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Comparative study of the speed of sound in seawater in the northwestern sector of the Black Sea

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Abstract. This paper presents a comparative study of the speed of sound in seawater in the northwestern sector of the Black Sea, using three distinct approaches: theoretical calculation using established empirical formulas (such as Mackenzie and UNESCO), remote sensing data retrieved from the Copernicus Marine Environment Monitoring Service, and direct in-situ measurements conducted with an autonomous underwater vehicle (AUV).

Each method is analyzed in terms of accuracy, consistency, and suitability under the specific hydrographic conditions of the region, which is characterized by low salinity, strong freshwater input from the Danube River, and seasonal thermal variations. The study reveals that while theoretical and satellite-based data provide useful estimates, they often lack precision in dynamic or stratified environments. AUV-based measurements, although more resource-intensive, offer superior accuracy and flexibility due to their ability to collect real-time data at specific depths.

The study concludes that AUV technology represents the most effective method for precise sound speed assessment in coastal and semi-enclosed marine areas, supporting its broader adoption in acoustic modeling and underwater applications.

Keywords: speed of sound, Black Sea, AUV, Copernicus, acoustic modeling, underwater acoustics

1. Introduction

The speed of sound in seawater is a fundamental parameter in underwater acoustics, with critical applications in sonar operations, submarine navigation, environmental monitoring, and underwater communication systems. Accurately estimating this parameter is particularly important in coastal and semi-enclosed marine environments, where complex hydrographic conditions introduce significant challenges to acoustic modeling.

Numerous empirical models have been developed to calculate the speed of sound based on salinity, temperature, and pressure, with two of the most widely adopted being the Mackenzie equation [1] and the UNESCO 1983 algorithm [2]. While these formulas are computationally efficient and broadly applicable, they often exhibit reduced accuracy in regions with significant water column variability, such as the northwestern Black Sea. Remote sensing platforms, including the Copernicus Marine Environment Monitoring Service [3], provide valuable large-scale oceanographic data, but are limited in vertical resolution and may not capture fine-scale temporal or depth-dependent variations essential for precise acoustic applications.

In recent years, autonomous underwater vehicles (AUVs) have emerged as advanced tools for collecting high-resolution in-situ measurements of oceanographic variables. Equipped with sensors for conductivity, temperature, and depth (CTD), AUVs enable real-time calculation of sound speed at various depths with high precision and spatial flexibility [4], [5]. These platforms are particularly well suited for deployment in dynamic marine systems where remote sensing and theoretical models may fall short.

This paper presents a comparative analysis of three distinct methods for determining the speed of sound in seawater in the northwestern sector of the Black Sea: theoretical calculations based on empirical formulas, remote sensing data obtained from the Copernicus service, and direct in-situ measurements collected using an AUV. The objective is to assess the accuracy, consistency, and operational practicality of each method under the specific hydrographic conditions of the region, with the ultimate goal of identifying the most effective approach for future marine acoustic research in complex coastal environments.

2. Materials and Methods

This section outlines the procedures, equipment, and methods used in the study to compare the speed of sound in seawater in the northwestern sector of the Black Sea. The study involved a combination of theoretical, remote sensing, and in-situ measurement approaches. Each method is described in detail below, including the materials and protocols employed to gather and process the data.

2.1 Study Area

The study was conducted in the northwestern part of the Black Sea, an area characterized by significant freshwater input from the Danube River, low salinity, and seasonal stratification. The region is known for its complex hydrography, which includes varying thermal layers, salinity gradients, and frequent changes in water mass characteristics. These factors contribute to significant spatial and temporal variability in the speed of sound. The specific coordinates of the study area were 43°42´.5 N 030°31´.8 E, and data collection took place on 17 May 2023, between 07:00 and 10:00 local time, capturing both seasonal and depth-related variations.

