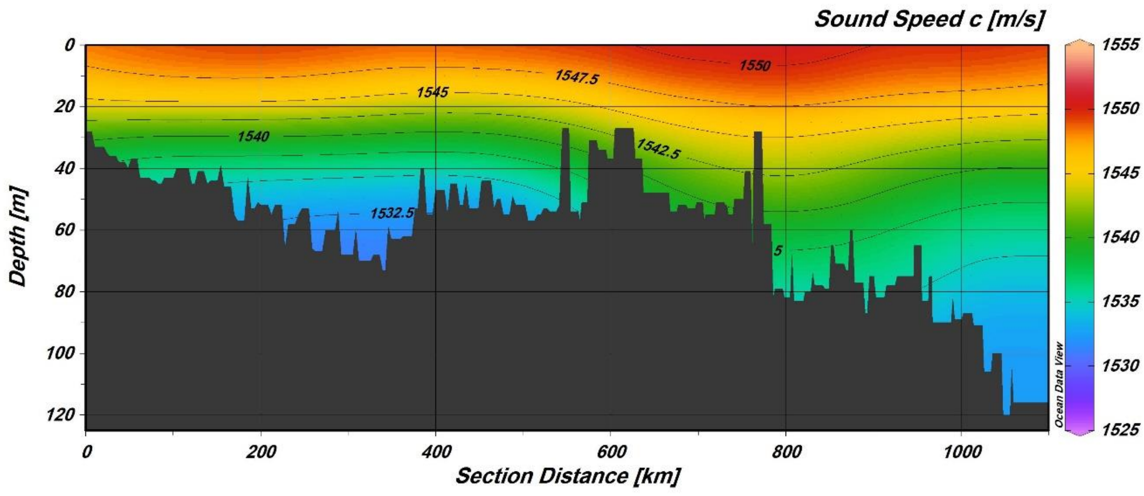

Figure 17. Two-dimensional cross-section of sound speed changes from the northwest of the Persian Gulf to the Sea of Oman (along the cross-section path of Figure 8) in the warm season (July)

Figures 18, 19 and 20 show two-dimensional variations in temperature, salinity and sound velocity from the Sea of Oman to the northern Indian Ocean over a distance of more than 700 km during the warm season of the region. In this season, as in the cold season of the region, there is a strong permanent thermocline due to the presence of depths of more than 1500 meters. Due to the increase in the surface air temperature, the water surface temperature has reached more than 30 degrees Celsius, causing the temperature to decrease by more than 25 units from the surface to the bottom. This significant decrease in temperature has caused a sharp decrease in the speed of sound, and due to this, a deep sound channel with speeds of 1500 to 1505 m per second has formed at depths of nearly 1000 m.

Like in the cold season, in this season, the intrusion of salty waters from the Persian Gulf into the Sea of Oman (Figure 19) is also visible. The intrusion of saltwater in this season affects fewer areas than in the cold season and mixes more rapidly with the surrounding waters. Other changes in the same depth layers are almost the same and no significant changes are observed in the layers.

