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PREVAILING PATTERNS OF THE SOUND SPEED DISTRIBUTIONS IN THE ENVIRONMENT OF THE SOUTHERN BALTIC

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The paper contains the results of experimental and theoretical research aimed at elaborating characteristic features of the acoustic conditions in the Southern Baltic. As there features are fully dependent on the hydrological conditions, the sound speed distribution is influenced by many factors and changes during the year. On the basis of hydrological data recorded from 1979 to 1991 by measurements at stations situated along the deeps of the Southern Baltic, the sound speed has been calculated using the procedure of Chen&Millero recommended by UNESCO. The data were averaged in one-months periods and subjected to a detailed analysis of the speed variations during the year. The patterns of the sound speed distribution characteristic for every month have been determined. Research was also conducted to find to what extent the synoptic patterns of the sound speed distribution differ from the averaged respective data. To solve the problem, several synoptic distributions established in different seasons are compared with the averaged distribution. Difficulties in specifying the acoustical conditions of the Southern Baltic are augmented by the appearance of short-term local phenomena changing considerably the sound speed distribution in certain areas. Examples of such phenomena are presented in the paper. The paper is based on a large number of *in situ* measurement data presented in the form of diagrams.

1. Introduction

Conditions of the acoustic wave propagation in shallow water differ considerably from those prevailing in the ocean. They depend on many factors such as the depth of the water related to the wave length and the boundary conditions specified by the type of the bottom [31, 14, 17] and the state of the sea [2]. Changes in the sound speed distribution in shallow water are the main factor influencing the wave propagation [10, 22]. This fact is often taken into consideration since the range of the action of the devices used in underwater investigation is greatly dependend on it [1, 20, 29].

Numerous publications treated that problem in several aspects confirm its importance. The phenomena having an impact on the wave propagation in the sea are considered in several fundamental monographs, for instance in [4, 8, 30]; the problems concerning the wave propagation in stratified areas are discussed in [3, 5], and the interaction of the atmosphere and the sea in [26, 11]. The matter of acoustic conditions of the Baltic Sea is examined in [15]. Data on the sound speed distribution obtained during cyclical investigations are published in the annual reports printed inter alia by the Polish Institute of Meteorology and Water Management and in the Reports of the German Baltic Sea Research Institute in Warnemünde. Measurements of the sound speed distribution are often carried out together with other oceanographic investigations and are analyzed jointly [12]. Sometimes they are treated separately and published independently [23, 24. 19].

Numerous underwater investigations conducted concurrently with measurements of the sound speed distribution testify to the recognition of the importance of that problem. However there are very few publications devoted to the general characteristics of the acoustic conditions in the Baltic Sea [13, 18].

Nearly all STD or CTD sounders are presently equipped with a sound speed meter or can offer information on the sound speed distribution calculated on the basis of hydrological parameters. However, in many cases it is necessary to calculate the sound speed having at disposal only the results of measurements of the temperature and salinity as function of depth. It requires an expression that describes adequately the influence of temperature, salinity and static pressure on the sound speed. This aspect is of great importance in view of the standardization of the measuring methods. Several expressions describing the dependence of the sound speed on temperature, salinity and static pressure are known [7, 21]. UNESCO suggests the expression obtained and verified by Chen and Millero [9].

The Baltic Sea can be regarded as a shallow sea at least in two aspects. Its depth is small in comparison with the depth of deep seas. Also assessing its properties from the point of view of the acoustic wave propagation, the Baltic should be treated as a shallow water for many waves of different frequencies, especially for the noise of technical provenance [31].

Because of its low depth, the Baltic is strongly influenced by the wind mechanisms and the changeable distribution of high- and low pressure areas. The acoustical conditions in the Baltic are fully dependent on hydrological conditions. Generally, two main layers can be distinguished in the Baltic Sea: the upper layer and the deep water layer. The acoustical conditions in the upper one are influenced by the inflow of solar energy into the sea surface and its transportation into the deeper parts of the sea, while the acoustical conditions in the deep water layer depend on inflows of highly saline water from the North Sea through the Danish Straits. Though the mechanisms of both of those phenomena are well known, they are not fully predictable. The meteorological phenomena influencing the processes occurring at the ocean — atmosphere border as well as the deep water inflows are carefully observed and monitored. The general trend in their changes during the year is stable, but the randomness factor modulating them plays a significant role in forming the hydrologic-meteorological situation [25, 27]. Additionally, the dynamics of dense bottom currents is strongly dependent on numerous physical factors as well as on the specific bottom topography. Therefore the long-term predictions as well as the short-term ones of the conditions of the acoustic wave propagation are burdened with a certain error.

The aim of the paper is to generalize the knowledge on the sound speed conditions in the southern Baltic Sea. An attempt to characterize the acoustic climate of that region has been made. Research was also conducted to find an answer to the question to what extent the synoptic patterns of the sound speed distribution, usually dependent on the meteorological conditions prevailing prior to the performed measurements, differ from the averaged respective data. It has also been pointed out that the underwater investigation may be affected by local morphological and hydrological conditions.

2. Material and method of investigations

The various patterns of the sound speed distribution presented in this paper are obtained on the basis of measurements of the temperature and salinity as a function of the depth according to the UNESCO standard. The formula describing the dependence of the speed of sound on temperature, salinity and the static pressure given by Chen and Millero is used in numerical calculation [9].

Results of measurements performed at the stations marked in Fig. 1 in the years 1979 – 1991 are the base of the investigation. For station P5 — Bornholm Deep and P1 — Gdańsk Deep, the accessible data are from 1960 – 1997. For each station the average sound speed distribution characteristic for each particular month from March to December was determined. The accessible number of measurements in every month was not identical. In the summer the measurements were done regularly, while in the winter it was not always possible to make them. Thus the distribution for January and February was not determined because of the lack of sufficient data. In Sec. 6 measurements performed by the Sea Fisheries Institute in 1994 and in 1996 were used for exemplifying the impact of local conditions on the patterns of the sound speed.

The averaged distribution of the sound speed c was estimated for each month separately for every station. Because of the scant number of samples being at our disposal, the Student's distribution was applied [16]. It was taken a priori without verification. The confidence interval was evaluated at each measurement depth using the following formula:

$$p(\bar{c} - t_\alpha S < \bar{c} < \bar{c} + t_\alpha S) = 1 - \alpha, \tag{1}$$

where $\bar{c}$ denotes the average value of the sound speed at a fixed depth:

$$\bar{c} = \frac{1}{n} \sum_{i=1}^{n} c_i \tag{2}$$

S — the error mean-square of measurements:

$$S = \sqrt{\frac{1}{n(n-1)} \sum_{i=1}^{n} (c - \bar{c})^2} \tag{3}$$

n — the number of measurements. The value of α depends on the number of measurements and the assumed confidence coefficient. The results of the estimation of the sound speed at every station in each considered month were used as the base for the determination of the averaged vertical distribution of the sound speed along the cross-section over the deeps of the southern Baltic.

Assuming that the distribution obtained in this way is representative for an individual month, the problem of the difference between the averaged distribution and the single synoptic distribution was considered. Apart from that, some phenomena occurring sporadically, but causing an anomaly in the sound speed distribution, were also taken into consideration.

