

Research Paper

An Empirical Approach to Investigate Environmental Effects on Acoustic Signal Speed in Oceanic Layers

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*Received November 2, 2025; revised January 3, 2026; accepted January 4, 2026;
available online January 26, 2026; version of record March 17, 2026; published issue March 27, 2026.*

This paper investigates and demonstrates the effects of three significant environmental contributors: temperature, depth and salinity impact on the acoustic signal propagation across distinctive ocean layers: mixed, thermocline, and deep layers. In the field of underwater wireless sensor networks (UWSN), exact and precise determination of coordinates for sensor localization is very crucial for data validation. Temperature dominates the upper layers; depth becomes the prime factor for the deeper domain with minimal thermal variations. Salinity while having a diminished effect, facilitates minor changes in propagation and deviation of acoustic signal speed. In our work we have analyzed these interdependencies by using different empirical models (e.g., Mckenzie, Medwin) customized to each layer, accounting to their incomparable environmental parameters. In mixed layers, changes in sound speed are mainly caused by thermal factors, where depth is of minimal importance, and the influence of salinity is insignificant, but with increasing depth, the temperature begins to decrease, and depth (pressure) begins to become important, and changes in salinity and temperature become almost equivalent. By evaluating ocean layer specified empirical formulas, we have calculated the average speed of sound and measure the corresponding contribution of all parameters. Our work has provided a substructure which helps to optimize the identification or localization of UWSN nodes. The results of this work underscored the essential to have an adaptive sound speed modeling in order to achieve enhanced and precise acoustic signal communication systems.

Keywords: acoustic signal speed, ocean layers, salinity, empirical formulas, sound speed modeling.



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1. Introduction

The underwater sensor network has been a pivotal field of scientific research for decades. The vast expansion of ocean has brought both known and yet-to-be known exploration and monitoring challenges to us. At present marine monitoring is increasing promptly. As it is more difficult to establish and monitor an underwater sensor network than a terrestrial network because of its positing in the rough environments. It is important to gather marine precise information of underwater location as it helps with underwater surveillance, ocean life exploration, natural disaster study and so on (TAN *et al.*, 2011). The understanding of the accurate node location in the underwater network is very important for both tracking and validating collected data. Electromagnetic radio waves have very poor performance underwater due to sea water because it also faces a high attenuation which makes it expensive and also affects the propagation for long ranges (KUKUCHUKU *et al.*, 2018). As radio signal has a low propagation range, we generally use an acoustic signal as a substitute (PAUL *et al.*, 2020). So, in underwater communication and other necessities such as distance measurements we usually use acoustic signals. The history of underwater velocity determination was started in the early 19th century, when scientists

used a tube to take measurements underwater which was suggested by the famous artist Da Vinci and scientists recorded the speed of the submerged bell proceeding across Lake Geneva (SCOWCROFT *et al.*, 2015). Another invention in the field of underwater communication was the invention of ‘Gertude’ or we could say a marine telephone that uses analog modulation and its carrier frequency was between 2 kHz to 15 kHz (STOJANOVIC, 2007). So, numerous researches have scrutinized diverse perspective of UWSN, furthering in the understanding and utilization of underwater communication with an array of different ranges and fields for AUV (autonomous underwater vehicles) and regardless of the type of positioning (submerged, indoor, outdoor, underneath). Many studies have proclaimed that environmental factors can bring variation to the acoustic signal speed. According to CHEN and MILLERO (1997), the speed of sound has been affected by temperature depth and salinity. The scope of this article is to understand and analyze environmental variable relationship with an acoustic signal as it is the core of underwater communication. This paper highlights the process of sound speed calculation and how in the ocean each layer is governed by a dominating ecological parameter. This work shows an empirical calculation using the values of different indicator available or introduced by many prominent researchers. Our work can be useful in fields of UWSN localization, ocean engineering and also for understanding underwater signal processing. In the article also the sound profiles of different empirical formulas are implemented. The major contributions of this article are arranged as follows:

1. This paper demonstrates how an average speed of sound is calculated underwater using divergent empirical formulas.
2. The analysis of the effect of temperature, depth and salinity for different oceanic layers is exhibited to observe ecological variable impact domination for different coverings.
3. Finally, the evaluation of empirical formulas’ behaviors of the environmental parameter for different oceanic layers is also performed in this research.

The remaining of the paper has been organized in different sections structurally. Section 2 which is divided into two parts: the problem field and review of the previous research work. In the problem field we have evaluated the issues that arose during the measurement of the acoustic speed velocity for UWSN and included a network architecture for a visualization purpose and also the way to examine the effects of environmental parameters on the speed of sound for marine communication using empirical formulas. Section 3 has shown a method of the work, and also including mathematical equation along with additional acronym and indicators. In Sec. 4 all the simulation works are shown with detail information. Section 5 offers a rivaling discussion and finally, in Sec. 6, the article concludes.

2. Background

2.1. Problem domain

In our proposed UWSN structure in Fig. 1, we consider a single beacon on the top of the water surface column and four submerged sensors are deployed underwater that require distance measurement. The sensor nodes can be considered in any layer, provided that the components meet the constrains from empirical formulas. For accurate measurement of acoustic speed or speed of sound we required the values of temperature, depth and salinity from both beacon and sensor region. Determining these variables for beacon is uncomplicated as temperature and salinity of the surface water traditionally determined at nil depth. However, if we do not integrate specific sensors (for example, temperature, depth, and brininess sensors) for deployed sensors it becomes very much difficult to grasp those variables accurately. In this paper, our focus is to investigate the effect of these three environmental variables on the acoustic velocity for three different ocean layers such as mixed layer, thermocline layer and deep layer using different empirical equations. For ease of comprehension, we think that all the deployed sensor are stationary at the moment of implementation time calculation. We have neglected the motility of the sensor nodes because our main concern here is to measure the average acoustic velocity and analyze the effect of environmental variables using various empirical equations. Our work uses the value of three underwater layer (mixed, thermocline, and deep layer) ranges to make our desired simulation.

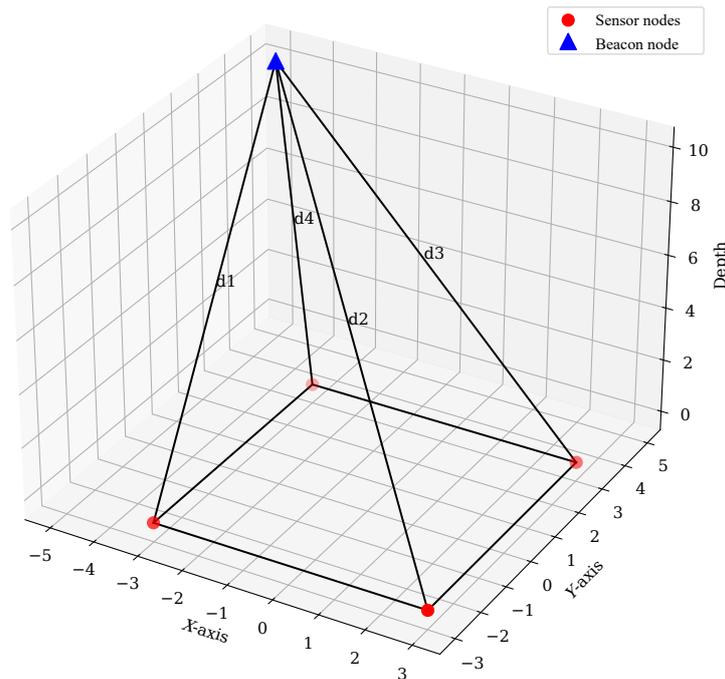


Fig. 1. Underwater network deployment considering one beacon and multiple submerged sensors.

2.2. Literature review

Numerous researches have scrutinized diverse perspective of UWSN, furthering in the understanding and utilization of empirical equations throughout an array of different ranges and fields. Multitudinous empirical formula exists that are established throughout the years to determine the acoustic velocity on the base of oceanographic variable like temperature, depth and salinity. RAHMAN *et al.* (2013a) has analyzed the ecological variables to see which parameters have high influence on an acoustic signal velocity for a vertical water column for a specific problem field, they considered one beacon on the top of the water surface and few submerged sensors which were deployed and needed to measure their distance. They used the Mackenzie equation and the triple integral method to measure the average speed of sound to analyze which environmental parameter among temperature depth and salinity has the greatest impact on the speed of sound for the considered configuration of UWSN with a single beacon and few submerged sensors. In this work, only one formula with a specific range was visited to investigate the influence of environmental elements. Another pivot research of RAHMAN (2014) has proposed an innovative manner to resolve sensor localization using the measurement of in-situ acoustic velocity with the Mackenzie formula and utilizing as minimal, as a single beacon. The coordinates of the mathematical system were solved using Cayley–Menger determinant followed by linearization and solving nonlinear equations, as it is considered that no node has information of the other node position after that for the distance measurement, he considered both radio and acoustic signals but as we all know radio signal has a minimal propagation range underwater and he used this to only synchronize the clock between beacon and deployed sensors. He has considered the surface plane as parallel but also shown a non-parallel state of subsets for both configurations, he has considered a minimal single beacon which is on the top of the water surface and submerged sensors that are installed underwater. Correspondingly, TALIB *et al.* (2011) has determined the value of speed of sound using a different empirical equation such as Del Grosso, Mackenzie, and Medwin as the efficacy of speed of sound is highly sensitive to temperature, density and salinity. They talk about the on-site monitoring of speed of sound for various types of water categories such as sea water, fresh water and inlet. Their work could be very helpful for hydrographer which will save time while electing the appropriate speed of sound in adjusting echo sound equipment and this observation will also be valid in countries with moderate atmospheric variations. HUANG *et al.* (2024) investigated the field of an underwater sound speed profile or in short SSP as synchronous and precise

establishment of zonal SSP plays a significant role in marine positioning, navigation and timing (PNT) systems as it appreciably influenced the signal propagation manner for an instance trajectory. There are generally two methods for construction of SSP, one is the direct SSP measurement another one is SSP inversion. For the direct SSP measurement they have used some efficiently functional empirical formulas, such as Wilson, Leroy, Medwin, Del Grosso, etc. These methods have helped promoting the rapid advancement in the field of underwater sensing apparatus.

3. Methodology

3.1. System overview and workflow

To deliver consistent insights of the research procedure, Fig. 2 demonstrated the general workflow applied in this study. Firstly, we have considered three oceanic layers named mixed layer, thermocline layer, and deep layer. The first layer of ocean is mixed layer or we can call it surface layer, it has a direct connection with atmosphere and it also has almost homogeneous vertical qualities in terms of temperature, depth, and salinity (GILL, 2016). The second layer thermocline layer is the middle layer between warmer seawater and deeper cold water in other words we can state that stratified, unstable water forms a thermocline layer, which develops frequent temperature drops (LANA *et al.*, 2017). This applies to oceans worldwide that are deeper than 200 m and also it is noted that the large area of the marine habitat can have their own general understanding, either negatively or positively depending on the circumstances (JAMIESON *et al.*, 2025). For each layer we have considered a range for the main three environmental parameters: temperature, depth, and salinity. Now, for the calculation of velocity of sound underwater we need to use formulas which are incorporated with these parameters and calculate the velocity of a vertical water column, and for that we have considered empirical formulas, such as Mackenzie, Medwin, Wilson, Leroy, etc. After calculating the speed value of vertical column we use the triple integral method to find the value of the average sound of the speed. Now we have analyzed the effect of temperature, depth, and salinity and for that we have considered some fixed values of these indicators and examined the change of the average speed for each layer for different empirical formulas. For the temperature change we have considered the fixed range surface temperature, for depth we considered a specific range of depth across three oceanic layers and for salinity for three layers we considered a range where we calculate the average speed for a slight variation of salinity.

