CALCULATION OF THE VERTICAL DISTRIBUTION OF THE SPEED OF SOUND IN THE BLACK SEA BASED ON SATELLITE DATA IN THE PERIOD SPRING – AUTUMN 2021

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Abstract. The indirect methods for determining the spatial distribution of hydrophysical characteristics in the marine environment become popular today due to the lack of new measured data on these characteristics in the World Ocean. Developed methods allow to simplify creating the model and forecast process for the spatial distribution of hydrophysical characteristics in different water areas of the World Ocean. The results of modeling and forecasting can be used for research and applied purposes. The speed of sound propagation is the main primary acoustic characteristic of the marine environment and the calculation of the vertical distribution of the speed of sound in the Black Sea is a significantly important task. The purpose of the article is to demonstrate the possibility of calculating the vertical distribution of the speed of sound in the active layer of the marine environment based on satellite data and process the detailed analysis of the obtained results. Calculation of the vertical distribution of the speed of sound in the active layer of the Black Sea deep-water area in the spring-autumn period was carried out on the basis of original methods which are based on mathematical and physical-statistical methods of analysis. These methods were developed in the State Institution "Hydroacoustic Branch of Institute of Geophysics by S.I. Subbotin name of the National Academy of Sciences of Ukraine". Calculations of the vertical distribution of the speed of sound were processed using the "Program module" application. The initial data were daily sea surface temperature data from satellite measurements (NASA: Terra MODIS satellite). The spatial interval of measurements was 4 km in latitude and longitude. One date per month in the period May-October 2021 was selected for the studies. Based on the results of calculations of

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the vertical distribution of the speed of sound according to satellite data, the maps of its distribution on zonal and meridional oceanographic sections were built. During the analysis of the built maps the features of the vertical distribution of the speed of sound were identified in these sections. An analysis was made of the distribution of the calculated average values and the values of the vertical gradient of the sound speed in the Black Sea in the period spring-autumn 2021. Developed "Program module" application for automatic processing the satellite data has shown good efficiency in research for calculating the vertical distribution of the speed of sound in the Black Sea. Based on the results of the analysis, it was concluded that the developed methods for calculating the vertical distribution of the speed of sound in the marine environment can be used for research and applied purposes in solving applied tasks of hydrography, hydroacoustic, oceanology, marine ecology, navigation, etc. These methods and principles of developing the "Program module" application for calculating the vertical distribution of the speed of sound in the marine environment based on satellite data can be applied to analyze other areas of the World Ocean taking into account their hydrological conditions.

1. Introduction

The propagation of sound vibrations in the marine environment is a complex phenomenon. It depends on the distribution of temperature (T) and salinity (S), pressure changes (P), sea depth (z) and the nature of the soil, sea surface condition, water turbidity by suspended impurities of organic and inorganic origin and the presence of dissolved gases.

Sea water is a heterogeneous acoustics environment. This heterogeneity consists primarily in the change in density with depth. As a result, the speed of sound (C) also changes with depth, and the propagation of sound vibrations occurs not along straight lines, but along more complex trajectories. The presence of gas bubbles, suspended particles and plankton in seawater causes scattering and absorption of sound energy during its propagation [1, p. 180].

For the propagation of sound in the marine environment, the absolute value of the speed of sound is not very important. The most important is the dependence of the speed of sound on the depth – the sound speed profile C(z) [2, p. 299; 3, p. 11].

The speed of sound propagation (C) is the main primary acoustic characteristic of the marine environment. The vertical distribution of the speed of sound, its spatial and temporal variability determine the conditions for sound propagation. Reliable data on the vertical distribution of the speed of sound are necessary as initial information for correct calculations of acoustic fields in the marine environment and the range of hydroacoustic tasks. Reliable data are also needed to develop acoustic methods and tools for studying the ocean and to solve many direct and inverse hydroacoustic tasks. The relevance of increasing the reliability and accuracy of the values of the vertical distribution of the speed of sound is due to the development of methods for calculating the speed of sound fields and the expansion of the range of tasks solved in hydroacoustics [4, p. 3].

When we have a big data, it is necessary to solve the problem of choosing a calculation formula to calculate the speed of sound. Currently, there is no generally accepted standard in this matter. Today, more than ten formulas for calculating the speed of sound are known. Calculations using different formulas lead to different results [5, p. 30].

To date, there is a big problem in obtaining in-situ data on the vertical distribution of thermohaline characteristics in the Black Sea [6; 7; 8]. Based on these characteristics, calculations of the speed of sound are made. Therefore, one has to resort to indirect methods for determining the vertical distribution of hydrophysical characteristics. These indirect definitions of hydrophysical characteristics are carried out by developing various methods for calculating their vertical distribution. In the absence of these in-situ measurements, forecasted or modelled values of thermohaline characteristics are used.

Calculation of the vertical distribution of the speed of sound in the Black Sea is important task. The solution of this task makes it operationally possible to calculate the vertical distribution of the speed of sound both locally and throughout the Black Sea, for research and applied purposes in the field of hydrography, hydroacoustic, oceanology, marine ecology, navigation, etc [7, p. 84].

In the works of the author of this paper [6; 8; 9], studies of the calculation of hydrophysical characteristics based on satellite and hydroacoustic data have already been considered. However, a detailed analysis of the results of calculating the vertical sound speed profile in the marine environment from satellite data on the basis of the developed methods [6; 7; 8] has not previously been carried out separately.