3. Averaged sound speed distribution

The acoustical conditions could be characterized by the vertical sound speed distribution in the main points of the considered area. In the southern Baltic such points were localized at the Gdańsk Deep, the Bornholm Deep and the Słupsk Furrow. The sound speed profiles estimated for the Bornholm Deep and Gdańsk Deep together with the confidence intervals are shown in Fig. 2. They were obtained on the basis of data from 1960 to 1997. The number of accessible data was various in every month.

The confidence interval was evaluated at each measurement depth from the formula (1) applying the t-Student distribution and assuming the confidence coefficient to be equal to 0.9. In the distributions determined for both the stations, seasonal changes characteristic for the southern Baltic are visible. However, a discerning analysis allows to denote several individual features of each of the stations. In the winter-months the distribution in the upper layer is almost uniform. The sound speed increases with the growth of the depth, reaching at the Bornholm Deep values greater by about 7 – 8 m/s than those at the Gdańsk Deep. This results from the greater salinity in the deep layer that is about 5 – 6 PSU. Consequently, the difference between the sound speed at the bottom and at the sea surface was equal to about 19 m/s in January and 26 m/s in March at the Gdańsk Deep, while it amounted to about 28 m/s in January and 33 m/s in February at the Bornholm Deep.

Greater values of the sound speed at the bottom in the Bornholm Deep region influence the vertical sound speed distribution during the whole year. There the minimum occurs practically from May to November at depths of about 50 m at the Bornholm Deep and at about 60 – 70 m at the Gdańsk Deep. The minimal value in both cases increases during the year and is greater at the Bornholm Deep than at the Gdańsk Deep from by about 2 m/s in May to 10 m/s in September. The difference between sound speed at the surface and the minimal value of the sound speed is greater at the Gdańsk Deep than in the Bornholm Deep region by about 3 – 11 m/s, whereas the difference between the sound speed at the bottom and the minimal value is greater at the Bornholm Deep by about 2 – 7 m/s.

4. Acoustic climate of the southern Baltic

Results of the estimation of the averaged value of the sound speed at each station marked at Fig. 1 are the base for the determination of the averaged sound speed distribution along the cross-section over the southern Baltic deeps. The next figures illustrate the estimated distribution in each month from March to December. Because of the lack of sufficient data, the distribution for January and February were not determined. However, the characteristics obtained allow to trace the changes in the acoustical conditions in the southern Baltic throughout the year.

The acoustical conditions in March and April (Fig. 3) could be classified as typical winter conditions in the southern Baltic. A nearly uniform distribution with the smallest yearly values of the sound speed (1415 – 1425 m/s) in the upper layer, and increasing sound speed with growing depth in the deep water layer are typical of them. The values of the sound speed at the Bornholm Deep (> 1450 m/s, at the bottom > 1455 m/s) are greater than in other deeps (1440 – 1450 m/s). The upper border of the area of increased sound speed caused by greater salinity could be illustrated by the isoline 1425 m/s. Its depth depends on the region and varies from about 50 m in the western part to about 60 – 70 m in the eastern one of the southern Baltic. In April the beginning of the process of water warming from the surface is observed, especially in the regions of smaller latitude laying closer to the land.

In May and June heat delivered from the atmosphere creates distributions typical for spring (Fig. 4) in which the minimum appears at the depth of about 50 m in the Bornholm Deep region and of about 60 m in the Gdańsk Deep region. The sound speed at the surface equals from 1445 to 1455 m/s in May and from 1455 to 1465 m/s in June, only close to the estuaries of the Vistula and the Odra it reaches values greater by about 6 – 10 m/s. In spring, in several points of the southern Baltic, the sound speed at the surface and at the bottom is approximately the same. Characteristic for those distribution patterns is the presence of a large volume of decreased sound speed lower than 1430 m/s. It occurs in the middle of the sea and its thickness varies from about 20 m in the western part to about 45 – 50 m in the eastern part of the area. This volume decreases with warming up of the upper layer of the sea.

The next three months: July, August and September could be characterised by the summer sound speed distribution with a well pointed out minimum and a high gradient of the temperature in the upper layer (Fig. 5 and Fig. 6). The difference between the value of the sound speed at the surface and the minimum value reaches 55 – 60 m/s. The depth of the minimum in the sound speed distribution changes from about 50 m at the Bornholm Deep to about 60 – 65 m at the Gdańsk Deep. The volume in which the sound speed is smaller than 1430 m/s decreases, and in August and September occurs only in the environment of the Gotland Deep and the Gdańsk Deep. The gradient of the sound speed in the deep layer is considerably smaller than in the upper one. The lowest value close to the bottom in main deeps is approximately 5 m/s smaller than the spring design.

From October the sound speed distribution changes significantly (Fig. 6 and Fig. 7). The change in the direction of the heat flow at the atmosphere-sea border is reflected also in the acoustical conditions. The value of the sound speed at the surface ranges from 1460 to 1465 m/s and its gradient in the upper layer is smaller than in the summer. A minimum in the vertical distribution still appears and its value is greater than in the summer by about 5 m/s. The configuration of the isoline in October is similar to the spring distributions, but the values are greater by about 5 – 10 m/s. In November and

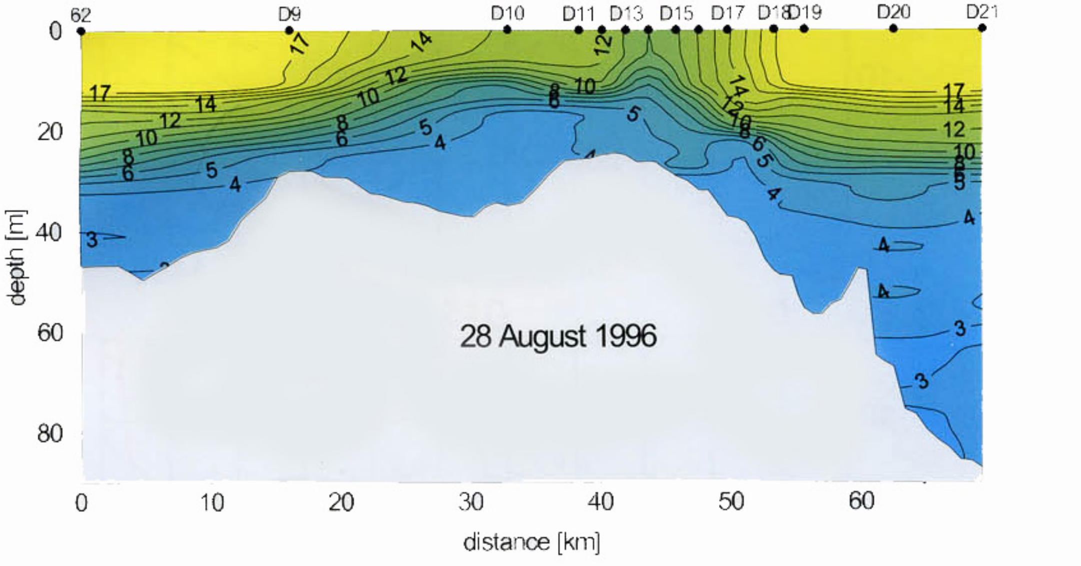


Fig. 13. The vertical temperature distribution at the cross-section shown in Fig. 11.