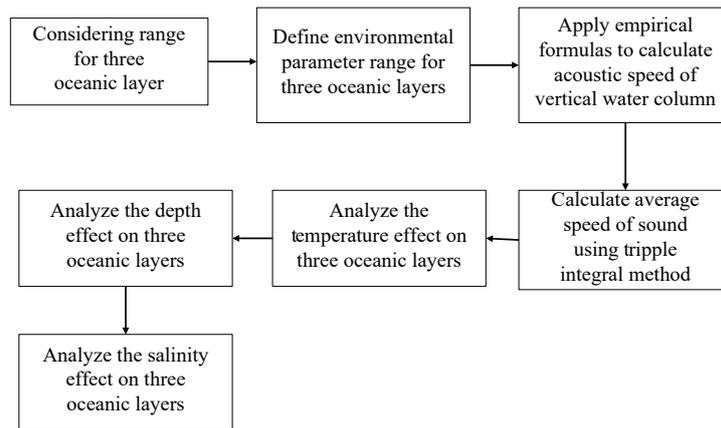


Fig. 2. Overview of the research workflow.

3.2. Analytical framework

In order to determine the distance from, the beacon to sensor position traditionally we consider the speed of sound and travel time and the equation becomes (TALIB *et al.*, 2011):

$$\text{Distance}(d) = \frac{1}{2} \times \text{Speed of sound}(v) \times \text{Travel time}(t). \quad (1)$$

In general, the acoustic signal is used instead of radio signal as it has the lowest propagation range than the acoustic signal (RAHMAN *et al.*, 2013a) the speed of sound or in this case the acoustic wave near the sea plane is considered about 1500 m/s which is four times faster than in air (RAHMAN, 2014). Nevertheless, the effect of environmental variable on the acoustic speed cannot be ignored. To calculate the sound speed velocity underwater we need to inspect the accurate value of temperature, depth, and salinity and for that we cannot use traditional formulas. So, to calculate the acoustic velocity we can use empirical formulas which take these three environmental values into account in the calculations. They are as follows:

1. Mackenzie empirical formula (MACKENZIE, 1981):

$$\begin{aligned} v_m = & 1448.96 + 4.591T - 5.304 \times 10^{-2}T^2 + 2.374 \times 10^{-4}T^3 \\ & + 1.34(S - 35) + 1.63 \times 10^{-2}D + 1.675 \times 10^{-7}D^2 \\ & - 1.025 \times 10^{-2}T(S - 35) - 7.139 \times 10^{-13}TD^3, \end{aligned} \quad (2)$$

where v_m is the speed of the Mackenzie formula under consideration, T stands for temperature, and D stands for depth.

2. Medwin empirical formula (MEDWIN, 1975):

$$v_md = 1449.2 + 4.6T - 0.055T^2 + 0.00029T^3 + (1.34 - 0.01T)(S - 35) + 0.016D, \quad (3)$$

where v_md is the speed of the Medwin formula under consideration.

3. Chen–Millero empirical formula (National Physical Laboratory [NPL], n.d.):

$$v_C = C_1(T, P) + C_2(T, P) \cdot S + C_3(T, P) \cdot S^{3/2} + C_4(T, P) \cdot S^2, \quad (4)$$

where

$$\begin{aligned} C_1(T, P) = & 1402.388 + 5.0383T - 0.058109T^2 + 0.00033432T^3 - 1.47797 \times 10^{-6}T^4 + 3.1419 \times 10^{-9}T^5 \\ & + (0.153563 + 0.00068999T - 8.1829 \times 10^{-6}T^2 + 1.3632 \times 10^{-7}T^3 - 6.126 \times 10^{-10}T^4)P \\ & + (3.126 \times 10^{-5} - 1.7111 \times 10^{-6}T + 2.5986 \times 10^{-8}T^2 - 2.5353 \times 10^{-10}T^3 + 1.0415 \times 10^{-12}T^4)P^2 \\ & + (-9.7729 \times 10^{-9} + 3.8513 \times 10^{-10}T - 2.3654 \times 10^{-12}T^2)P^3, \end{aligned}$$

$$\begin{aligned} C_2(T, P) = & 1.389 - 0.01262T + 7.166 \times 10^{-5}T^2 + 2.008 \times 10^{-6}T^3 - 3.21 \times 10^{-8}T^4 \\ & + (9.4742 \times 10^{-5} - 1.2583 \times 10^{-5}T - 6.4928 \times 10^{-8}T^2 + 1.0515 \times 10^{-8}T^3 - 2.0142 \times 10^{-10}T^4)P \\ & + (-3.9064 \times 10^{-7} + 9.1061 \times 10^{-9}T - 1.6009 \times 10^{-10}T^2 + 7.994 \times 10^{-12}T^3)P^2 \\ & + (1.1 \times 10^{-10} + 6.651 \times 10^{-12}T - 3.391 \times 10^{-13}T^2)P^3, \end{aligned}$$

$$C_3(T, P) = -0.01922 - 4.42 \times 10^{-5}T + (7.3637 \times 10^{-5} + 1.795 \times 10^{-7}T)P,$$

$$C_4(T, P) = 0.001727 - 7.9836 \times 10^{-6}P,$$

where v_c is the speed of the Chen–Millero formula, P stands for pressure, and S denotes for salinity. In the formula under consideration C_1 to C_4 are its coefficients.

4. Wilson empirical formula (WILSON, 1977):

$$v_W = 1449.14 + v_1 + v_2 + v_3 + v_{tpS}, \quad (5)$$

where

$$v_1 = 4.5721T - 4.4532 \times 10^{-2}T^2 - 2.604 \times 10^{-4}T^3 + 7.9851 \times 10^{-6}T^4,$$

$$\begin{aligned}
v_2 &= 1.60272 \times 10^{-1}P + 1.0268 \times 10^{-5}P^2 + 3.5216 \times 10^{-9}P^3 - 3.3603 \times 10^{-12}P^4, \\
v_3 &= 1.39799(S - 35) + 1.69202 \times 10^{-3}(S - 35)^2, \\
v_{tpS} &= (S - 35)\left(-1.1244 \times 10^{-2}T + 7.7711 \times 10^{-7}T^2 + 7.7016 \times 10^{-5}P - 1.2943 \times 10^{-7}P^2\right. \\
&\quad \left.+ 3.158 \times 10^{-8}PT + 1.579 \times 10^{-9}PT^2\right) \\
&\quad + P\left(-1.8607 \times 10^{-4}T + 7.4812 \times 10^{-6}T^2 + 4.5283 \times 10^{-8}T^3\right) \\
&\quad + P^2\left(-2.5294 \times 10^{-7}T + 1.8563 \times 10^{-9}T^2\right) + P^3\left(-1.9646 \times 10^{-10}T\right),
\end{aligned}$$

where v_w is the speed of the Wilson formula. In the formula under consideration v_1 , v_2 , and v_{tpS} are its coefficients.

5. Leroy empirical formula (LEROY, 1969):

$$v_L = 1492.9 + 3(T - 10) - 0.006(T - 10)^2 - 0.04(T - 18)^2 + 1.2(S - 10) - 0.01(S - 35)(T - 18) + D/61, \quad (6)$$

where v_L is the speed of the Leroy formula.

6. Coppens empirical formula (COPPENS, 1981):

$$\begin{aligned}
v_{Co} &= v_0 + (16.23 + 0.0253T) \cdot 0.001Z + (0.213 - 0.01T) \cdot 0.000001Z^2, \\
v_0 &= 1449.05 + 4.57T - 0.0521T^2 + 0.00023T^3 + (1.333 - 0.0126T + 0.00009T^2)(S - 35).
\end{aligned} \quad (7)$$

7. Del Grosso empirical formula (NPL, n.d.):

$$v_D = C_{000} + \Delta C_T + \Delta C_S + \Delta C_P + \Delta C_{STP}, \quad (8)$$

where

$$\begin{aligned}
C_{000} &= 1402.392, \\
\Delta C_T &= 5.012285T - 0.0551184T^2 + 0.000221649T^3, \\
\Delta C_S &= 13.2953S + 0.0001288598S^2, \\
\Delta C_P &= 0.1560592P + 0.0002449993P^2 - 8.833959 \times 10^{-8}P^3, \\
\Delta C_{STP} &= 0.006353509TP - 4.383615 \times 10^{-7}T^3P - 0.00001593895TP^2 + 2.656174 \times 10^{-8}T^2P^2, \\
&\quad + 5.222483 \times 10^{-10}TP^3 - 0.01275936ST + 9.688441 \times 10^{-5}ST^2 - 0.0003406824STP, \\
&\quad + 4.857614 \times 10^{-6}S^2TP - 1.616745 \times 10^{-8}S^2P^2,
\end{aligned}$$

where v_D is the speed of the Del Grosso formula, and C_{000} to C_T , C_P , C_{STP} are its coefficients.

Each equation has different types of range for the three environmental parameters. In this work our desired environmental parameter unit for temperature is Celsius, for salinity it is p.s.u, and for depth it is meter but as discussed in (HUANG *et al.*, 2024) for Eq. (5) and Eq. (7) the depth unit is 1000 kg/cm³ and Eq. (3) the unit is 1000 bar. To determine the velocity of vertical water column and also to measure the average speed of sound it is needed to convert them to our desired parameter. To convert the depth value into meters we use the formula from (NPL, n.d.), to convert pressure to depth in meters:

$$Z_s(P, \Phi) = \frac{9.72659 \times 10^2 P - 2.512 \times 10^{-1} P^2 + 2.279 \times 10^{-4} P^3 - 1.82 \times 10^{-7} P^4}{g(\Phi) + 1.092 \times 10^{-4} P}, \quad (9)$$

where $g(\Phi)$ (variation of gravity with latitude) is considered 1000 m/s² and P is around 9.81×10^6 n/m², and as the equation with these values provided a yield value which do not align with expected physical depths,