The purpose of the paper is to demonstrate the possibility of calculating the vertical distribution of the speed of sound in the active layer of the marine environment based on satellite data. Carrying out a detailed analysis of the results obtained.

In the process of research, the following tasks were solved:

– calculation of the vertical distribution of water temperature in the Black Sea based on satellite information according to the methods [6];

– calculation of the vertical distribution of the speed of sound in the Black Sea based on satellite information according to the methods [7; 8].

The calculation of the vertical sound speed profile in the active layer of the Black Sea was carried out on the basis of original methods for calculating the vertical distribution of water temperature from satellite data [6] and the speed of sound from water temperature data [7].

These methods were developed in the State Institution "Hydroacoustic Branch of Institute of Geophysics by S.I. Subbotin name of the National Academy of Sciences of Ukraine".

2. Methods for calculating the speed of sound in the marine environment based on satellite data

The upper 50-meter layer in the Black Sea is characterized by high seasonal variability in water temperature [5, p. 30]. Also, the highest value on the speed of sound in this layer affects the change in sea water temperature. Therefore, we can represent the dependence of the speed of sound as a function of temperature: $C = f(T)$ [7, p. 85].

The calculation of the vertical distribution of sound speed in the Black Sea based on satellite data was carried out in the deep-water part sea at standard levels of 0, 10, 20, 25, 30, 50 meters in the period spring-autumn 2021. Calculations of the vertical distribution of the speed of sound in the active layer of the Black Sea should be presented in two main stages [8, p. 15–16; 9, p. 107].

1. Calculations of the vertical distribution of water temperature in the Black Sea at standard levels from satellite data [6];

2. Calculations of the vertical distribution of the speed of sound in the Black Sea according to the built regression equations, according to the methods [7; 8].

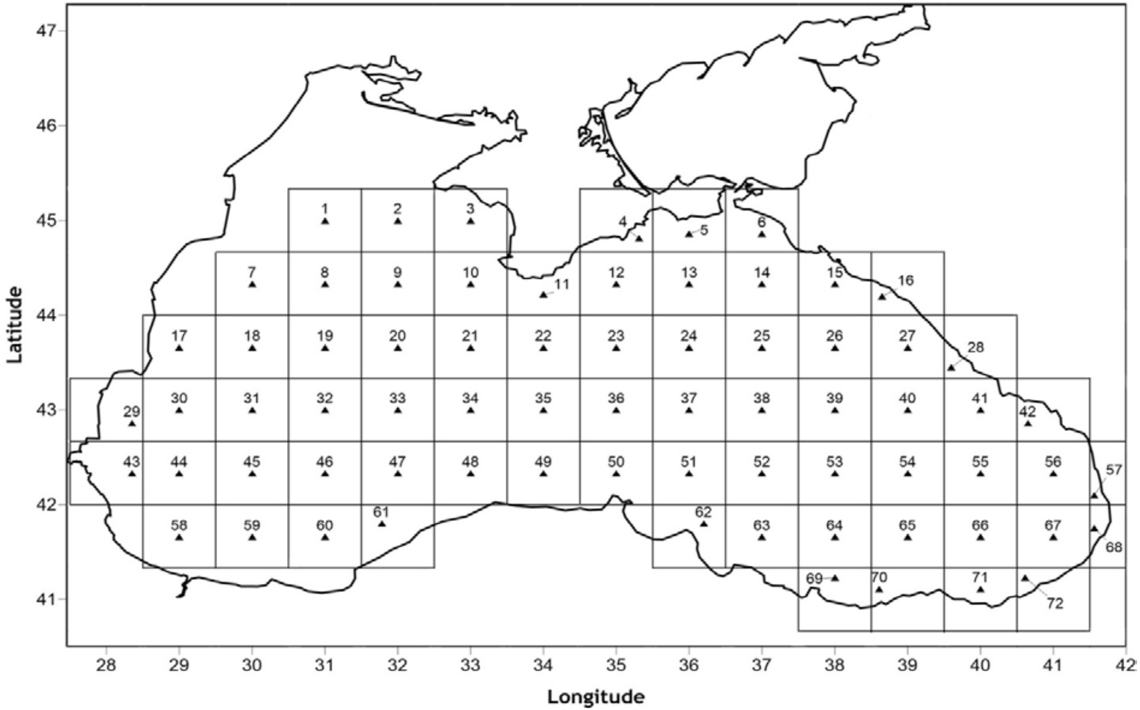

Figure 1. Location of squares (square size 40’ to 60’) for calculating regression equations in the Black Sea

Source: [6, p. 99]

The calculations in the first stage are based on the built in conditional squares (Figure 1) 864 equations of exponential and linear regression for calculating the vertical distribution of water temperature in the Black Sea by months in the period May-October. The established criterion (±ΔT) determines by which regression equations to calculate the vertical distribution of water temperature. To increase the accuracy of calculations, corrections are introduced, calculated according to the built regression equations [6].

The calculations in the second stage are based on the built linear regression equations (Table 1) depending on the part of the Black Sea (Figure 2).

Table 1

Regression equations for calculating the speed of sound in the Black Sea deep-water area in the period spring-autumn at a level of 0–50 meters

Parts of the Black Sea	The regression equations
Western part	$C = C_0 + 3.295T - 0.028z + 33.516$
Central part	$C = C_0 + 3.240T - 0.011z + 35.262$
Eastern part	$C = C_0 + 3.185T - 0.003z + 35.508$

In table 1, the parameters C are the speed of sound (m/s); C_0 – the speed of sound at T, S (salinity), $z = 0$ and is equal to $C_0 = 1402.388$ (m/s); T – calculated value of water temperature based on satellite data (°C); z – sea depth (meters).