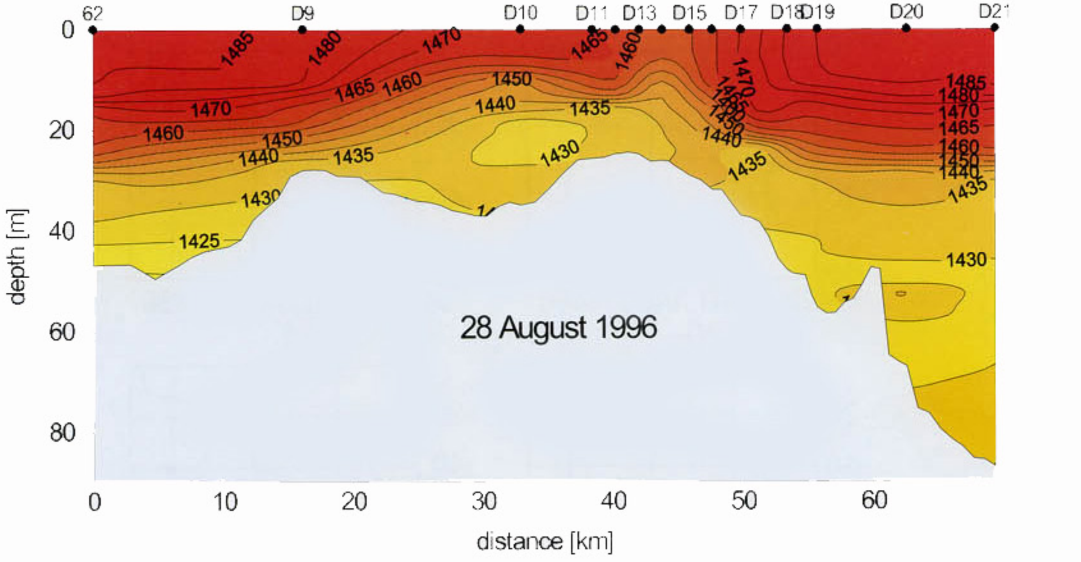


Fig. 14. The vertical sound speed distribution at the cross-section shown in Fig. 11.

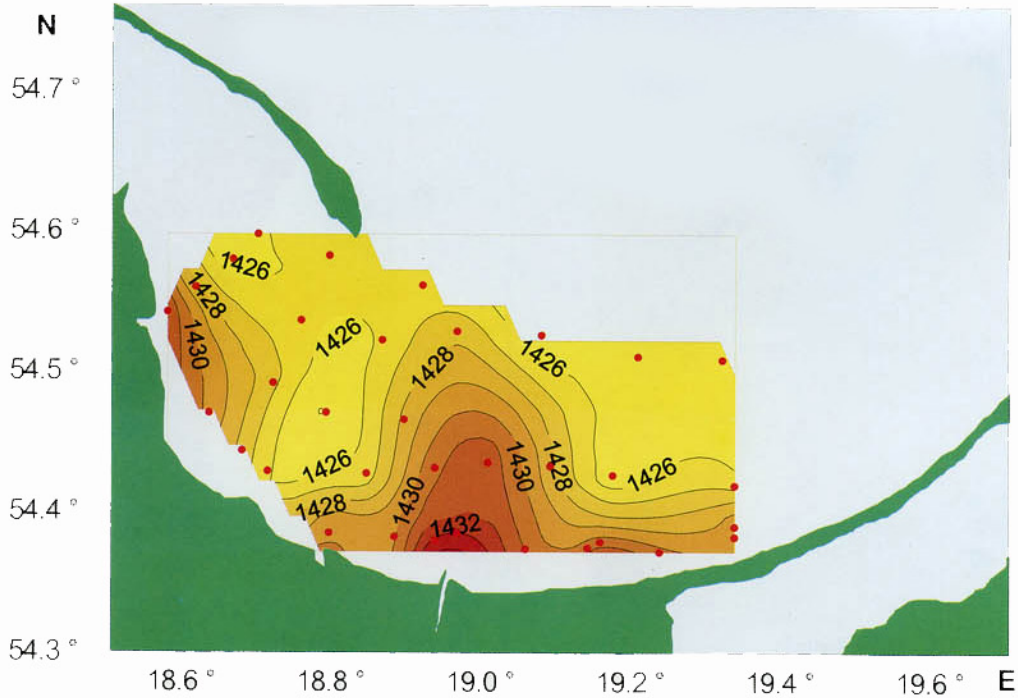


Fig. 15. The sound speed distribution at the surface of the Gulf of Gdańsk in April 1994.