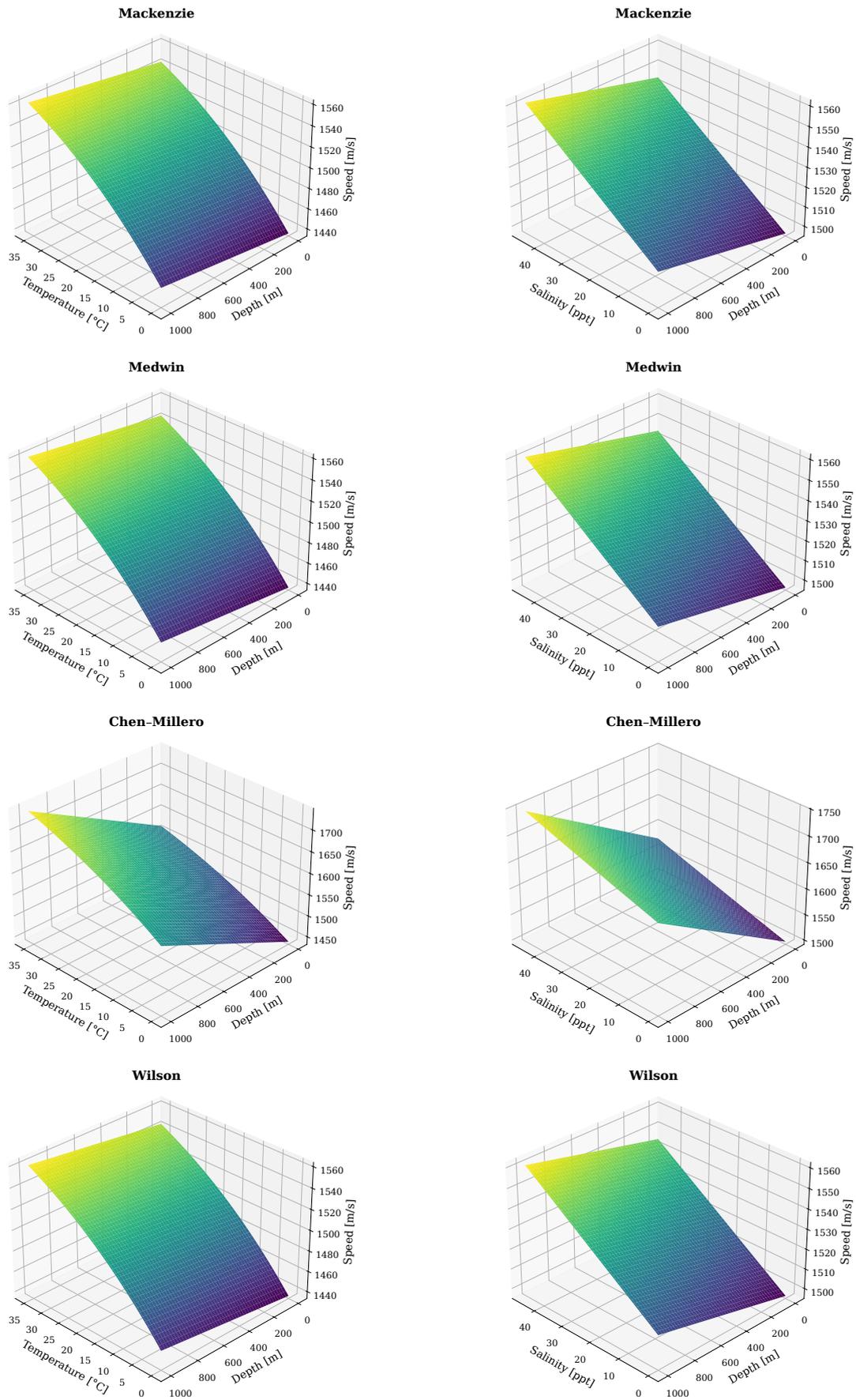


Fig. 3. Acoustic profile for Mackenzie, Medwin, Chen-Millero, and Wilson (temperature/salinity vs. depth).

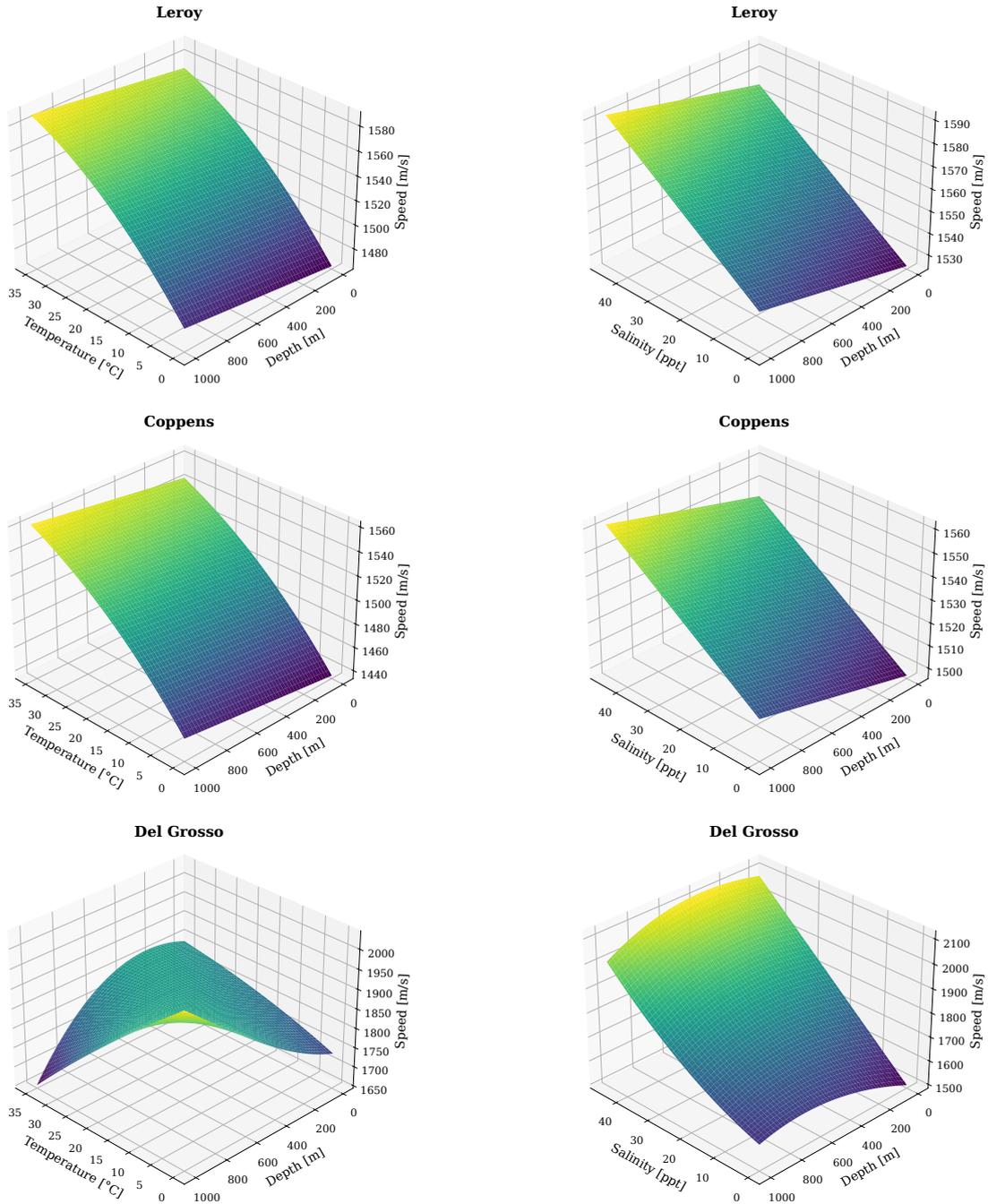


Fig. 4. Acoustic profile for Leroy, Coppens, and Del Grosso (temperature/salinity vs. depth).

we have used the scaling factor of 0.08593 which gives the depth value as 8000 m for 1000 kg/cm³ and for 1000 bar the scaling factor is considered 0.008618 which give us a depth of same 8000 m. In Table 1, we can see the comparison of different empirical formula range for temperature, depth and salinity.

After determining and transferring the numeric values of temperature, depth and salinity with the top beacon which has all the information from top to the bottom region, we can calculate the average speed of an acoustic signal by RAHAMAN *et al.* (2013b) using:

$$V_{avg} = f_{avg}(T, D, S) = \frac{1}{A} \int \int \int_R f(T, D, S) = \frac{1}{A} \int_{S_i}^{S_f} \int_{D_i}^{D_f} \int_{T_i}^{T_f} f_{avg}(T, D, S) dT dD dS. \quad (10)$$

Table 1. Comparison of different empirical formulas for speed of sound.

Empirical formula	Proposed year	Applicable range		
		Temperature [°C]	Depth [m]	Salinity (p.s.u)
Mackenzie (Mackenzie, 1981)	1981	2 to 30	0 to 8000	25 to 40
Medwin (Medwin, 1975)	1975	0 to 30	0 to 1000	0 to 40
Chen–Millero (NPL, n.d.)	1980	0 to 40	0 to 8000	5 to 40
Wilson (Wilson, 1977)	1960	0 to 30	0 to 1000	0 to 37
Leroy (Leroy, 1969)	1969	–2 to 40	0 to 1000	0 to 42
Coppens (Coppens, 1981)	1981	0 to 35	0 to 4000	0 to 45
Del Grosso (NPL, n.d.)	1974	0 to 30	0 to 8000	30 to 40

Considering the ranges of all empirical formulas from Table 1, we can initialize the upper and lower ranges for all empirical formulas and plot their acoustic profile using the Python simulation environment and Fig. 3 and Fig. 4 have demonstrated that.

In this work, A considers the area produced by the limits of T , D , S ; $f(T, D, S)$ which is for all empirical equations the same as in Eq. (2) to Eq. (8). The right sides of Fig. 3 and Fig. 4 represent the acoustic profile for salinity and depth where temperature is constant and in the left side acoustic profile is for temperature and depth where salinity is constant. So, by the help of the acoustic profile we can visualize the three environment parameters.

4. Simulation results

4.1. Environmental constraints

In this work, the entire underwater environment has been taken into account in three factors, which are temperature, depth, and salinity, and these variables fluctuated depending on different layers such as mixed layer, thermocline layer, and deep layer. According to KUNDU (2016), each ocean layer has its own range for environmental parameters and it highly impacts the ecological parameters which are listed in Table 2.

Table 2. Environmental variable range for different layers.

Ocean layers	Depth [m]	Temperature [°C]	Salinity (p.s.u)
Mixed	0 to 450	30 to 25.5	25 to 25.045
Thermocline	450 to 1000	10 to 4	34 to 34.5
Deep	1000 to 8000	4 to 2	34.8 to 35.1

To investigate the effect of environmental parameters on an acoustic speed, we have simulated different empirical models which align with our ranges of sea layers given in Table 2 using the Python environment. The simulation was conducted by applying Python 3.12 utilizing a cloud-based environment facilitated by Google Collab. Throughout the computation, a suite of Python libraries was implemented; each of the library was selected based on specific computational conditions. The NumPy library was applied to perform efficient computational operations, specifically for optimizing numerical arrays for the environmental variable range. The SciPy library was implemented to perform mathematical integration for calculating average sound speed by utilizing the quad function. The Matplotlib library was also applied for visualization purposes like, originating computational plots to differentiate environmental variables to observe their characteristics. Each empirical equations have been developed as a custom function in the Python that takes temperature, depth, and salinity as input and return a comparable sound speed. The resulting simulation calculates the average sound speed for different empirical formulas, then visualizes the outcomes into the labeled subplot to help with comparative analysis. In this work Table 2 shows the simulation environment parameter which later was simulated using the Python environment mentioned above. An average speed of sound was calculated for six empirical models for mixed layers and thermocline layers (Mackenzie, Medwin, Leroy, Wilson, Coppens, and Chen–Millero) and for deep layers there

are only five (Mackenzie, Leroy, Wilson, Coppens, Chen–Millero) that are consistent with the simulation ranges and the Del Grosso empirical formula was not included in the simulation or analysis and its range does not satisfy our desired range of simulation. To calculate the average speed for mixed, thermocline, deep layers the temperature range is considered from 25.5 °C, 4 °C, and 2 °C for the bottom temperature and 30 °C, 10 °C, and 2 °C for the surface temperature. Respectively, in Fig. 5, Fig. 6, and Fig. 7 for mixed, thermocline, and deep layers the variation of salinity are 0.045 p.s.u, 0.5 p.s.u, and 0.3 p.s.u with the added Gaussian noise, estimated at 1% of the mean acoustic speed of each empirical model in order to reproduce measurement uncertainties, it has been directly added in the ‘average speed’ of sound. After 100 iterations, the mean average speed has been