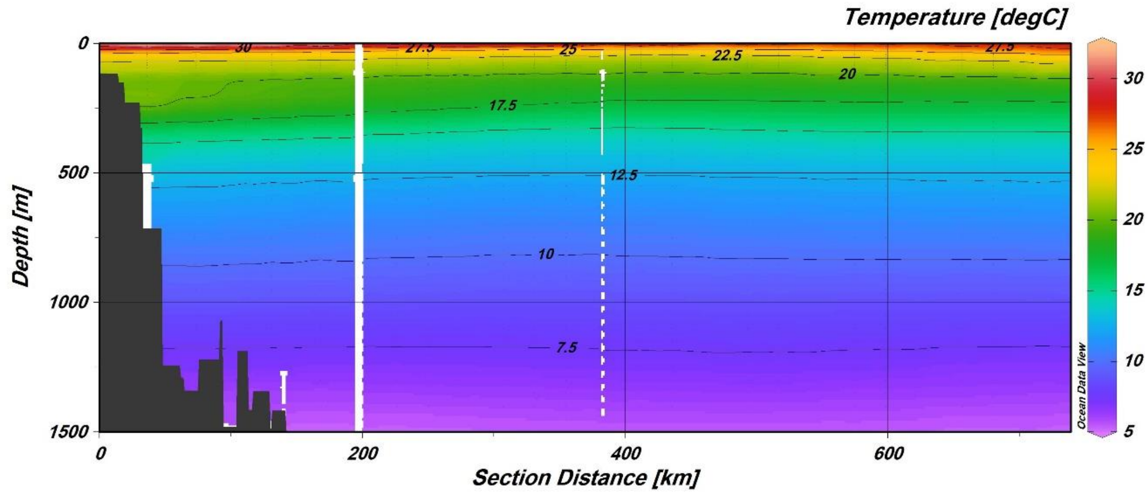

Figure 18. Two-dimensional cross-section of temperature changes from the center of the Oman Sea to the northern Indian Ocean (along the cross-section path of Figure 9) in the warm season (July)

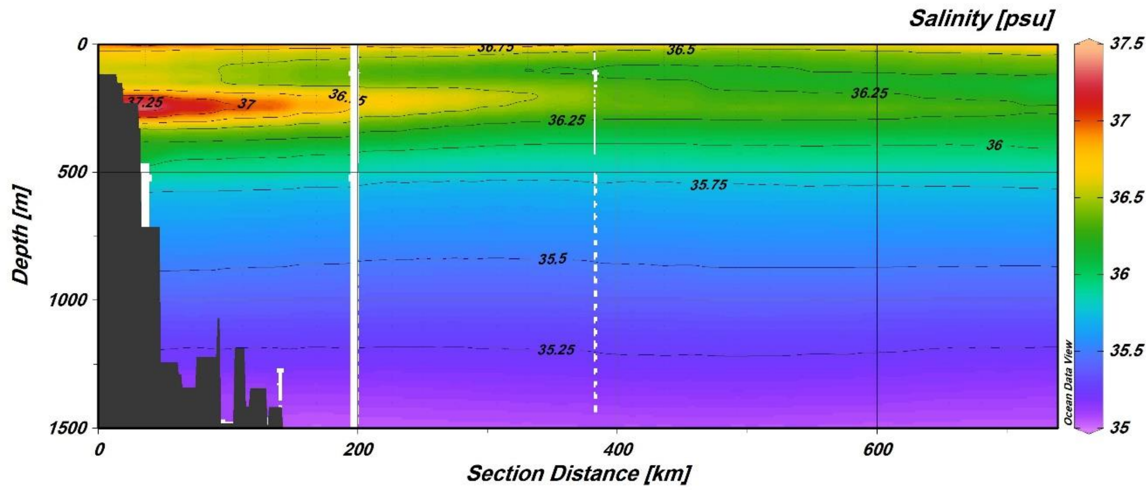

Figure 19. Two-dimensional cross-section of salinity changes from the center of the Oman Sea to the northern Indian Ocean (along the cross-section path of Figure 9) in the warm season (July)

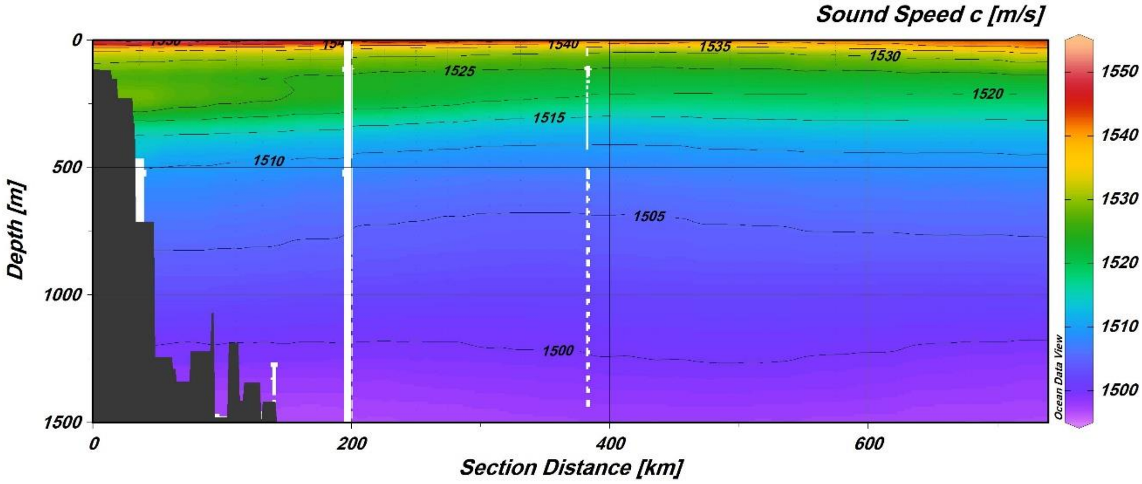

Figure 20. Two-dimensional cross-section of sound speed changes from the center of the Oman Sea to the northern Indian Ocean (along the cross-section path of Figure 9) in the warm season (July)