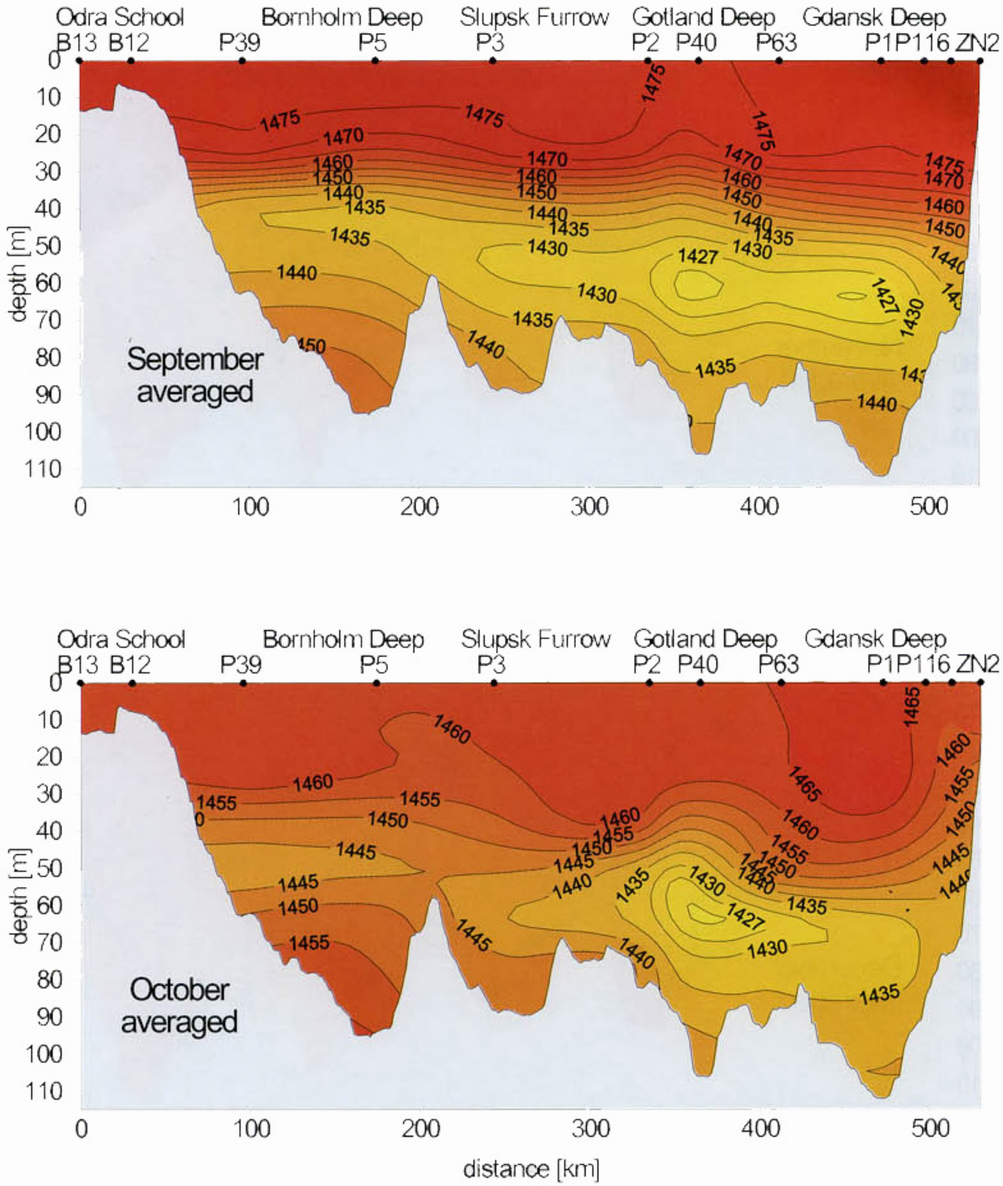


Fig. 6. The averaged vertical sound speed distribution in September and October in the years 1979 – 1991.

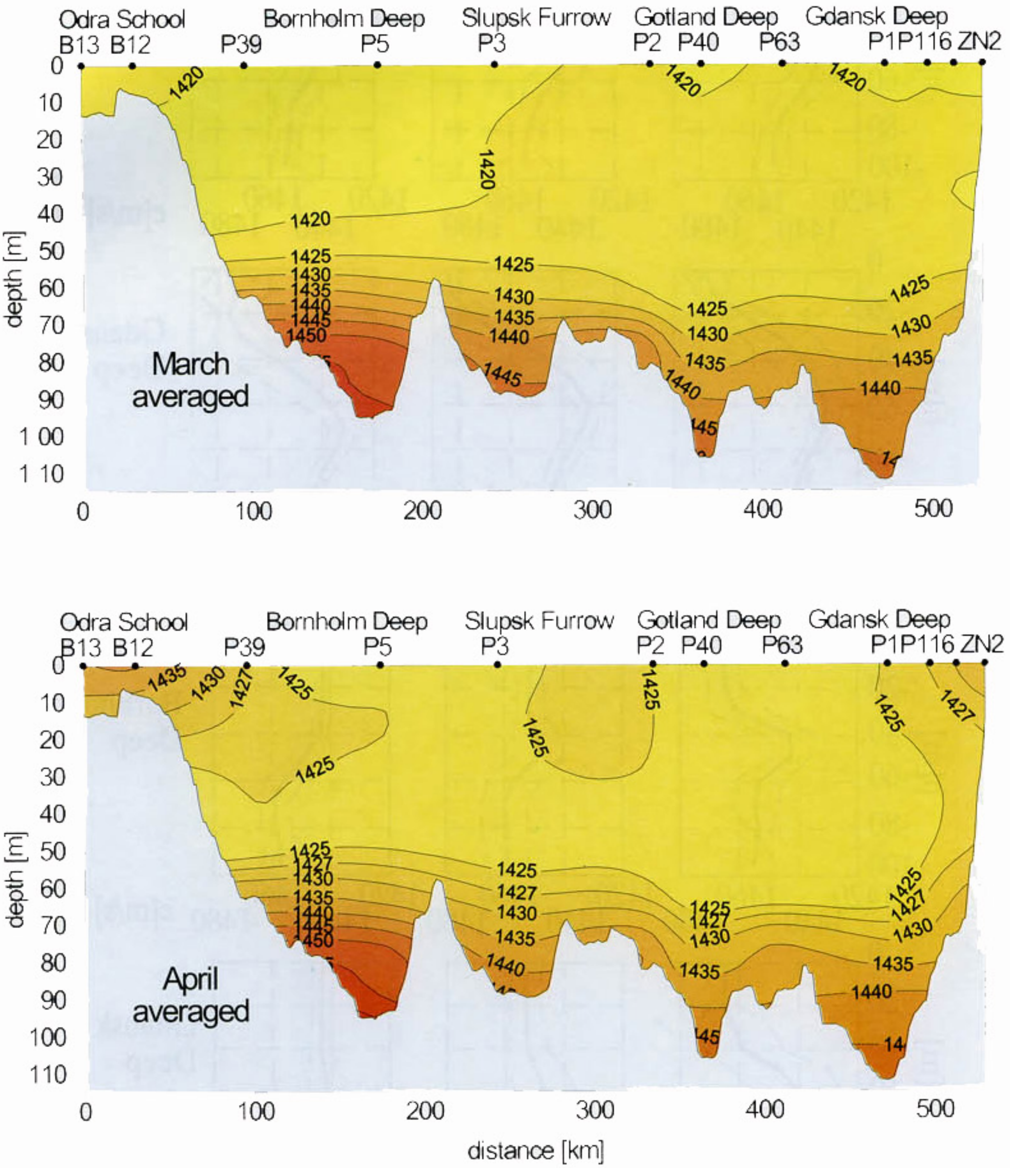


Fig. 3. The averaged vertical sound speed distribution in March and April in the years 1979 – 1991.