The local calculation of the vertical distribution of the speed of sound in the Black Sea by satellite data in the layer 0–50 meters at several stations can be easily carried out by applying the developed methods [5; 6]. But if the whole water area of the Black Sea should be counted, this process is very time-consuming. Therefore, the author of this paper has developed the "Program module" application for the automatic use of satellite information to calculate the vertical distribution of the speed of sound in the Black Sea based on sea surface temperature data. The "Program module" application takes into account all the listed regression equations and criteria that are included in the above two stages of calculating the speed of sound in the marine environment. This "Program module" application is included as a

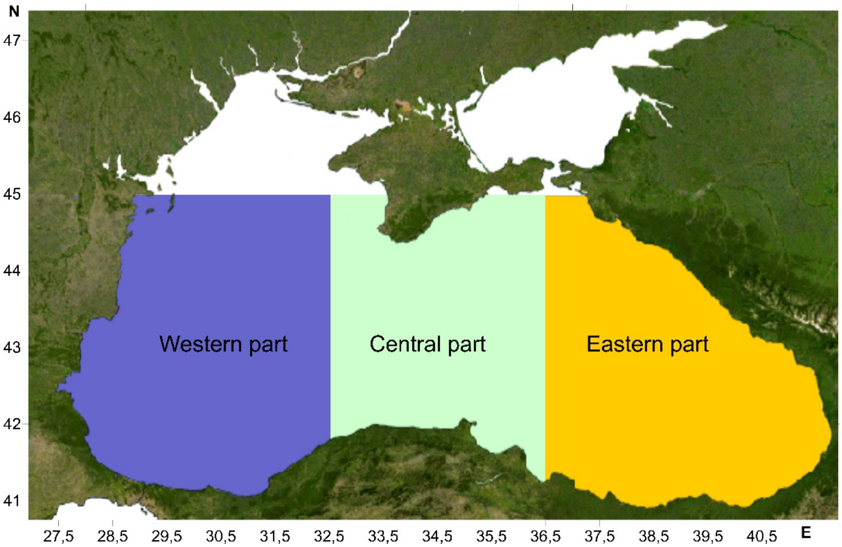

Figure 2. Map of the parts of the Black Sea used for calculating the speed of sound in the marine environment

Source: [7, p. 85]

component of the Automated Program Complex (APC). The APC allows to calculate the vertical distribution of hydrophysical characteristics in the Black Sea deep-water area in the layer 0–50 meters in the period spring-autumn [9, p. 108].

The "Program module" application automatically determines where and by what equations the vertical distribution of speed of sound in the Black Sea deep-water area in the layer 0–50 meters can be calculated. The initial data for calculations using the "Program module" application are only daily satellite data on the sea surface temperature.

3. Results of the calculation of the vertical distribution of the speed of sound and their analysis

Calculations of the vertical distribution of the speed of sound were carried out using the "Program module" application. The initial data were daily satellite data of the sea surface temperature measured by the NASA satellite (Terra MODIS) [10]. The spatial interval of measurements was 4 km in latitude and longitude. One date per month in the period May-October 2021 was selected for the studies: 11.05.2021, 08.06.21, 16.07.2021, 25.08.2021, 10.09.2021, 22.10.2021. The dates selected as an example are represented by the largest amount of data from satellite measurements of the Black Sea surface temperature.

The spatial distribution of sea surface temperature data is presented in Figure 3. Maps of spatial distribution of the surface temperature of the Black Sea on satellite data (Figure 3) were built with the help of specialized software NASA – SeaDAS [11]. The missing satellite data can be seen in Figure 3 as a white area. The reason of this might be a high cloud cover at the time of measurement. Temperature scale corresponds to the original scale for these measurements [10].

The spatial distribution of water temperature on the surface in the Black Sea (Figure 3) corresponds to the most characteristic features that are inherent in the Black Sea. This is an increase in water temperature in the direction from the northwest to the southeast.

To visualize the results of calculations of the vertical distribution of the speed of sound, maps of its spatial distribution on zonal and meridional oceanographic sections were built.

In Figure 4 presents maps of the spatial distribution of the values of the speed of sound on zonal sections at latitudes: 42,52°N for 11.05.2021; 43,85°N for 08.06.2021; 43,19°N for 16.07.2021; 43,77°N for 25.08.2021; 43,40°N for 10.09.2021; 42,31°N for 22.10.2021.

The isolines of the speed of sound are drawn through 5 m/s (Figure 4). Let us consider in more detail the spatial distribution of the values of the speed of sound on zonal sections.

Figure 4 (a) shows that the maximum values of the speed of sound are located at the level of 0–5 meters. The distribution of the maximum is observed from the western part of the sea to its central part. There are also two maxima in the eastern part of the sea at longitudes 39,10°E and 40, 35°E. At the level of 15 meters, starting from the western part of the sea to its central part, there is a dense layer of isolines 1470–1475 m/s. In the layer of 20–50 meters the speed of sound was in the range of 1460–1470 m/s.