4. Conclusion

The main objectives of the present project have been to investigate the vertical changes in the physical parameters of the water column, including the speed of sound propagation in the seas adjacent to the south of the country and the northern regions of the Indian Ocean. In this regard, the temperature, salinity and speed of sound indices have been evaluated at 5 stations in the northern Indian Ocean, the central Oman Sea, the central Strait of Hormuz, the central Persian Gulf and the northwestern Persian Gulf in the two cold and warm seasons of the region. The results indicate the existence of a permanent thermocline in the deep parts of the Oman Sea and the northern Indian Ocean, as well as a seasonal thermocline in the shallow areas of the Strait of Hormuz and the Persian Gulf. Due to the sharp decrease in the speed of sound with increasing depth in the deep regions of the Oman Sea and the Indian Ocean, a deep acoustic channel exists throughout the year. The only seasonal difference in these areas is related to the depth of the surface homogeneous layer. In the cold season, the depth of the mixed layer is more than 100 m, while this depth reaches less than 50 m in the warm season of the region. This difference is due to different weather conditions resulting from prevailing systems in different seasons, especially unstable weather conditions caused by the winter and summer monsoons.

In the shallow parts of the studied areas, including the Strait of Hormuz and the Persian Gulf, due to the shallowness of the area and unstable atmospheric conditions in the cold season, the water mass is almost homogeneous, which is lost in the warm season and the relative stability of atmospheric conditions, and with the warming of the air temperature at a height of 2 meters, a relatively strong seasonal thermocline layer is created in these areas. Changes in the speed of sound propagation in the warm season of the Persian Gulf have caused the creation of a sound channel near the bed, which causes sound rays to collide with the bed multiple times along their propagation path due to the shallowness of the area and the conditions of vertical changes in the speed of sound propagation. Since the use of acoustic equipment in marine subsurface activities is necessary and inevitable, the environmental conditions of the area should be examined and monitored before any action is taken. Therefore, in the first step, a comprehensive and complete understanding of how the speed of sound waves changes as the most effective factor in the use of sound equipment at different times and places should be obtained. Therefore, what has been evaluated and studied in the present plan can be a useful step in this field so that its results can be used for secondary activities such as the applications mentioned at the beginning of this document. The two-dimensional changes in various parameters, which have been evaluated in the form of cross-sections along the Persian Gulf to the northern Indian Ocean, well indicate how physical parameters change along the region and different seasons. The two-dimensional diagrams obtained in this section show how changes occur in the horizontal direction and over a length of more than 2000 kilometers of the study area. Accordingly, the intrusion of salty waters of the Persian Gulf in the deep parts of the Sea of Oman has existed at all times and can be traced well up to the middle of the Sea of Oman. The permanent thermocline is visible in the deep areas of the Sea of Oman and the Indian Ocean throughout the year, and its difference in different seasons is only in the thickness of the surface homogeneous layer and the beginning of the thermocline layer. Also, considering the changes in the speed of sound in different seasons of the Persian Gulf section, it can be concluded that the propagation of sound waves in these shallow areas will face a very high loss due to multiple collisions with the surface and the bed. Based on the data used in the present design and also known numerical models of sound propagation and adding several parameters such as the depth of the sound source, the frequency of the sound source, the type of bed, the way of vertical changes in density, the location of the receiver and the distance between the transmitter and the receiver, it is possible to achieve the propagation of sound waves in different areas. These results will be able to identify the main paths of sound wave propagation at different frequencies and depths of sound sources, along with complete information about the loss caused by the transmission of sound waves. Also, from the results of these issues, dark spots (shadows) can be identified for the use of different detection and tracking systems in different regions and seasonal conditions to maximize their use.

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