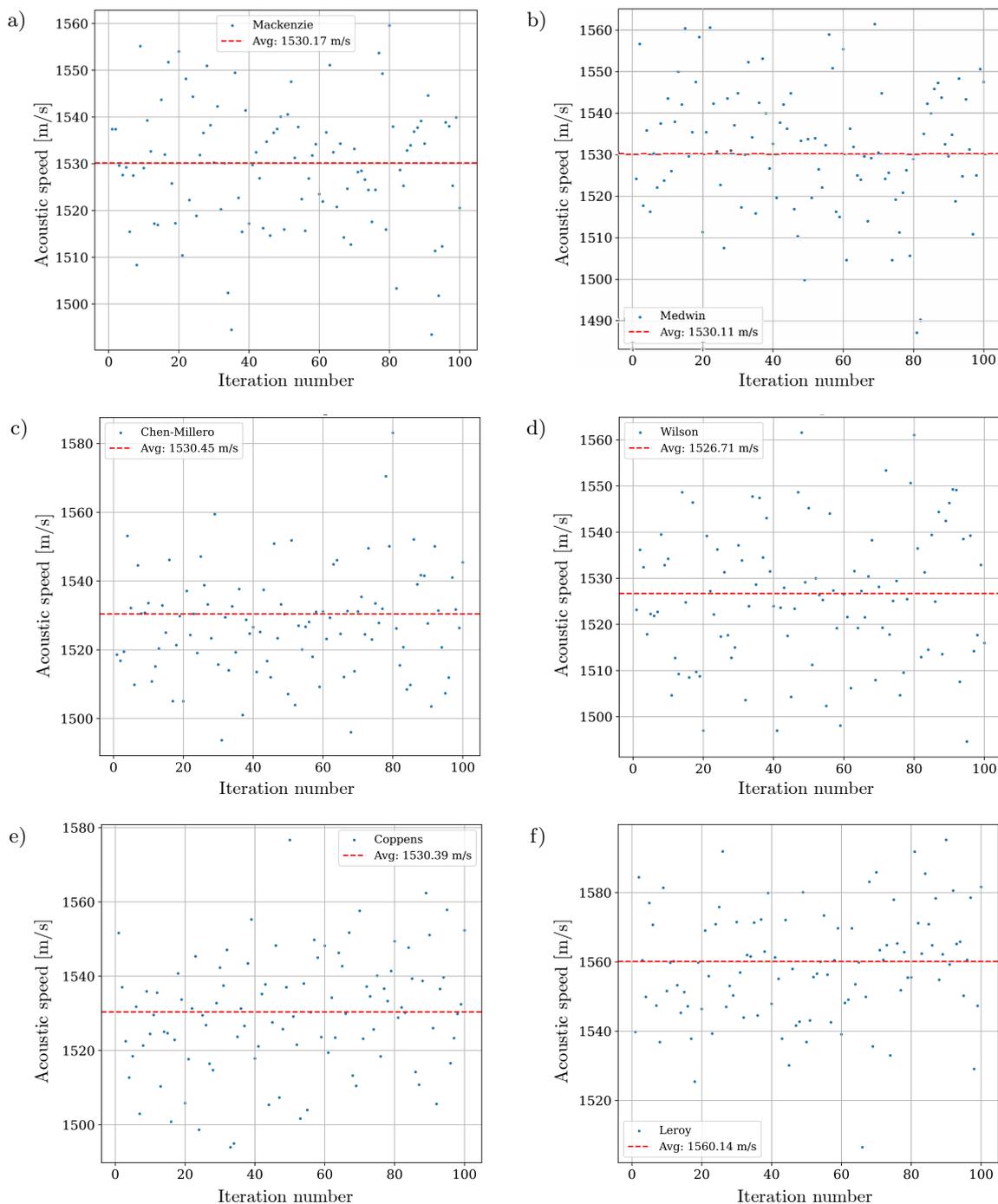


Fig. 5. Average sound speed variation for mixed layers:
a) Mackenzie, b) Medwin, c) Chen–Millero, d) Wilson, e) Coppens, f) Leroy.

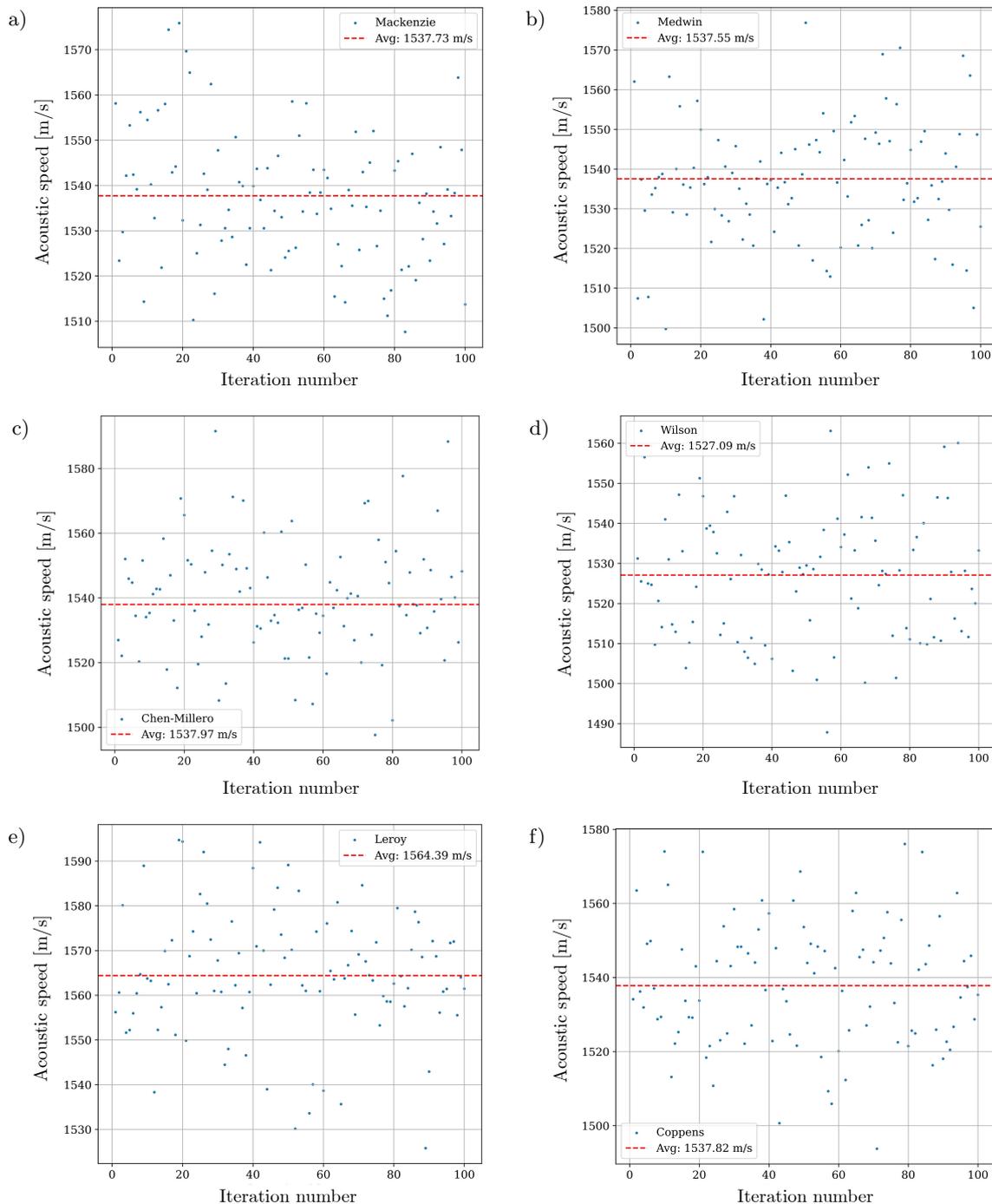


Fig. 6. Average sound speed variation for thermocline layers:
a) Mackenzie, b) Medwin, c) Chen–Millereo, d) Wilson, e) Leroy, f) Coppens.

in the range of 1526.71 m/s to 1560.14 m/s for mixed layers, 1527.09 m/s to 1564.39 m/s for thermocline layers, and 1524.19 m/s to 1597.12 m/s for deep layers.

Figure 8 has portrayed the effect of temperature on the average speed of sound for mixed layers. The bottom temperature is considered from 10 °C to 30 °C under the surface temperature fixed to 25 °C and 28 °C. Additionally, in Fig. 9, for thermocline layers the bottom temperature –8 °C to 2 °C and the surface temperature is fixed to 4 °C as well as 6 °C whereas, 10 is for deep layer where the surface temperature is fixed at 2 °C and 4 °C where a bottom is varying for –20 °C to 0 °C. In mixed layers the average speed increases by 2 m/s to 2.25 m/s per 1 °C increment in surface temperature for Leroy and Coppens formulas and on the other-hand, Mackenzie,

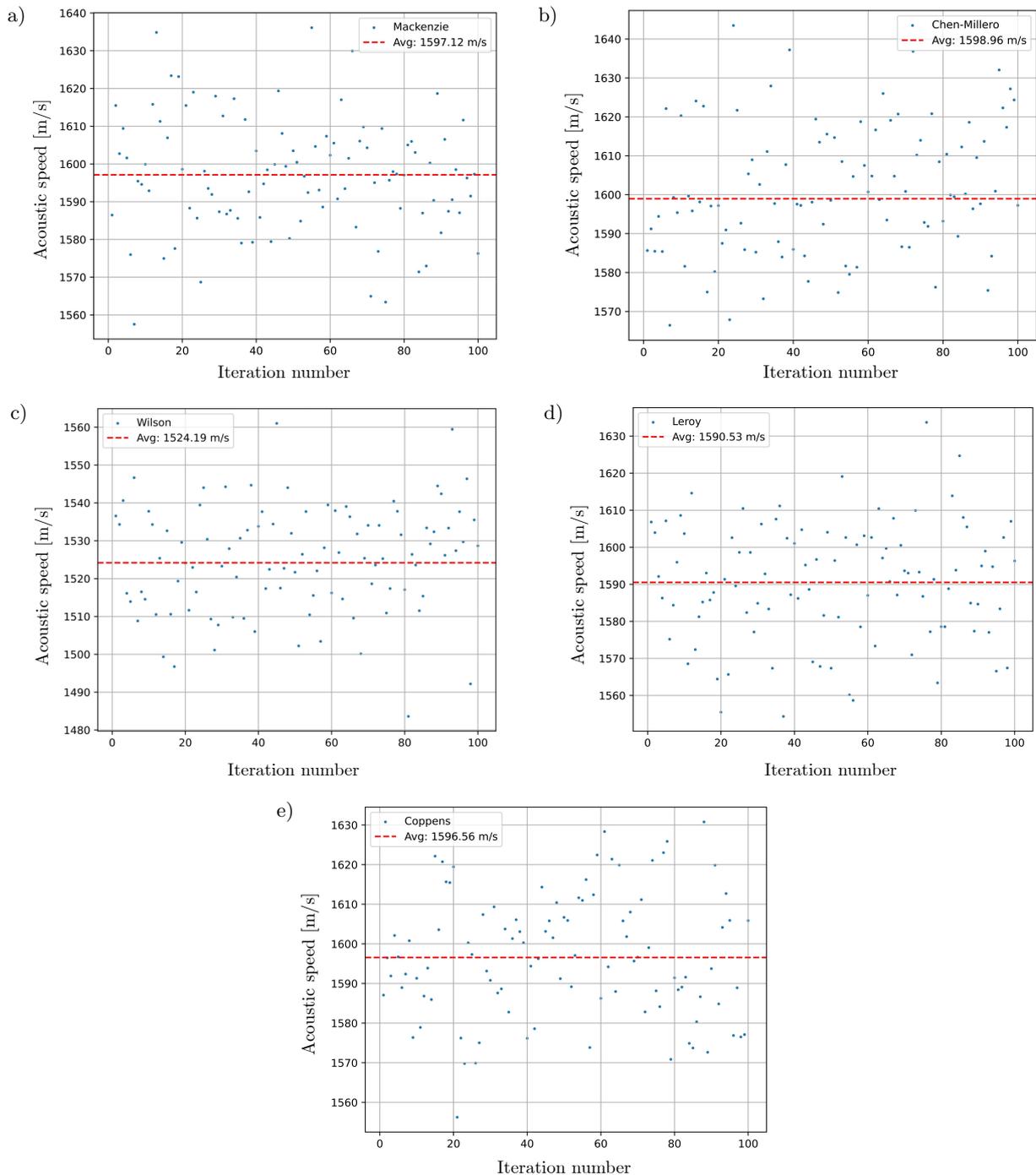


Fig. 7. Average sound speed variation for deep layers:
 a) Mackenzie, b) Chen–Millero, c) Wilson, d) Leroy, e) Coppens.