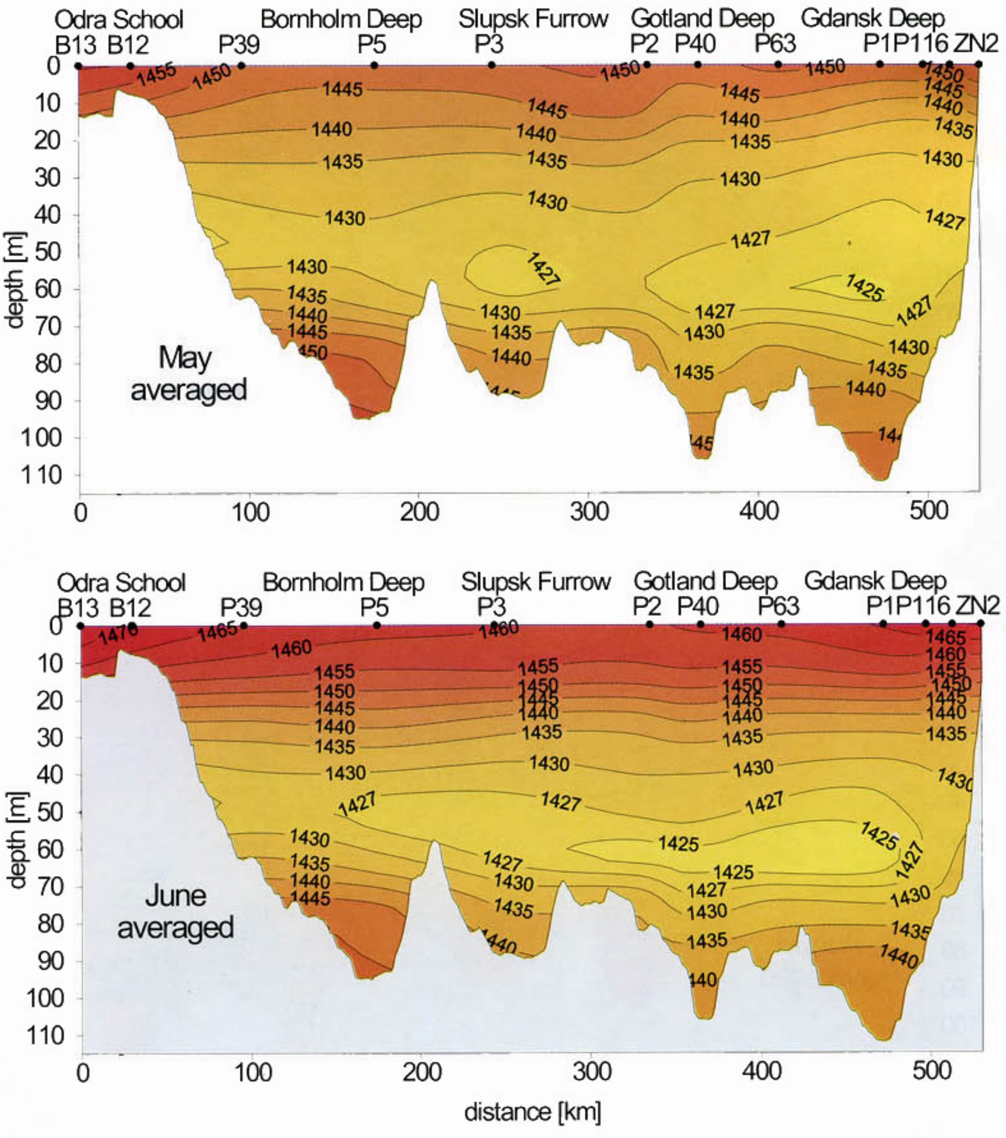


Fig. 4. The averaged vertical sound speed distribution in May and June in the years 1979 – 1991.

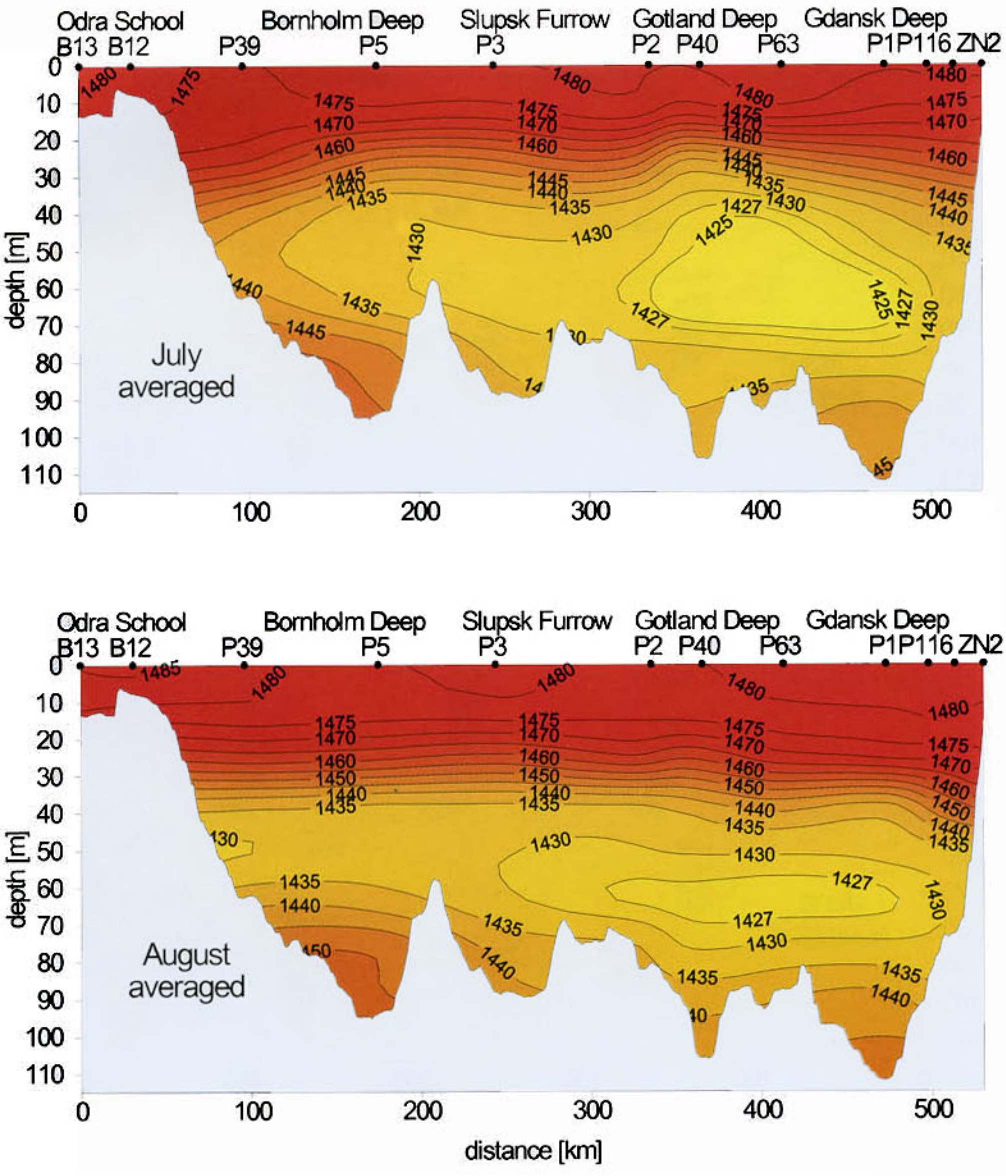


Fig. 5. The averaged vertical sound speed distribution in July and August in the years 1979 – 1991.