Figure 4 (b) shows that the maximum values of the speed of sound are located at the level of 0–5 meters. The maximum distribution is observed in

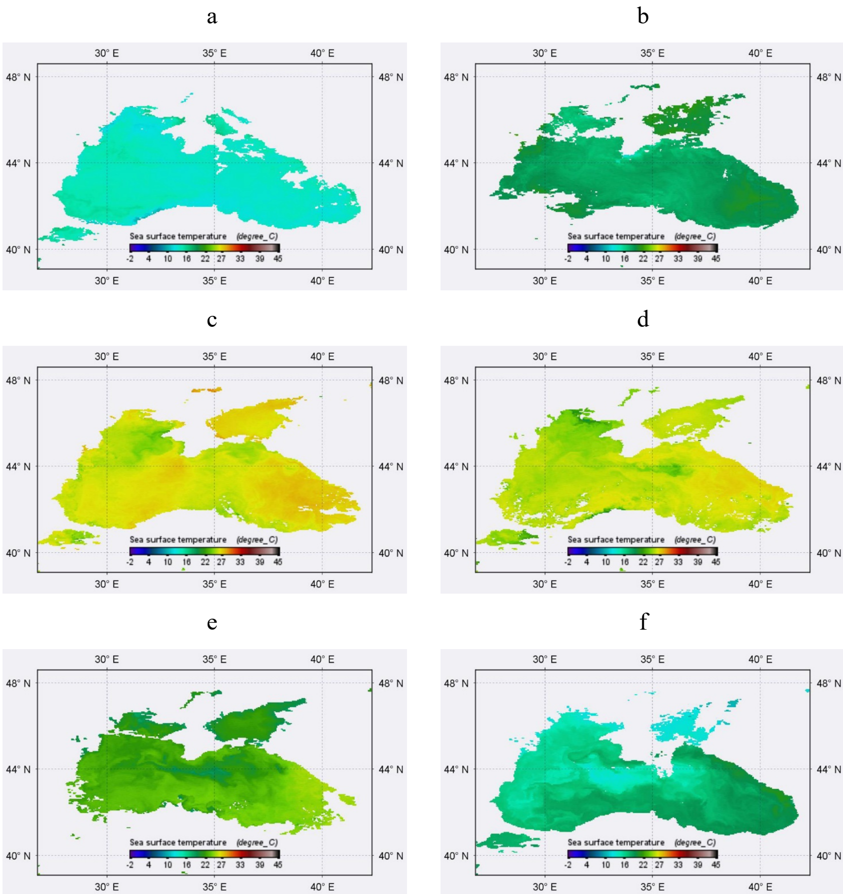

Figure 3. Spatial distribution of sea surface temperature data from satellite data for 11.05.2021 (a), 08.06.21 (b), 16.07.2021 (c), 25.08.2021 (d), 10.09.2021 (e), 22.10.2021 (f)

the western part of the sea (from the beginning of the section to longitude 30,73°E) and starting from the central part of the sea to its eastern part. At the level of 15 meters, a dense layer of isolines 1475–1485 m/s is observed throughout the section. In the layer of 20–50 meters the speed of sound was in the range of 1460–1470 m/s. At a longitude of 30°E, a well-pronounced

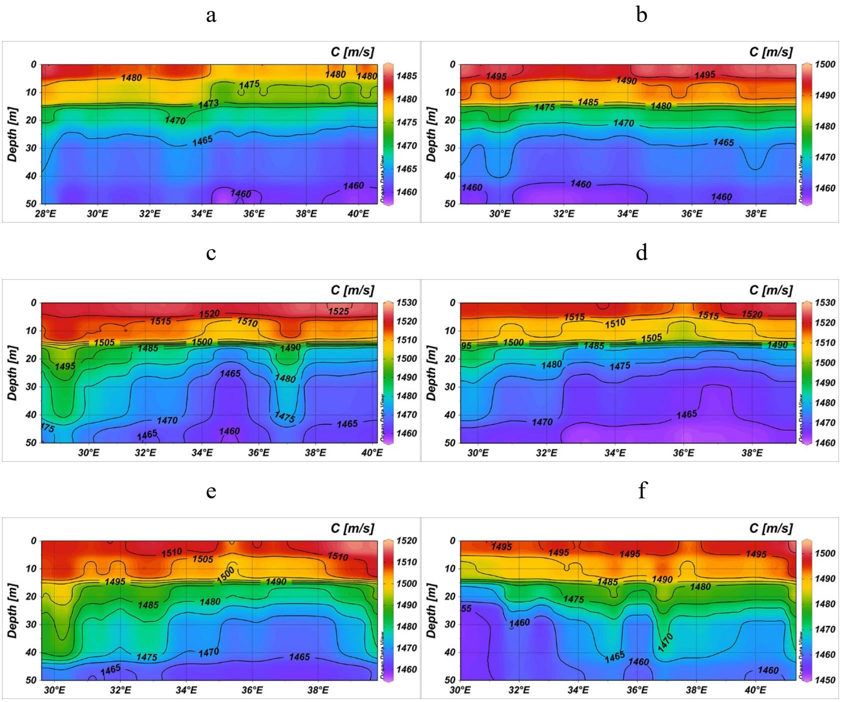

Figure 4. Distribution of the calculated values of the speed of sound (C) on zonal sections in the Black Sea at latitudes: 42,52°N for 11.05.2021 (a); 43,85°N for 08.06.2021 (b); 43,19°N for 16.07.2021 (c); 43,77°N for 25.08.2021 (d); 43,40°N for 10.09.2021 (e); 42,31°N for 22.10.2021 (f)

vertical descent of the isolines is observed along the entire depth of the section. This is a vertical profile of the speed of sound with higher values relative to the distribution of the speed of sound by depth.