Medwin, Wilson, and Chen–Millero showcase a moderate level sensitivity which is approximately 1.37 m/s for the set bottom temperature range. A 5 °C rise in bottom temperature will increase the average sound speed by 0.46 % to 0.66 % depending on the formula while formula like Leroy and Coppens reacts most with an increase around 0.62 % and 0.66 %. The rest of the formulas has an overall increment around 0.46 %. Meanwhile for thermocline layers the increase in average sound speed has been increased, as 1 °C ranges from 1.5 m/s to 2 m/s. Again Mackenzie, Medwin, Wilson, and Chen–Millero recorded a slight increase of 1.5 m/s but Leroy and Coppens recorded the high increase of 2 m/s so, this is observed with the highest sensitivity. Again for a 5 °C bottom temperature increases the speed around 0.29 % to 0.41 % for all the formula. It is 0.29 % to 0.31 % for Medwin,

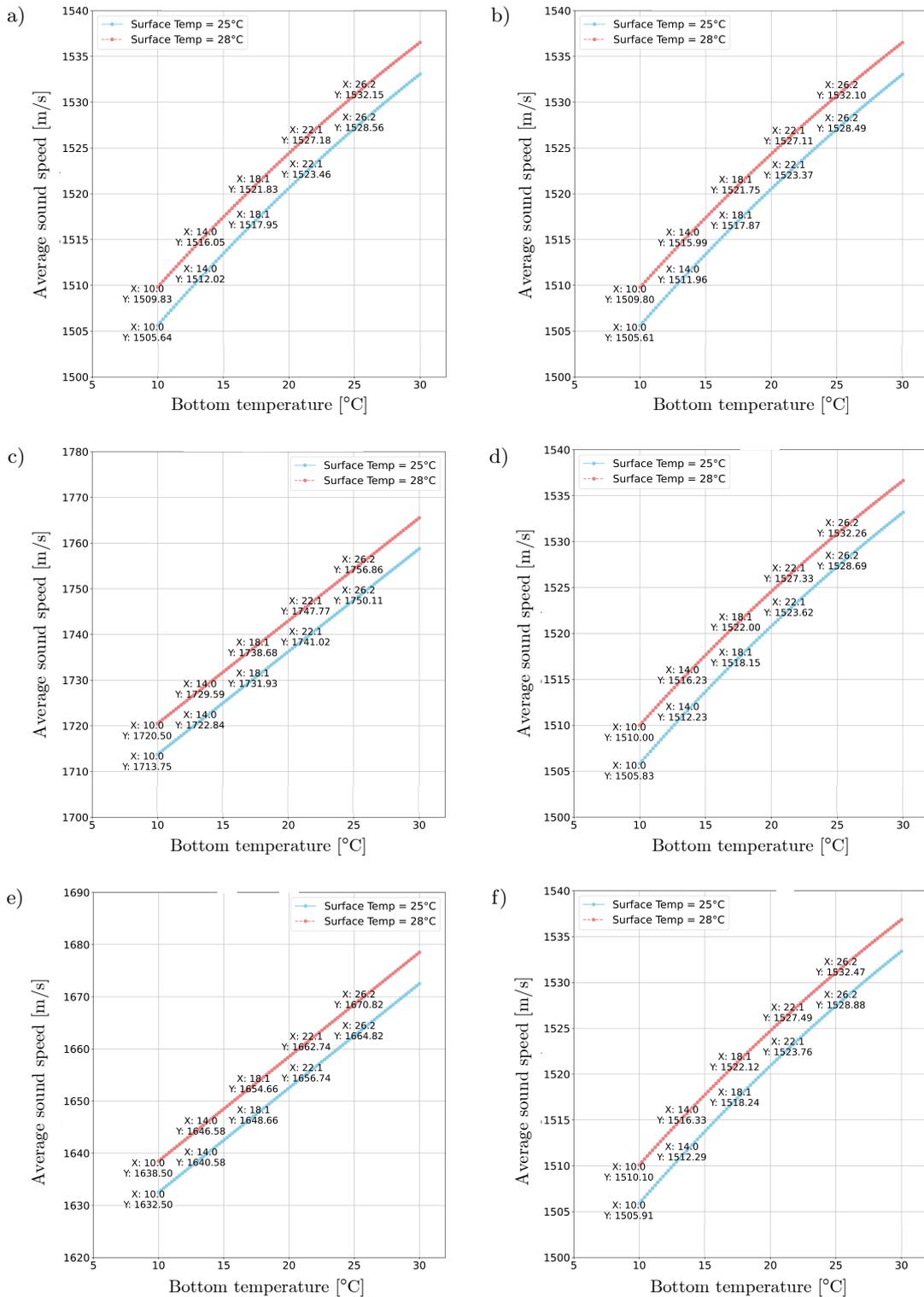


Fig. 8. Average sound speed variation due to temperature changes for mixed layers: a) Mackenzie, b) Medwin, c) Leroy, d) Wilson, e) Coppens, f) Chen–Millero.

Wilson, Chen–Millero, and for Leroy and Coppens it is around 0.37% and 0.41%. Lastly, for deep layers the effect of temperature on average speed becomes weaker. The average sound speed increased only 1 m/s to 1.2 m/s, while with a 5°C increase in bottom temperature, the speed of sound increased again 0.21% to 0.31%, with Leroy and Coppens showing the highest sensitivity.

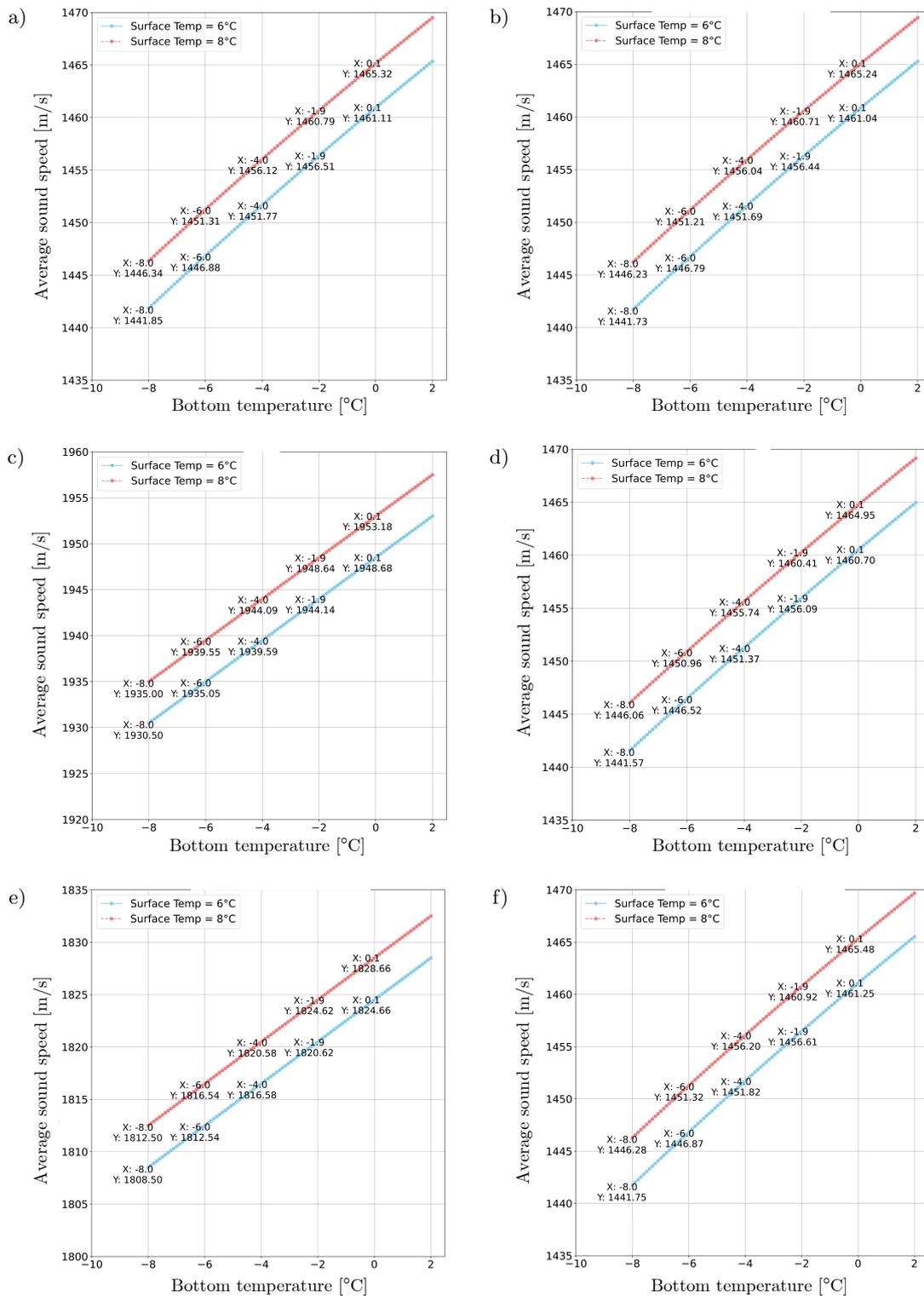


Fig. 9. Average sound speed variation due to temperature changes for thermocline layers:
 a) Mackenzie, b) Medwin, c) Leroy, d) Wilson, e) Coppens, f) Chen-Millero.