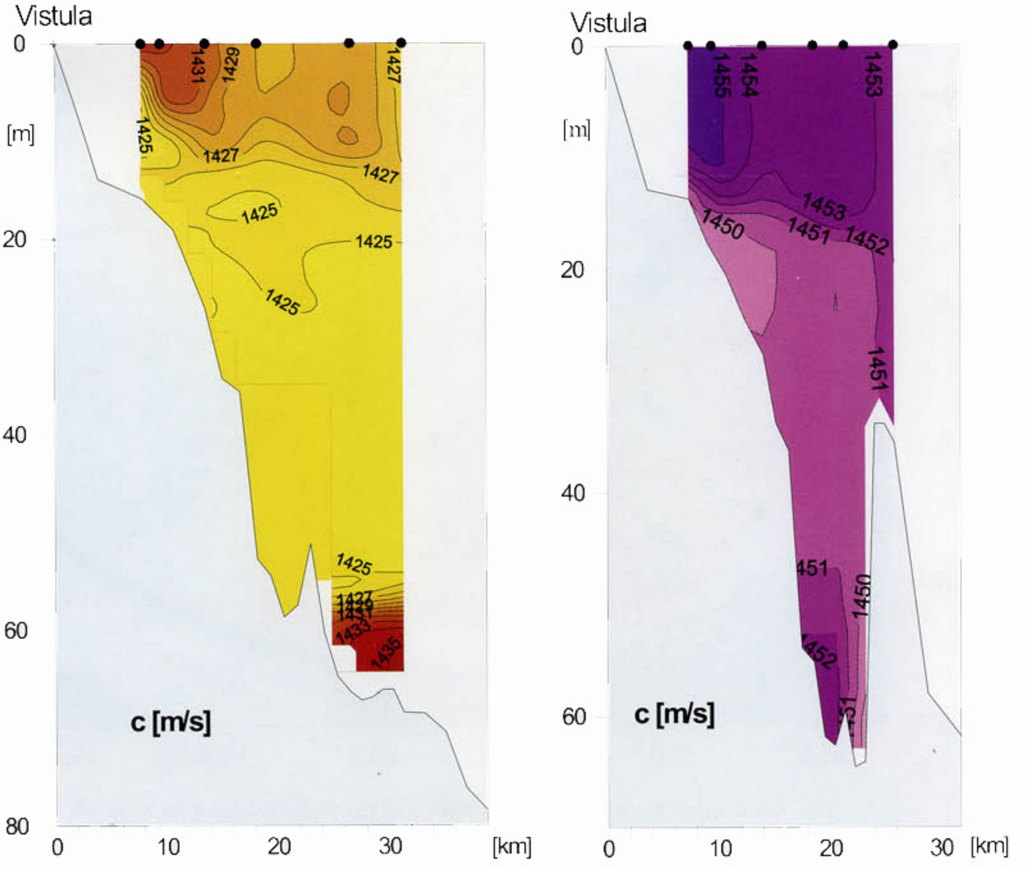


Fig. 16. The vertical sound speed distribution in the Gulf of Gdańsk in April and November 1994.

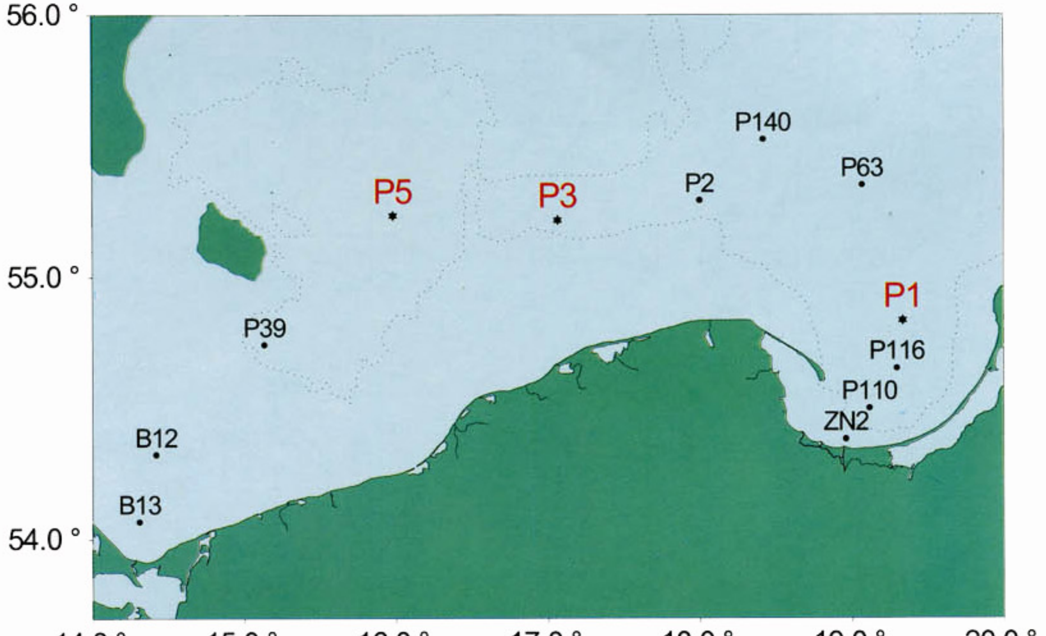
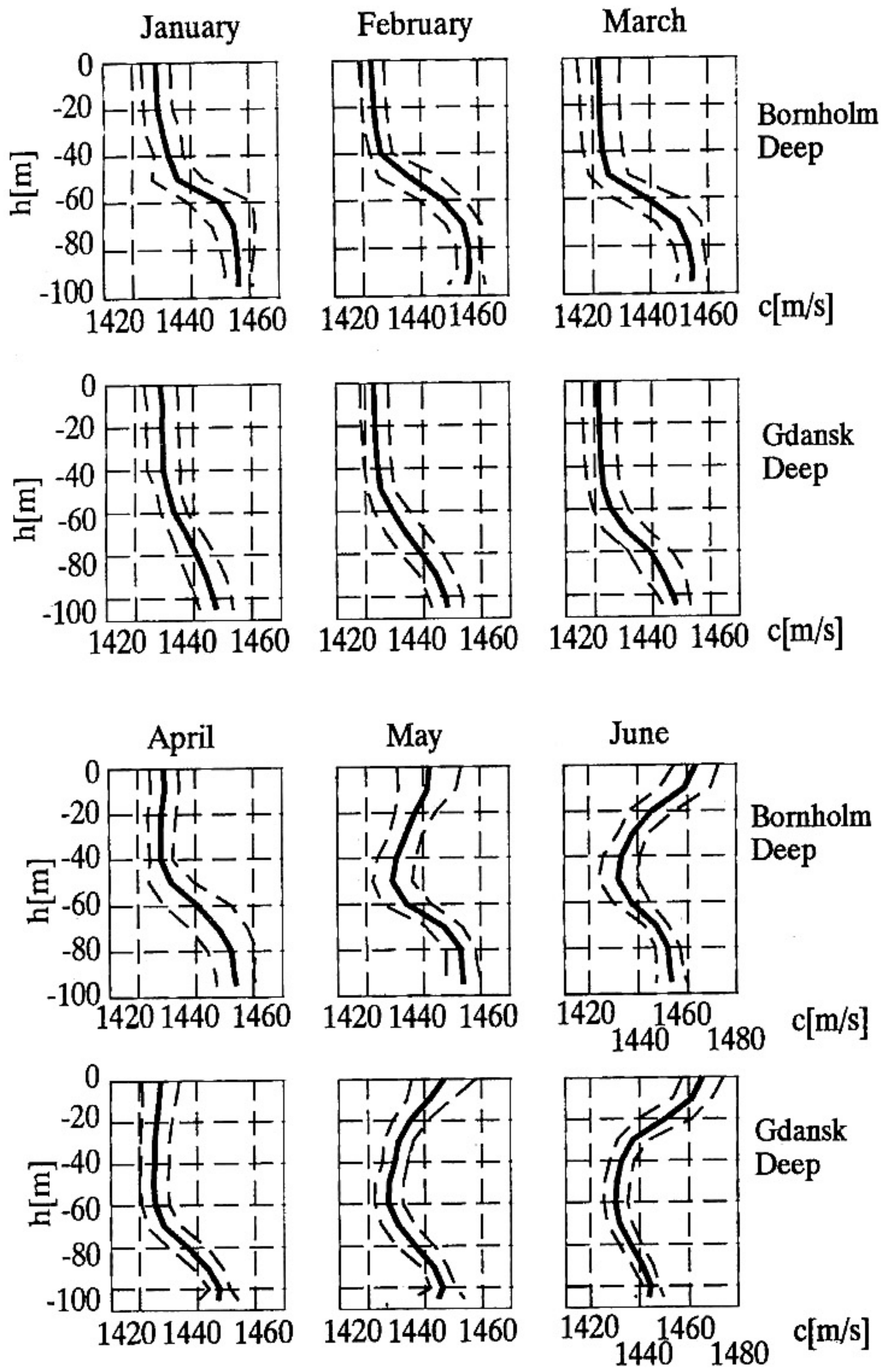