Figure 4 (c) shows that the maximum values of the speed of sound are located at the level of 0–5 meters. The maximum distribution is observed in the eastern part of the sea (longitude 38,85°E). At the level of 15 meters between longitudes 31,60°E – 36.35°E and 37,77°E and up to the end of the section there is a dense layer of isolines 1485–1505 m/s. At longitudes of 29°E and 37°E a well-pronounced vertical descent of the isolines is observed along the entire depth of the section. These is a vertical profiles of the speed of sound with higher values relative to the distribution of the speed of sound by depth. At a longitude of 35°E the rise of isolines at a depth of 5–50 meters is clearly visible. This is a vertical profile of the speed of sound with lower values relative to the distribution of the speed of sound by depth.

Figure 4(d) shows that the maximum values of the speed of sound are located at the level of 0–5 meters. The distribution of the maximum is observed in the central part of the sea (longitude 33,65°E) and the eastern part of the sea (at longitude 37,10°E – 39,27°E). At the level of 15 meters between longitudes 32,65°E – 39,27°E there is a dense layer of isolines 1480–1505 m/s. At longitude 29,48°E – 33,48°E, a well-pronounced vertical descent of isolines is observed throughout the entire depth of the section. These is a vertical profiles of the speed of sound with higher values relative to the distribution of the speed of sound by depth. At a longitude of 36,92°E, the rise of isolines at a depth of 15–50 meters is clearly visible. This is a vertical profile of the speed of sound with lower values relative to the distribution of the speed of sound by depth.

Figure 4(e) shows that the maximum values of the speed of sound are located at the level of 0–5 meters. The distribution of the maximum is observed in the eastern part of the sea (at longitude 38,65°E – 39,81°E). At the level of 15 meters between longitudes 30,56°E – 39,65°E there is a dense layer of isolines 1490–1500 m/s. Between the longitude of 33.40°E – 39.40°E there is a well-pronounced vertical rise of the isolines along the entire depth of the section. This is a vertical profile of the speed of sound with lower values relative to the distribution of the speed of sound by depth.

Figure 4(f) shows that the maximum values of the speed of sound are located at the level of 0–5 meters. The maximum distribution is observed in the eastern part of the sea (between longitudes 41,10°E – 41,35°E). At the level of 15 meters, a layer of isolines 1480 – 1485 m/s is observed throughout the section. A well-pronounced vertical rise of isolines at depths of 5–50 meters is observed in the western part of the sea (between longitudes 30,00°E – 33,00°E). There are also two more areas of vertical rise of isolines at a depth of 15–50 meters: in the central part of the sea (between longitudes 35,48°E – 36,52°E) and in the eastern part of the sea (between longitudes 39,52°E – 41,10°E).

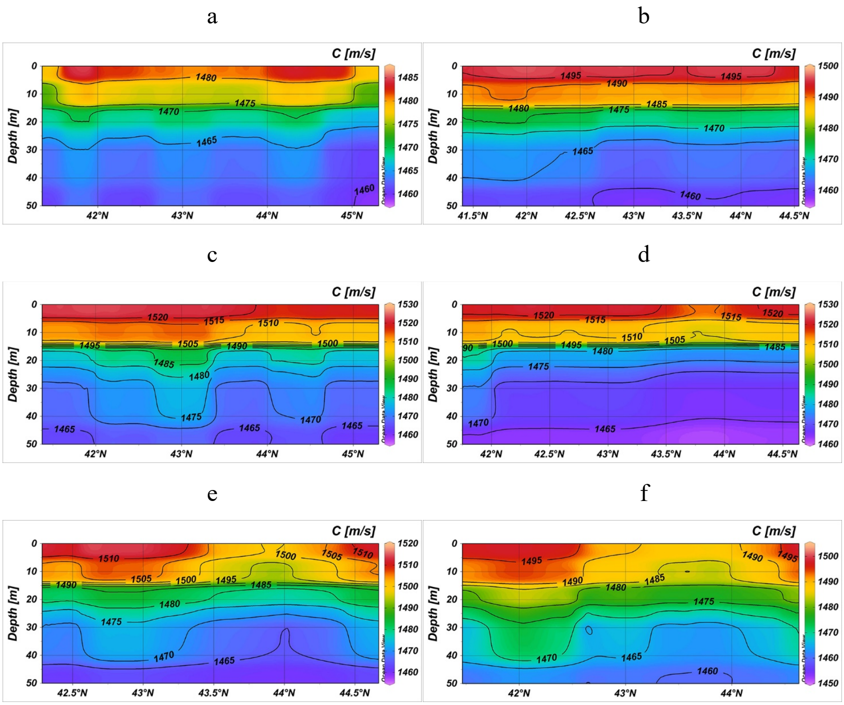

Figure 5. Distribution of the calculated values of the speed of sound (C) on the meridional sections at longitudes: 30,98°E for 11.05.2021 (a); 37,15°E for 08.06.2021 (b); 30,90°E for 16.07.2021 (c); 36,27°E for 25.08.2021 (d); 35,15°E for 10.09.2021 (e); 37,06°E for 22.10.2021 (f)

In Figure 5 presents maps of the spatial distribution of the values of the speed of sound on meridional sections at longitudes: 30,98°E for 11.05.2021; 37,15°E for 08.06.2021; 30,90°E for 16.07.2021; 36,27°E for 25.08.2021; 35,15°E for 10.09.2021; 37,06°E for 22.10.2021.

The isolines of the speed of sound are drawn through 5 m/s (Figure 5). Let us consider in more detail the spatial distribution of the values of the speed of sound on meridional sections.