In Fig. 11, Fig. 12, and Fig. 13 the depth measurement accuracy on the computed speed of sound was systematically for 450 m water column for mixed layers, 1000 m for thermocline layers and 8000 m for deep layers. In mixed layer the speed of sound increment is 0.08 m/s to 0.085 m/s for each 10 m increase in the depth and for thermocline and deep layers the increase of sound per 10 m increment is 0.16 m/s to 0.166 m/s and 0.12 m/s

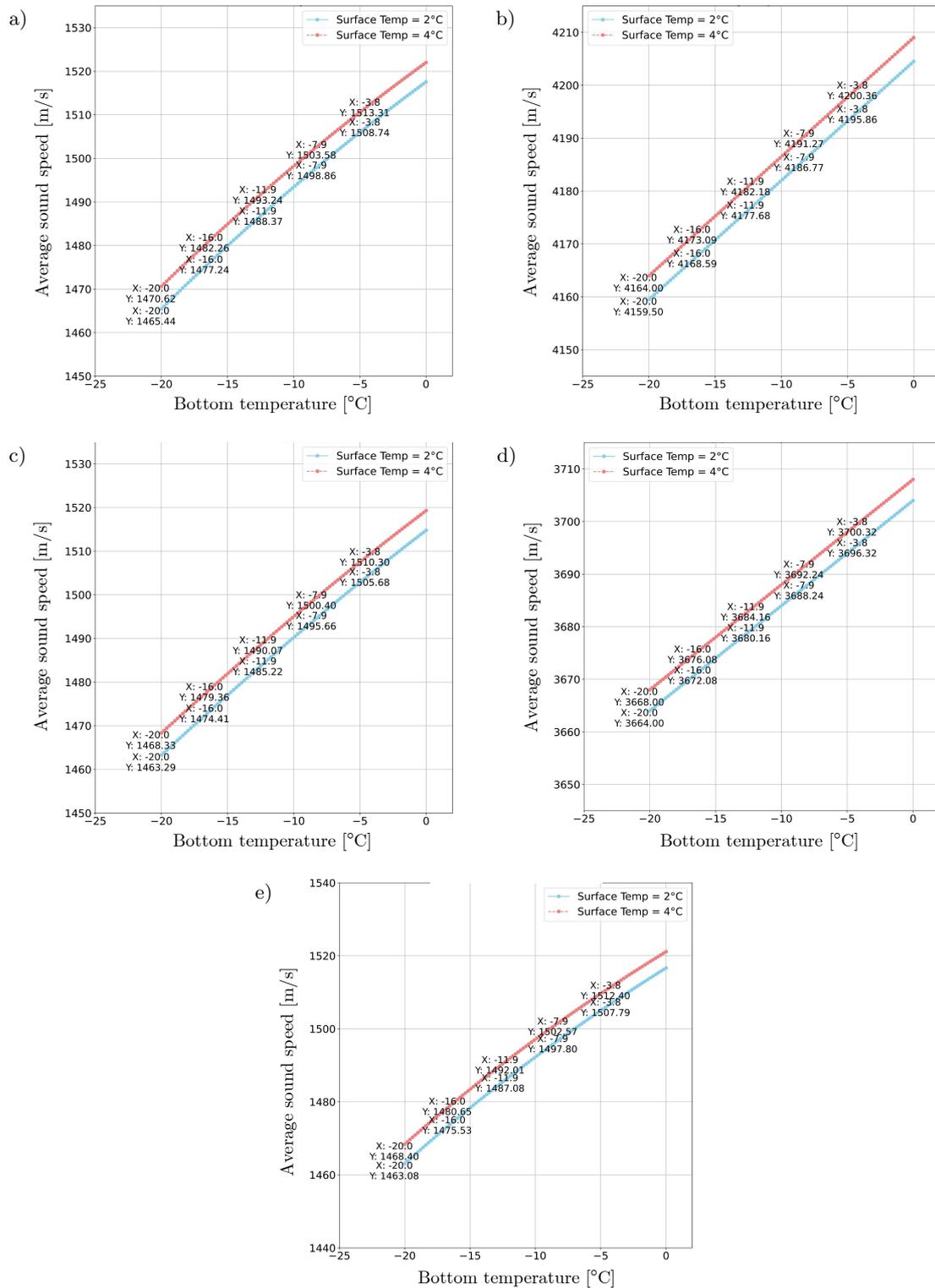


Fig. 10. Average sound speed variation due to temperature changes for deep layers:
 a) Mackenzie, b) Medwin, c) Leroy, d) Wilson, e) Coppens, f) Chen–Millero.

to 0.13 m/s. In all layers Coppens has the high response and for thermocline and deep layers along with Coppens Mackenzie also shows a great impact around 0.022 % to 0.4 % and 0.019 % to 0.4 %. Now if we consider 5 % error for mixed (22.2 m), thermocline (50 m), and deep layers the effect on the average speed increment is 0.18 m/s to 0.19 m/s (0.012 %), 0.8 m/s to 0.83 m/s (0.055 %), and 4.8 m/s to 5.3 m/s (0.3 % to 0.35 %). The negligible

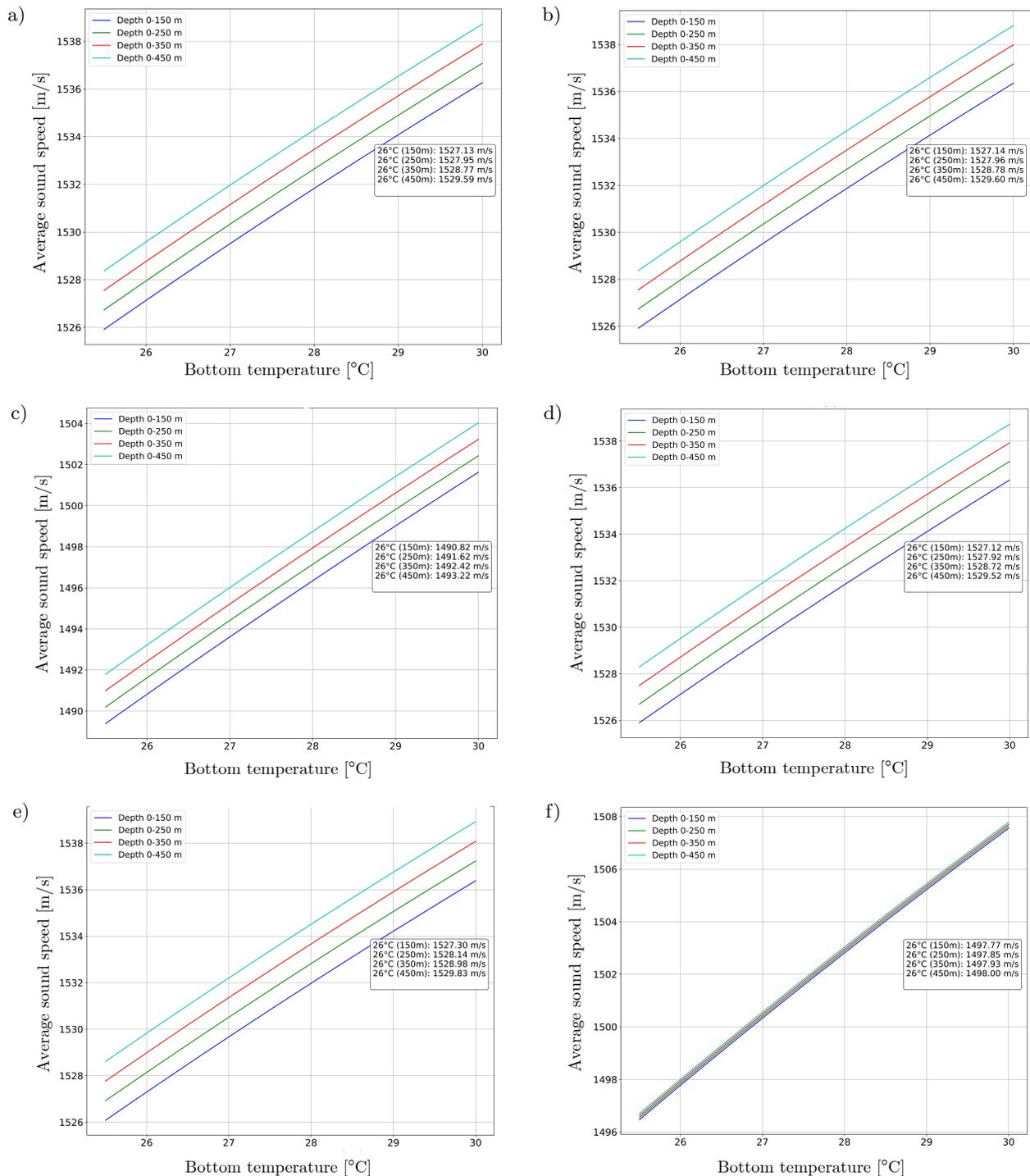


Fig. 11. Average sound speed variation due to depth changes for mixed layers: a) Mackenzie, b) Medwin, c) Leroy, d) Wilson, e) Coppens, f) Chen-Millero.

depth can be for each layer such as: $[\leq 50 \text{ m}]$, $[\leq 100 \text{ m}]$, and finally $[\leq 200 \text{ m}]$. So, finally we can say that the rate of change of sound for mixed, thermocline, and deep layers is accordingly to $0.0083 \text{ m s}^{-1} \text{ m}^{-1}$, $0.0165 \text{ m s}^{-1} \text{ m}^{-1}$, and $0.013 \text{ m s}^{-1} \text{ m}^{-1}$ which means the sound speed rises to 0.083 m/s , 0.0165 m/s , and 0.013 m/s for each 1 m increment on the depth.

The effect of salinity has been portrayed in Fig. 14, Fig. 15, and Fig. 16, respectively. To observe the salinity impact on the three oceanic layers we consider a fixed temperature for all the three layers which are 27°C , 5°C , and 2°C , respectively. Considering the salinity increases to 0.045 ppt for mixed layer shown in Fig. 14,

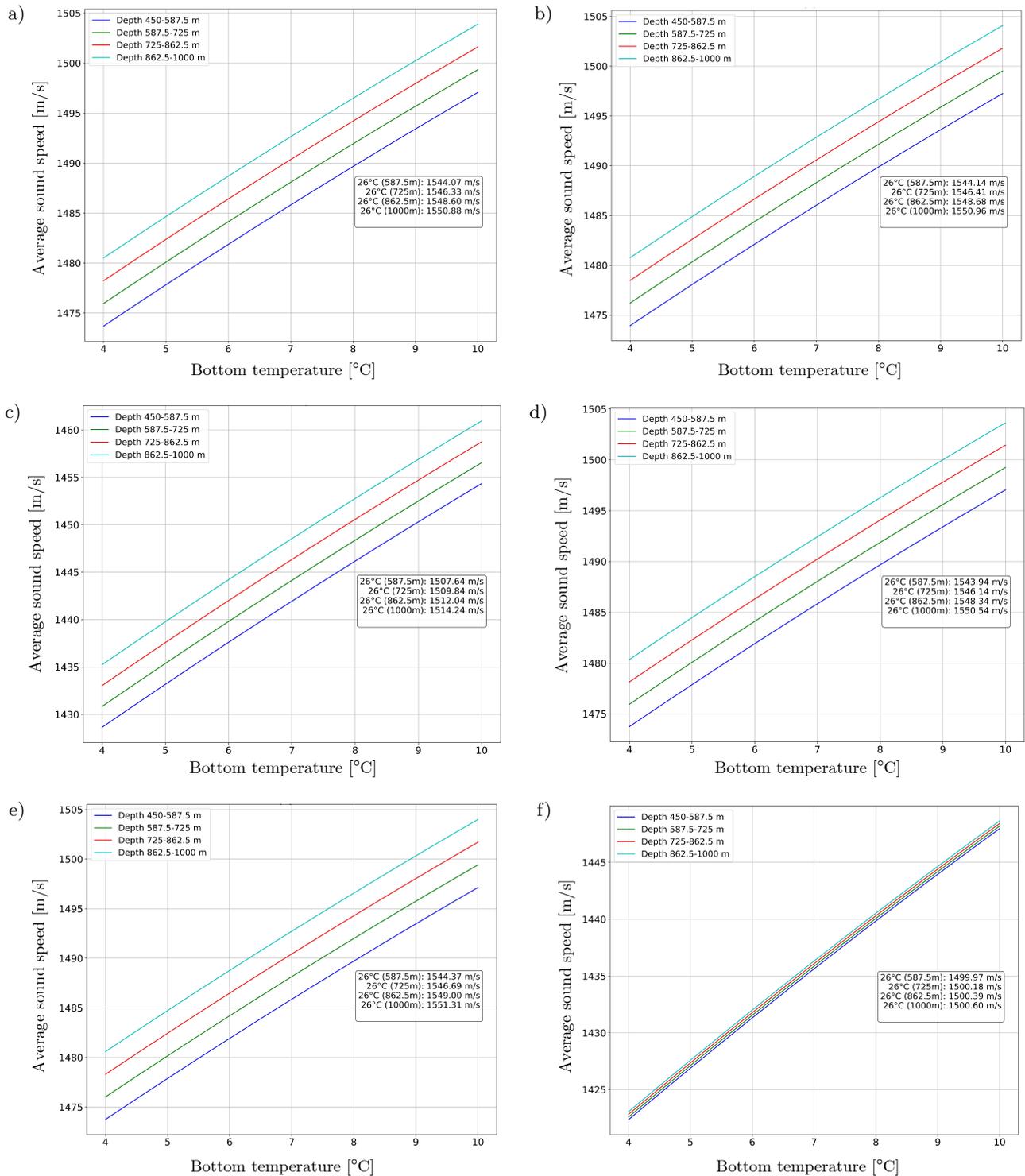


Fig. 12. Average sound speed variation due to depth changes for thermocline layers:
 a) Mackenzie, b) Medwin, c) Leroy, d) Wilson, e) Coppens , f) Chen–Millero.