Fig. 1. Distribution of the measurement stations.



January
February
March
Bornholm Deep
Gdansk Deep
April
May
June
h[m]
0
-20
-40
-60
-80
-100
1420
1440
1460
1480
c[m/s]

[Fig. 2a]

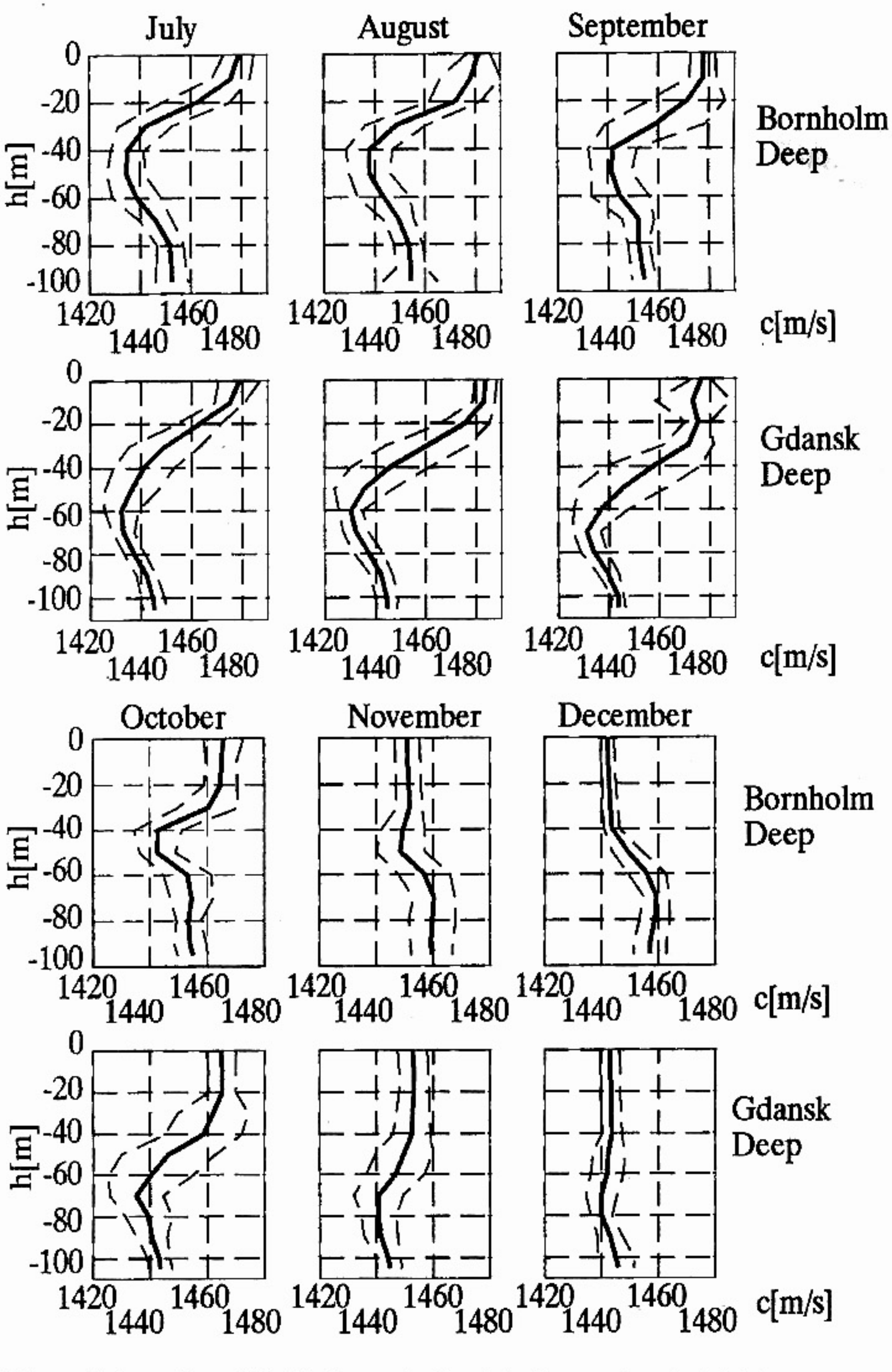


Fig. 2. The vertical sound speed distribution at the Bornholm Deep and at the Gdańsk Deep averaged for the period 1960 – 1997: (—) estimated averaged value, (- - -) confidence interval.