Figure 5(a) shows that the maximum values of the speed of sound are located at the level of 0–5 meters. The distribution of the maximum is observed along the entire meridional section (between latitudes 41,52°N – 45,02°N). At the level of 15 meters, a layer of isolines 1470–1475 m/s is observed throughout the section. In a layer of 20–50 meters, the speed of sound was within 1460–1470 m/s.

Figure 5 (b) shows that the maximum values of the speed of sound are located at the level of 0–5 meters throughout the section. At the level of 15 meters there is a dense layer of isolines 1475–1485 m/s. In a layer of 20–50 meters, the speed of sound was within 1475 m/s (in the southern part of the section) to 1460 m/s.

Figure 5(c) shows that the maximum values of the speed of sound are located at the level of 0–5 meters. The distribution of the maximum is observed in the southern direction of the section (between latitudes 43,85°N – 41,40°N). At the level of 15 meters, a layer of isolines 1490 – 1505 m/s is observed throughout the section. Well-defined three vertical rises of isolines (three domes) at depths of 15–50 meters. The centers of the vertical sections of these domes are located at latitudes: 41,60°N; 43,69°N; 45,02°N. In these vertical layers, the sound speed is characterized by lower values relative to its distribution over the entire meridional section.

Figure 5(d) shows that the maximum values of the speed of sound are located at the level of 0–5 meters. The distribution of the maximum is observed in the southern direction of the section (between latitudes 43,44°N – 41,77°N) and in the northern direction of the section (between latitudes 44,27°N – 44,60°N). At the level of 15 meters, a layer of isolines 1480 – 1505 m/s is observed throughout the section. There is a well-pronounced vertical lowering of the isolines along the entire depth of the section between latitudes 41,77°N – 42,02°N. This is a vertical profile of the speed of sound with higher values relative to the distribution of the speed of sound by depth.

Figure 5(e) shows that the maximum values of the speed of sound are located at the level of 0–5 meters. The distribution of the maximum is observed in the southern direction of the section (between latitudes 43,31°N – 42,31°N) and in the northern direction (between latitudes 44,48°N – 44,65°N). At the level of 15 meters, a layer of isolines 1485–1495 m/s is observed throughout the section. Well-pronounced two domes at depths of 5–50 meters. The centers of the vertical sections of these domes are located at latitudes: 42,40°N; 43,90°N. In these vertical layers, the speed of sound is characterized by lower values relative to its distribution throughout the meridional section.

Figure 5(f) shows that the maximum values of the speed of sound are located at the level of 0–5 meters. The distribution of the maximum is observed in the southern direction of the section (between latitudes 42,56°N – 41,48°N) and in the northern direction (between latitudes 44,40°N – 44,60°N). A well-defined dome is observed in the layer of 0–50 meters. The center of the vertical section of this dome is located at latitude 43,60°N. In this vertical layer, the speed of sound is characterized by lower values relative to its distribution over the entire meridional section.

Figures 4 and 5 are built using computer program Ocean Data View (ODV) that is intended for the interactive exploration and graphical display of oceanographic and other geo-referenced profile, trajectory or time – series data [12].

As mentioned above, the variability of the distribution of the values of the speed of sound in the active layer of the Black Sea depends on the variability of the water temperature in this layer. Therefore, the vertical distribution of the speed of sound in the Black Sea characterizes the vertical distribution of water temperature.

Based on the calculated values of the speed of sound, graphs of its average vertical distribution in the Black Sea at standard levels of 0, 10, 20, 25, 30, 50 meters were built. The calculation results are shown in Figure 6.

The maximum average values for the speed of sound on the surface of the Black Sea (Figure 6(a)) are 1522,06 m/s. The minimum average values for the speed of sound are 1480,90 m/s.

In Figure 6(b) shows that the maximum average values for the speed of sound at a depth of 10 meters are 1512,26 m/s. The minimum average values for the speed of sound are 1476,07 m/s.

The maximum average values for the speed of sound at a depth of 20 meters (Figure 6(c)) are 1484,97 m/s. The minimum average values for the speed of sound are 1468,78 m/s.

In Figure 6(d) shows that the maximum average values for the speed of sound at a depth of 25 meters are 1478,56 m/s. The minimum average values for the speed of sound are 1465,53 m/s.