2.2 Methods

Three primary methods were used to estimate the speed of sound in the study area:

1. Theoretical Models: The Mackenzie equation [1] was employed to estimate sound speed using standard environmental parameters, such as salinity, temperature, and depth.
2. Copernicus Remote Sensing Data: Oceanographic data from the Copernicus Marine Environment Monitoring Service (CMEMS) [3] were utilized to extract temperature, salinity, and depth profiles. These data were used to calculate the sound speed with the UNESCO 1983 formula [2]
3. Autonomous Underwater Vehicle (AUV): An Slocum Glider G3 equipped with a SeaBird CTD sensor was used for in-situ measurements of sound speed at varying depths.[6]

2.2.2 Software and Data Processing

Data collected by the AUV and the Copernicus service were processed using Excel, which allowed for the conversion of temperature, salinity, and pressure into sound speed using the appropriate equations.

3. Results and Discussions

This section presents the main results obtained by applying the three methods for estimating the speed of sound in seawater: theoretical models, Copernicus remote sensing data, and AUV in-situ measurements. The results are structured by method and compared systematically.

3.1 Sound Speed Estimation Using Theoretical Models

For the theoretical estimation of sound speed, the Mackenzie equation [1] was used, requiring temperature, salinity, and depth profiles as inputs. These profiles were directly measured using the AUV.

Mackenzie Equation (Eq. 1):

$$c = 1449.2 + 4.6T - 0.055T^2 + 0.00029T^3 + (1.34 - 0.010T) * (S - 35) + 0.016Z \quad (1)$$

Where:

- c = **sound speed** (m/s)
- T = **temperature** (°C)
- S = **salinity** (ppt)
- Z = **depth** (m)

Using the AUV's temperature, salinity, and depth data, sound speed was computed at various depths in the study area. The results indicated a range of sound speeds from 1465.737368 m/s to 1484.295778 m/s , with higher values observed in shallower regions due to increased temperature and salinity.

The results revealed a range of sound speeds from 1476.299698 m/s to 1483.206664 m/s, with higher sound speed values observed in shallower regions, influenced by elevated temperature and salinity levels. These variations reflect the impact of local hydrographic conditions, such as thermal stratification and salinity gradients, which affect sound propagation in the water column.

Figure 1 shows the resulting vertical sound speed profile, where the X-axis represents the depth (in meters) and the Y-axis represents the calculated sound speed (in meters per second). This profile highlights the relationship between sound speed and depth in the study area, providing insights into the stratification and variations in the marine environment.

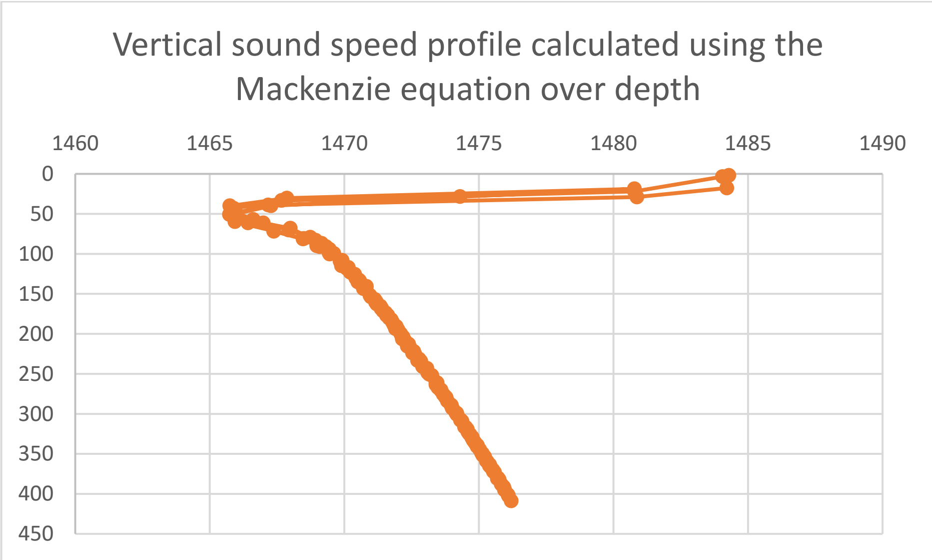

Figure 1. Vertical profile of sound speed derived from data calculated with Mackenzie equation

3.2 Sound Speed Estimation Using Copernicus Remote Sensing Data

Data from the **Copernicus Marine Environment Monitoring Service (CMEMS)** [3] were processed to estimate sound speed using the **UNESCO formula**. The Copernicus data provided temperature, salinity, and depth profiles across different locations in the study area. Using these profiles, sound speed was calculated using the UNESCO equation, which incorporates the effects of temperature, salinity, and depth on sound propagation in seawater.