for thermocline in Fig. 15, and deep layer from the Fig. 16 it is shown to be 0.5ppt and 0.3ppt. All formulas show a positive rise in the average speed of sound. In mixed layer the rise in average speed is +0.049 m/s to +0.068 m/s when Mackenzie and Medwin show a positive rise of +0.049 m/s (0.0033%) Leroy and Wilson show a very high effect around +0.059 m/s (0.00398%) and +0.068 m/s (0.00441%) although this time Coppens has the lowest impact which is +0.049 m/s (0.00185%). The effect of salinity is still negligible. In thermocline layer with

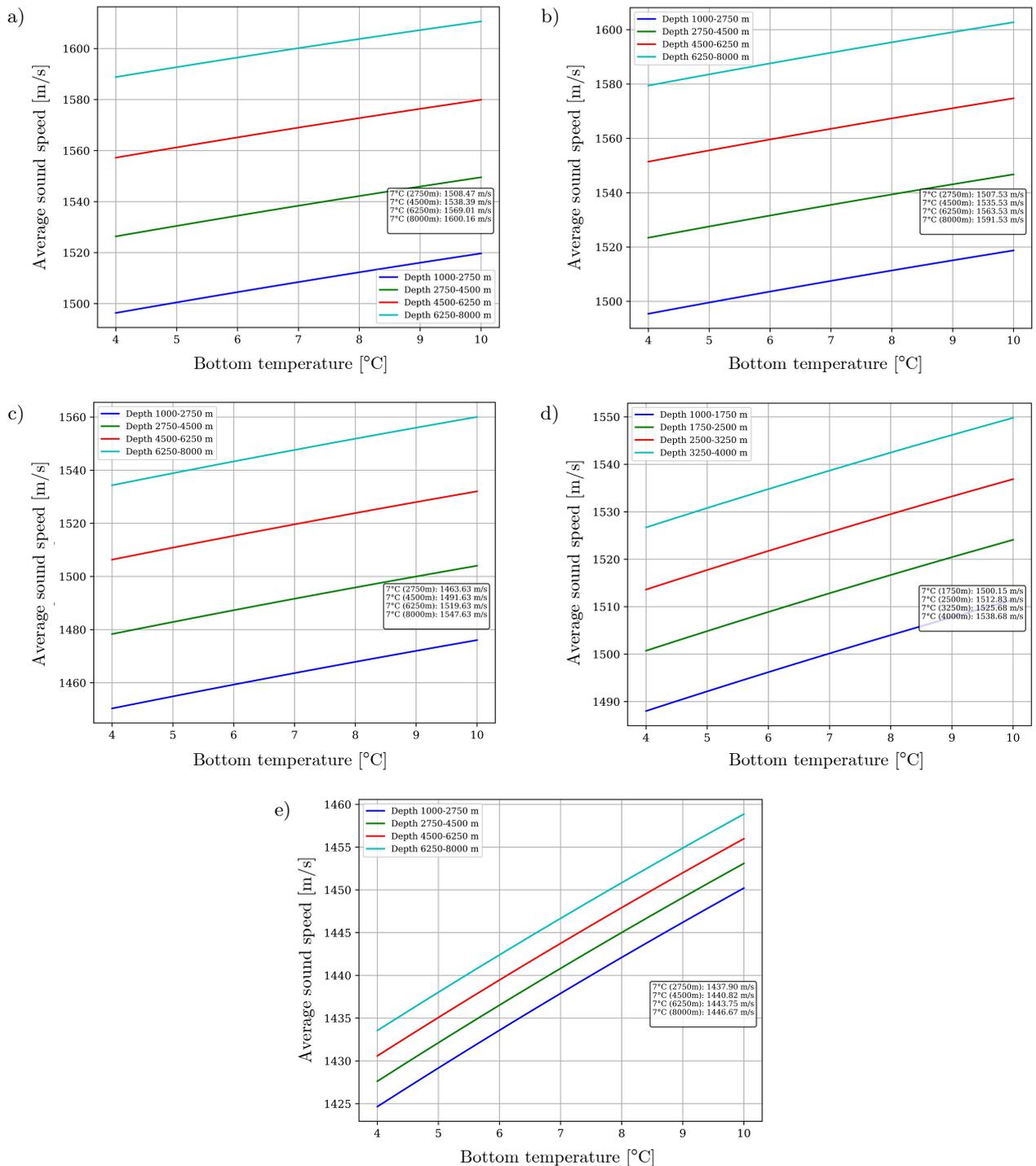


Fig. 13. Average sound speed variation due to depth changes for deep layers: a) Mackenzie, b) Medwin, c) Leroy, d) Wilson, e) Coppens, f) Chen–Millero.

an increase in salinity variation the domination increases. The average speed rise for all formula is still positive and it is around 0.73 m/s to 0.9 m/s. Mackenzie shows +0.75 m/s (0.05 %), Medwin it is +0.73 m/s (0.048 %) and for Leroy, Wilson, Coppens, and Chen–Millero it is correspondingly +0.82 m/s (0.055 %), +0.9 m/s (0.058 %), +0.7 m/s (0.026 %), and +0.78 m/s (0.053 %). The influence of salinity is still less than that of temperature, but it cannot be ignored. Lastly, for deep layer the variation is just 0.3ppt but its influence is noticeable for an increase of the speed of the sound. All formulas still show a positive increase from +1.2 m/s to +1.35 m/s, where Mackenzie, Leroy, Wilson, Coppens, and Chen–Millero are concerned, respectively, +1.2 m/s (0.08 %), +1.28 m/s

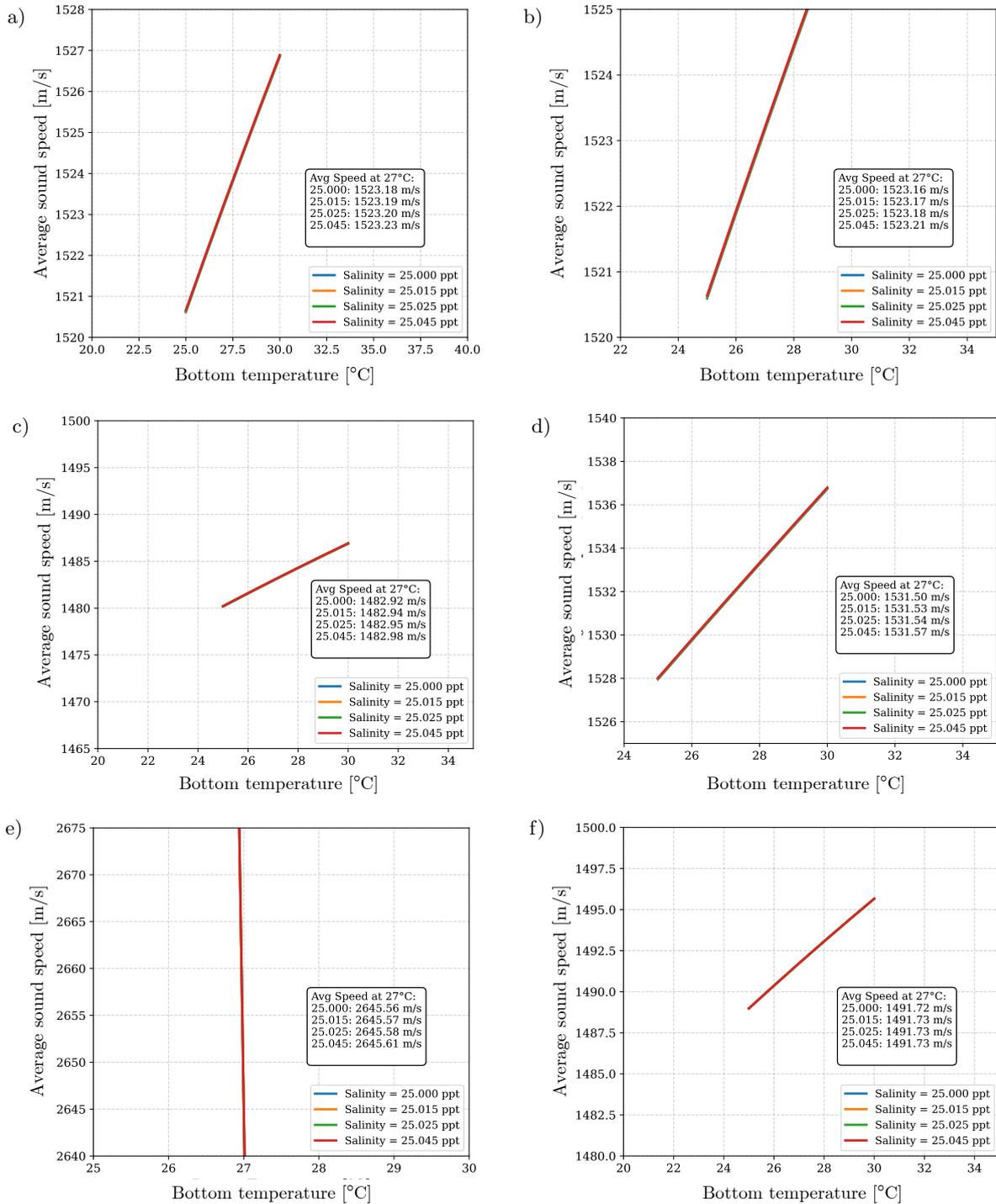


Fig. 14. Average sound speed variation due to salinity changes for mixed layers:
 a) Mackenzie, b) Medwin, c) Leroy, d) Wilson, e) Coppens, f) Chen-Millero.

(0.087%), +1.35 m/s (0.089%), +1.15 m/s (0.043%), +1.3 m/s (0.085%), so we can say Mackenzie has the least effect and Wilson has the highest effect. Comprehensively, the salinity effect increases layer by layer.