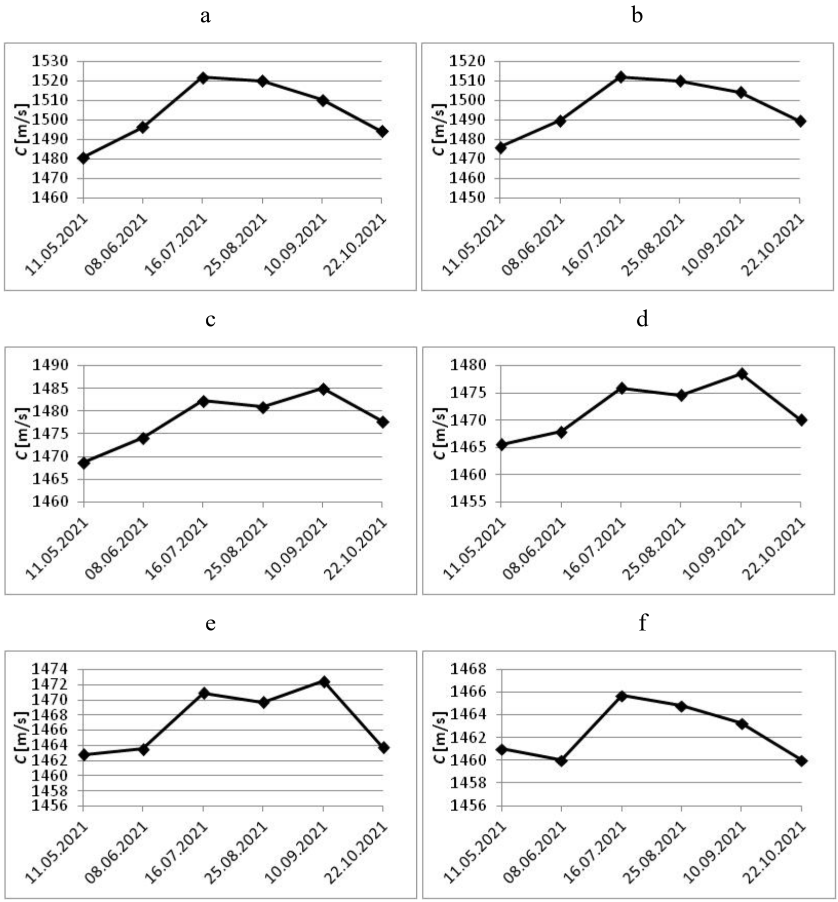

Figure 6. Distribution of average values of sound speed (C) at standard levels in the Black Sea: 0 meters (a); 10 meters (b); 20 meters (c); 25 meters (d); 30 meters (e); 50 meters (f)

In Figure 6(e) shows that the maximum average values for the speed of sound at a depth of 30 meters are 1472,50 m/s. The minimum average values for the speed of sound are 1462,77 m/s.

The maximum average values for the speed of sound at a depth of 50 meters (Figure 6(f)) are 1465,68 m/s. The minimum average values for the speed of sound are 1460,0 m/s (08.06.2021) and 1460,04 m/s (22.10.2021).

Figure 6 shows that the maximum average values for the speed of sound in the Black Sea are observed at the level of 0, 10, 50 meters in July and at the level of 20, 25, 30 meters – in September. The minimum average values at the levels of 0, 10, 20, 25, 30 meters are observed in May and at the level of 50 meters – in June and October.

Based on the values of the speed of sound, vertical gradients of the speed of sound in the Black Sea during the spring-autumn 2021 period were calculated. The sound speed gradients were calculated between standard levels. The vertical gradients of the calculated values of the speed of sound per 1 meter of depth in the Black Sea are shown in Figure 7.

In Figure 7(a) shows that the maximum sound speed gradient is located in the layer of 10–20 meters and is 0,73 m/s per 1 meter of depth. The minimum sound speed gradient is located in the layer of 30–50 meters and is 0,09 m/s per 1 meter of depth.

The maximum sound speed gradient in Figure 7(b) is located in the layer of 10–20 meter and is 1,57 m/s per 1 meter of depth. The minimum sound speed gradient is located in the layer of 30–50 meters and is 0,17 m/s per 1 meter of depth.

The vertical distribution of sound speed gradient values are the same in Figure 7(c) and Figure 7(d). The maximum sound speed gradients are located in the layer of 10–20 meters and are 3,00 m/s (Figure 7(c)) and 2,93 m/s (Figure 7(d)) per 1 meter of depth. The minimum sound speed gradients are located in the layer of 30–50 meters and are 0,26 m/s (Figure 7(c)) and 0,25 m/s (Figure 7(d)) per 1 meter of depth.

Figure 7(e) shows that the maximum sound speed gradient is located in a layer of 10–20 meters and is 1,94 m/s per 1 meter of depth. The minimum sound speed gradient is located in the layer of 30–50 meters and is 0,46 m/s per 1 meter of depth.

The vertical distribution of sound speed gradient values in Figure 7(f) is different from the previous distributions of the sound speed gradients. The maximum sound speed gradient has shifted to a layer of 20–25 meters and is 1,54 m/s per 1 meter of depth. The minimum sound speed gradient is located in the layer of 30–50 meters and is 0,18 m/s per 1 meter of depth.