UNESCO formula (Eq. 2):

$$c = 1449.2 + 4.6T - 0.055T^2 + 0.00029T^3 + (1.34 - 0.010T)(S - 35) + 0.016Z \qquad (2)$$

Where:

- c = sound speed (m/s)
- T = temperature (°C)
- S = salinity (psu, practical salinity units)
- Z = depth (m)

Figure 2 shows the resulting vertical sound speed profile derived from the Copernicus data for a representative station within the study area. The plot displays the variation in sound speed with depth, offering insights into the hydrographic conditions and sound propagation characteristics of the region.

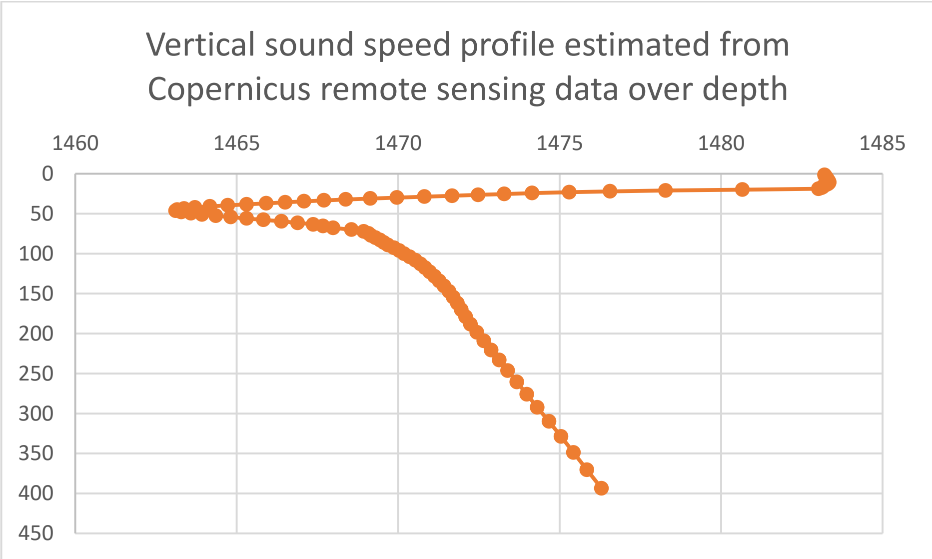

Figure 2. Vertical profile of sound speed derived from Copernicus remote sensing data

The Copernicus method, relying on remote sensing data, produced fewer data points and less detailed depth profiles compared to the Mackenzie method, which utilized higher-resolution in-situ measurements from the AUV.

3.3 Sound Speed Estimation Using AUV In-Situ Measurements

The third method involved using the AUV, which was capable of directly measuring temperature and salinity at various depths. Based on these measurements, the AUV automatically calculated the sound speed at each depth, providing high-resolution, real-time data profiles throughout the study area. This method allowed for precise and detailed sound speed estimates, with the AUV's depth control system ensuring accurate measurements at specific depths within the water column.