5. Discussion

In this study, we have systematically analyzed the effect of three environmental parameters which are temperature, depth, and salinity. The effects of these parameters on the acoustic signal for three ocean layers are

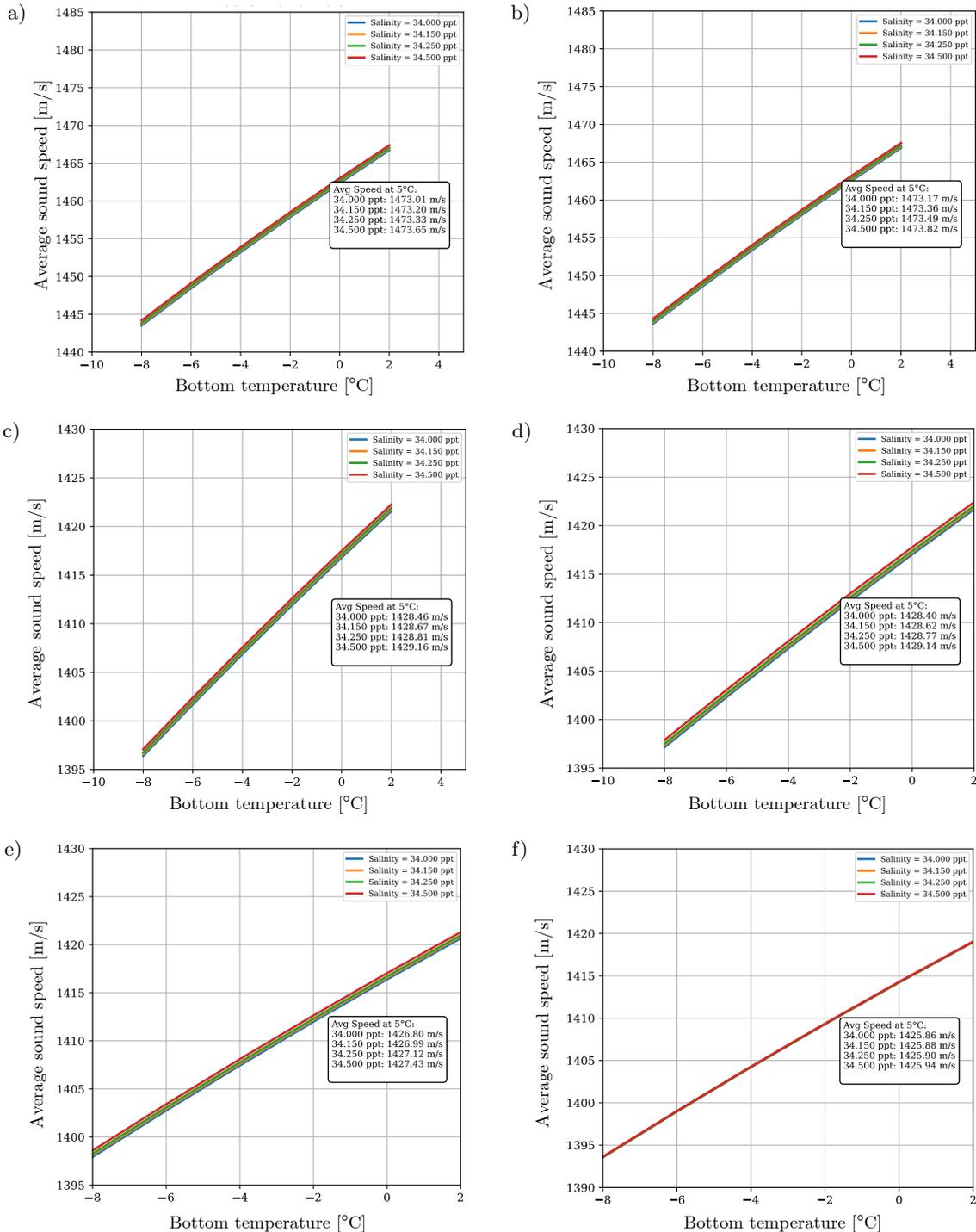


Fig. 15. Average sound speed variation due to salinity changes for thermocline layers: a) Mackenzie, b) Medwin, c) Leroy, d) Wilson, e) Coppens, f) Chen-Millero.

demonstrated using different empirical formulas. Each formulas compute the mean speed of sound considering the ranges of deep-ocean conditions. After considering the different empirical formulas and all parameters were calculated using the average speed for empirical formulas which satisfied the simulation range and got the mean average sound speed around 1526.71 m/s to 1560.14 m/s for all three oceanic layers and for practicality we introduced the Gaussian noise with a mean 0 and standard deviation for 100 iterations. For the computation of average sound speed the triple integral method was considered. In Table 3 a detailed interpretation of this research work has been presented. The three prime oceanic layers (mixed, thermocline, deep) have been observed to estimate

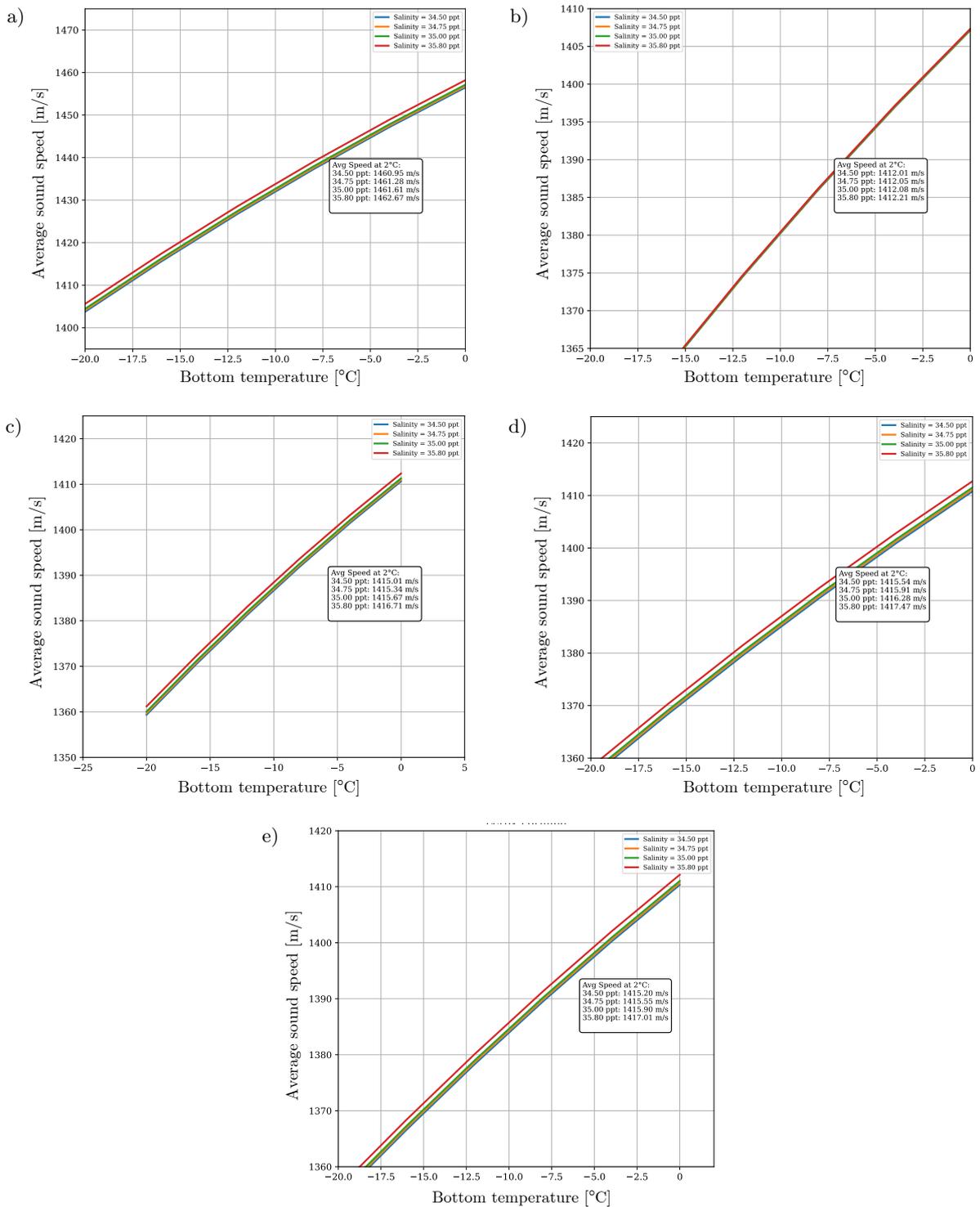


Fig. 16. Average sound speed variation due to salinity changes for deep layers:
 a) Mackenzie, b) Medwin, c) Leroy, d) Wilson, e) Coppens, f) Chen–Millero.

the variation in the mean sound speed and each layer has its own range of the environmental parameter which has been demonstrated in Table 2. Each layer displays a unique response to the major environmental variables: temperature, depth, and salinity. The effects of these parameters depend on difference between each layer range and also upon different empirical formulas including Mackenzie, Medwin, Leroy, Wilson, Coppens, and Chen–Millero. Table 3 highlights the amplitude of changes in the average speed of sound due to gradual variation in the values of temperature, depth, and salinity.

Table 3. Analysis of environmental parameter influence on oceanic layers.

Oceanic layer	Temperature effect	Depth effect	Salinity effect	Constrain effect on formulas	Parameter role
Mixed layer	1 °C rise in the temperature can cause a significant impact on the average speed around 2 m/s to 2.5 m/s	10 m rise can cause the arise of average sound speed is only 0.08 m/s to 0.085 m/s	Salinity has a minimal effect of only 0.049 m/s to 0.068 m/s for variation of 0.045 ppt	The Mackenzie and Medwin formulas show a high sensitivity in the mixed layer where temperature effect is around 0.32 %	Mixed layers temperature is the most domination parameter among them and depth and salinity effect can be ignored as they influence the speed just 0.04 % and 0.003 %
Thermocline layer	1 °C rise in the temperature cause fluctuation on average speed around 1.5 m/s to 2 m/s	10 m rise can cause the arise of average sound speed is only 0.16 m/s to 0.166 m/s	Salinity effect is only 0.73 m/s to 0.9 m/s for a variation of 0.5 ppt	In thermocline layer, formulas like Wilson, Leroy, and Coppens show sensitivity to all parameters like for temperature it is 0.3 % and for depth is 0.05 % (specially for Wilson)	In thermocline layer temperature effects starts to fall and slowly around 0.5 m/s, depth and salinity started to influence the speed more the increment can be shown almost 0.8 m/s and 0.3 m/s
Deep layer	1 °C temperature hikes the average speed is just 1 m/s to 1.2 m/s	10 m rise in depth causes a change in average speed is 4.8 m/s to 5.3 m/s	Salinity is 1.2 m/s to 1.35 m/s for a small variation of 0.3 ppt	Mackenzie, Coppens, and Chen–Millero show a sensitivity and this time is for depth around 0.6 %	Deep layer temperature is considered as the weakest impact and depth has the highest effect around 0.6 % and salinity effect also increase to 0.01 % which is higher than the temperature effect of 0.001 %

6. Conclusion

This work has drawn attention to the fact that the three main environmental parameters have different effect on an acoustic sound speed based on the oceanic layer. When the signal passes from the layer close to a surface, it has the maximum effect due to temperature and the salinity effect can be ignored but as we start thinking of going deeper the influence of temperature gradually decreases and other two parameters which are depth and salinity effect began to increase in the deepest part of the ocean. The sound seed is very sensitive to depth and temperature and the depth effect becomes the same and also minimal. This understanding can be crucial for deploying and developing underwater communication networks much more effectively as this ecological variation can introduce unpredictable noise which will also bring an effect on the speed, direction, supervision and the timing of the marine communication and can also helps in the development of more optimized sonar and navigation algorithms.

FUNDINGS

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

CONFLICT OF INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

AUTHORS' CONTRIBUTIONS

Khondoker Munim Salehin contributed in experimental data analysis and manuscript drafting. Md. Khalid Mahbub Khan contributed in manuscript writing, modeling, and also in conceptualization. Anisur Rahman supervised as well as conceptualized the entire research. All authors reviewed and approved the final manuscript.

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