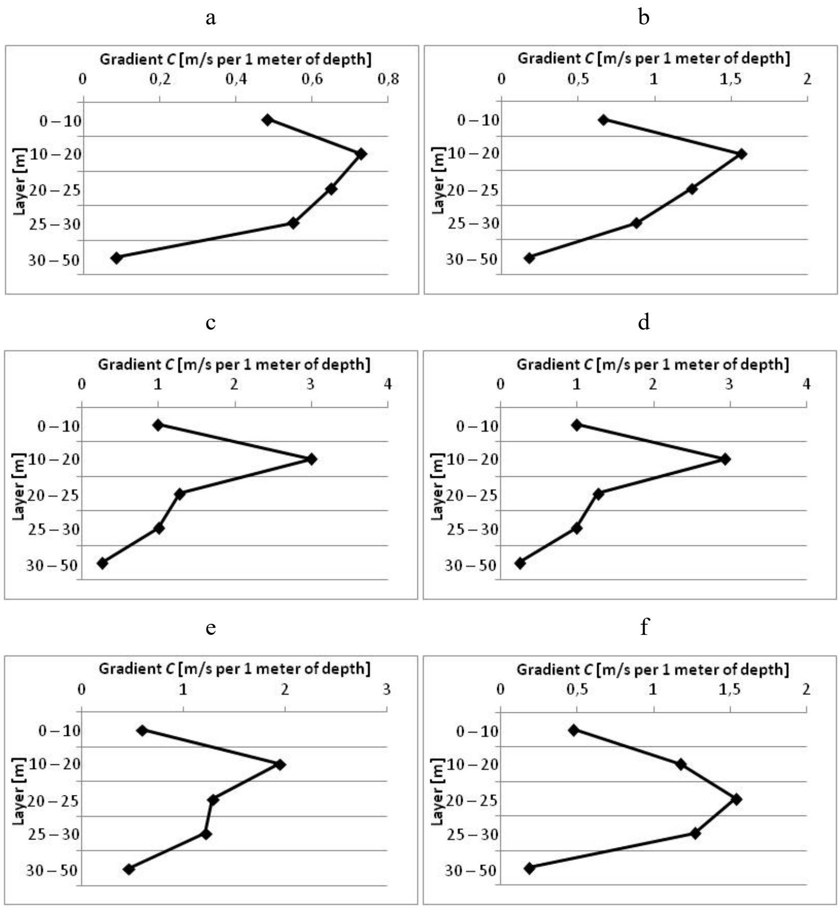

Figure 7. Distribution of the sound speed gradients (C) per 1 meter of depth in the Black Sea in layers between standard levels for: 11.05.2021 (a); 08.06.2021 (b); 16.07.2021 (c); 25.08.2021 (d); 10.09.2021 (e); 22.10.2021 (f)

The distribution of sound speed gradients (m/s per 1 meter of depth) in the Black Sea and their maximum and minimum values in the period May-October 2021 are presented in Table 2.

In the period spring-autumn 2021 (using the selected dates as an example) the maximum sound speed gradients in the 0–10 and 10–20 meters layer are observed in July-August (Table 2). In the layers 20–25 and 25–30 meters maximum in October. In the layer 30–50 meters maximum is observed in September. The minimum sound speed gradients are observed in May in all layers and in October – the layer 0–10 meters. The minimum sound speed gradients in the layer of 0–10 meters coincide in May and October. They are equal to 0,48 m/s per 1 meter of depth.

Table 2

The sound speed gradients (m/s per 1 meter of depth) in the Black Sea layers between standard levels in the period May-October 2021

Date	Layer [meters]				
	0–10	**10–20**	**20–25**	**25–30**	**30–50**
11.05.2021	0,48	0,73	0,65	0,55	0,09
08.06.2021	0,66	1,57	1,24	0,88	0,17
16.07.2021	0,98	3,00	1,27	1,00	0,26
25.08.2021	0,99	2,93	1,27	0,98	0,25
10.09.2021	0,59	1,94	1,28	1,21	0,46
22.10.2021	0,48	1,18	1,54	1,27	0,18
Maximum	0,99	3,00	1,54	1,27	0,46
Minimum	0,48	0,73	0,65	0,55	0,09

The author draws attention to the fact that when calculating the average values and values of the vertical gradient of the sound speed in the Black Sea, only the initial data on the sea surface temperature were taken into account. Thus, when analysis the distribution of these values over the Black Sea water-area, the part of the sea in which there were no initial data on the sea surface temperature was not taken into account.

4. Conclusions

Based on the results of calculations of the vertical distribution of the speed of sound in the active layer of the Black Sea deep-water area in the spring-autumn period the following conclusions are:

1. Based on the built maps of the vertical distribution of the speed of sound in zonal and meridional sections the features of its distribution were revealed:

– The maximum values of the speed of sound in the Black Sea are in the layer 0–5 meters;

– At the level of 15 meters, a dense layer of isolines of the speed of sound is concentrated. In July and August, this layer reached its maximum and amounted to 25 m/s;

– From July to October in the layer of 15–50 meters there is a vertical rise in the isolines of the speed of sound in the form of so-called "domes". The vertical profile of the speed of sound in these "domes" is characterized by lower values relative to the distribution of the speed of sound over depth in oceanographic sections. The appearance of such "domes" is explained by the presence of a cooler vertical distribution of water temperature in this area. Basically, these cool water temperature profiles are formed under the influence of marine water circulation.

2. The distribution of the calculated average values of the speed of sound at standard levels in the Black Sea in the spring-autumn period showed:

– The maximum values of the speed of sound in the Black Sea are observed at the level of 0, 10, 50 meters in July and at the level of 20, 25, 30 meters – in September.

– The minimum values at the levels of 0, 10, 20, 25, 30 meters are observed in May, and at the level of 50 meters – in June and October.

3. The distribution of sound speed gradients (m/s per 1 meter of depth) in the Black Sea in layers between standard levels showed:

– The maximum gradients of the speed of sound in the layer 0–10 and 10–20 meters are observed in July-August. In the layer 20–25 and 25–30 meters maximum in October. The maximum in the layer 30–50 is observed in September.

– The minimum gradients of the speed of sound are observed in May in all layers and in October – the layer 0–10 meters. The minimum sound speed gradients in the layer of 0–10 meters coincide in May and October. They are equal to 0,48 m/s per 1 meter of depth.

The developed "Program module" application for the automatic use of satellite information for calculating the vertical distribution of the speed of sound in the Black Sea has shown good efficiency in research.

The developed methods for calculating the vertical distribution of the speed of sound in the marine environment can be used for research and applied purposes in solving applied tasks of hydrography, hydroacoustic, oceanology, marine ecology, navigation, etc. These methods and principles of building the "Program module" application for calculating the vertical distribution of the speed of sound in the marine environment based on satellite data can be applied to analysis other areas of the World Ocean taking into account their hydrological conditions.

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