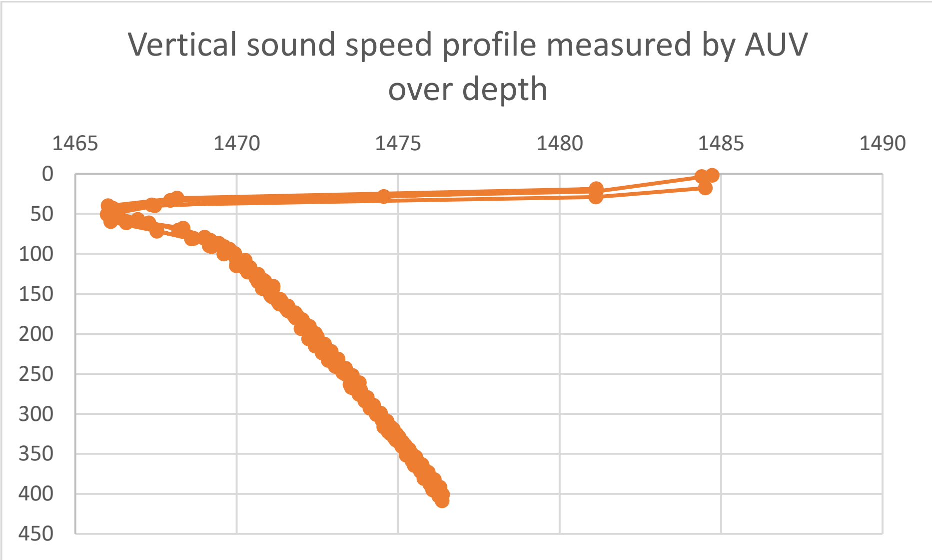

Figure 3. Vertical profile of sound speed derived from AUV measured data

The AUV method provided more data points across a wide range of depths, allowing for a more detailed and precise sound speed profile. With higher frequency measurements and the ability to capture fine-scale variations in temperature, salinity, and sound speed, this method offered greater accuracy compared to the other approaches, resulting in a more comprehensive understanding of sound speed variations throughout the water column.

3.4 Comparative Analysis

The three methods used to estimate sound speed—Mackenzie equation, Copernicus remote sensing data, and AUV-based in-situ measurements—offer distinct advantages and limitations, which are summarized below.

1. **Mackenzie Equation**: The Mackenzie method provides a theoretical estimation of sound speed, but it requires significant prior knowledge about the sound speed variations in the specific environment being studied. To apply the formula, data on temperature, salinity, and depth are essential. While it offers a general estimate, it is less effective in environments where these parameters fluctuate significantly, and it doesn't provide as high a resolution compared to the other methods.
2. **Copernicus Remote Sensing Data**: Copernicus offers valuable large-scale oceanographic data, but it suffers from a lack of resolution in capturing detailed sound speed profiles. The vertical stratification, particularly below 30 meters, is not well-represented, leading to less accurate sound speed estimates. Additionally, the Copernicus method generates fewer data points, which reduces its precision when compared to more direct measurement approaches.
3. **AUV-Based In-Situ Measurements**: The AUV method, while requiring specialized knowledge in piloting and sensor operation, proved to be the most precise. The AUV calculates sound speed on-site, offering real-time, high-resolution data at various depths throughout the water column. The method is highly accurate due to its direct measurement of environmental parameters and its ability to capture fine-scale variations in the water column. Although it requires more resources and expertise, the AUV

method provides the most reliable sound speed profiles and is the best option for accurate, in-depth marine acoustic studies.

4. Conclusion

In conclusion, each method presents its own set of challenges and benefits. The Mackenzie equation is limited by the need for prior knowledge and the assumption that sound speed varies in predictable ways, which can be difficult to apply in dynamic marine environments. Copernicus remote sensing data, while accessible, does not offer the level of precision required for detailed sound speed profiles, particularly in regions with vertical stratification.

The AUV method, although resource-intensive and requiring specific expertise, stands out as the most precise and reliable method. By calculating sound speed directly from in-situ measurements, the AUV provides the most accurate and high-resolution data, making it the most effective method for sound speed estimation in coastal and semi-enclosed marine environments.

Ultimately, while theoretical models and remote sensing provide useful estimates, AUV-based measurements should be considered the preferred method for precise sound speed assessments. Combining AUV data with other methods could further enhance the accuracy of sound speed profiles and contribute to more comprehensive acoustic modeling in complex marine settings.

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