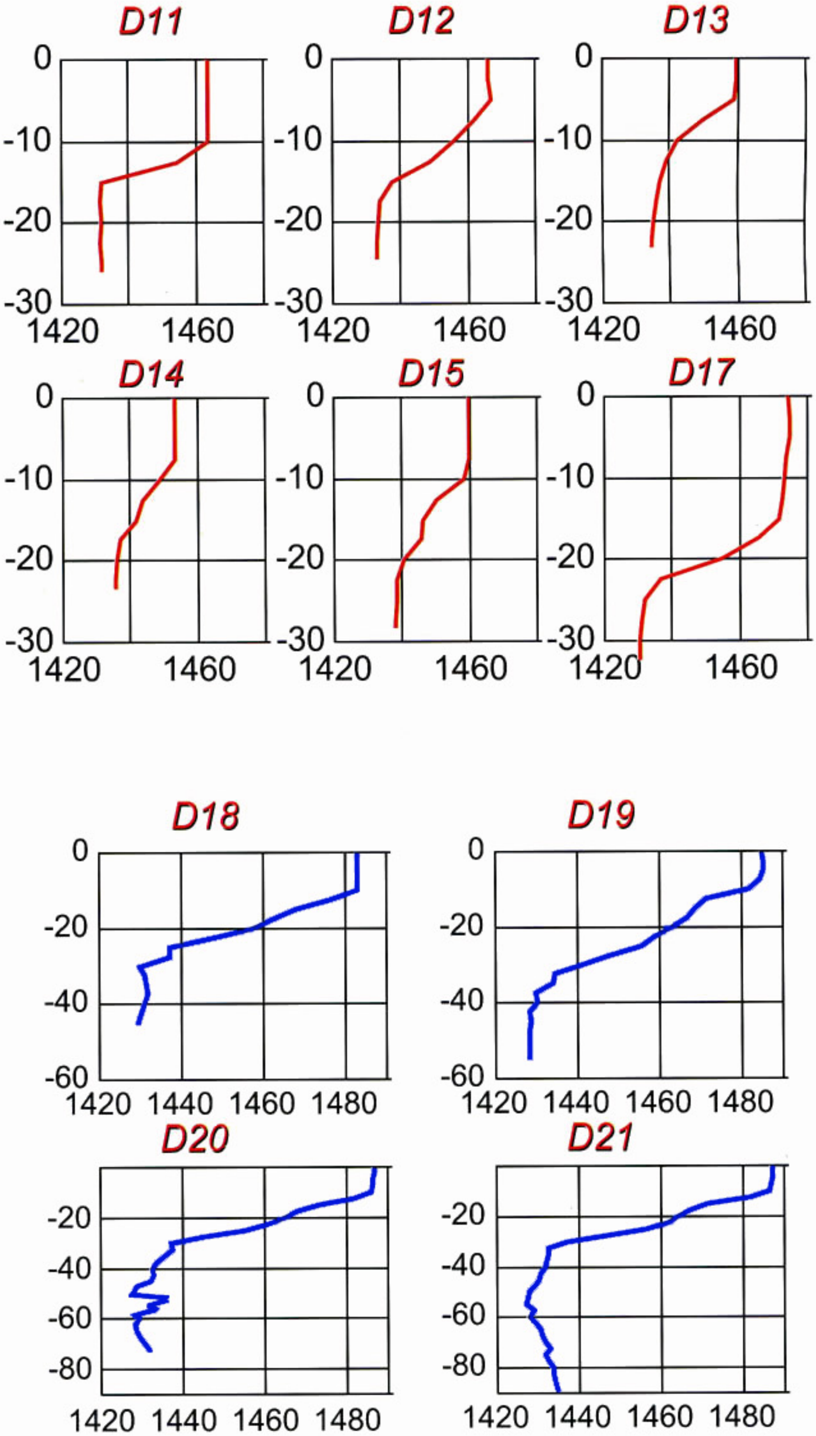


Fig. 12. The sound speed distribution at chosen stations in the vicinity of Rozewie — 28th August 1996.

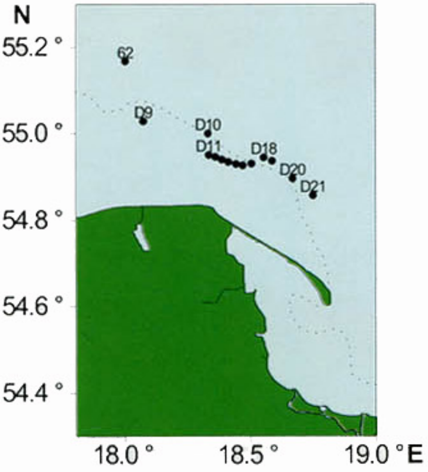


Fig. 11. The distribution of the measurement stations near Rozewie in August 1996.

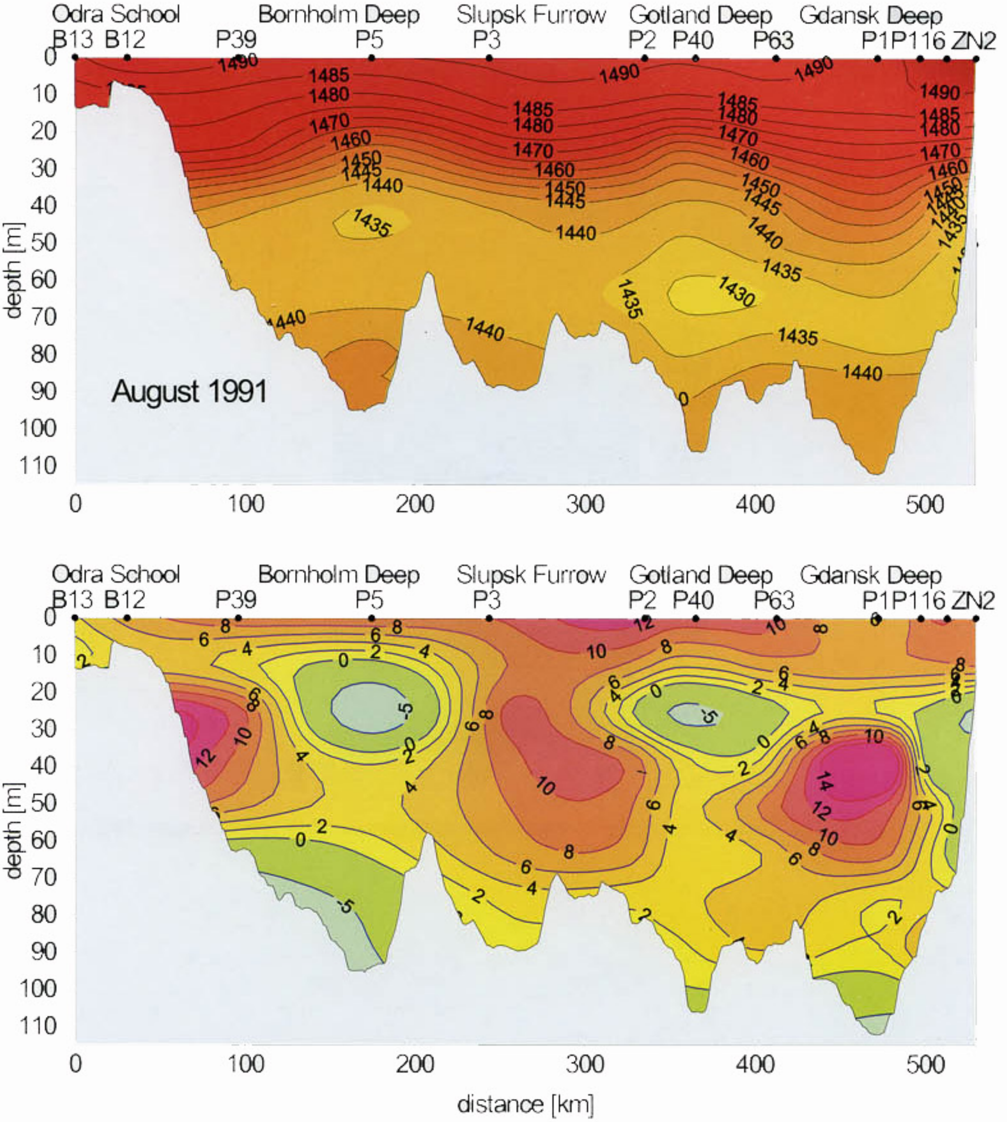


Fig. 10. The vertical sound speed distribution in August 1991 and the difference between it and the averaged distribution in August in the years 1979 – 1991.

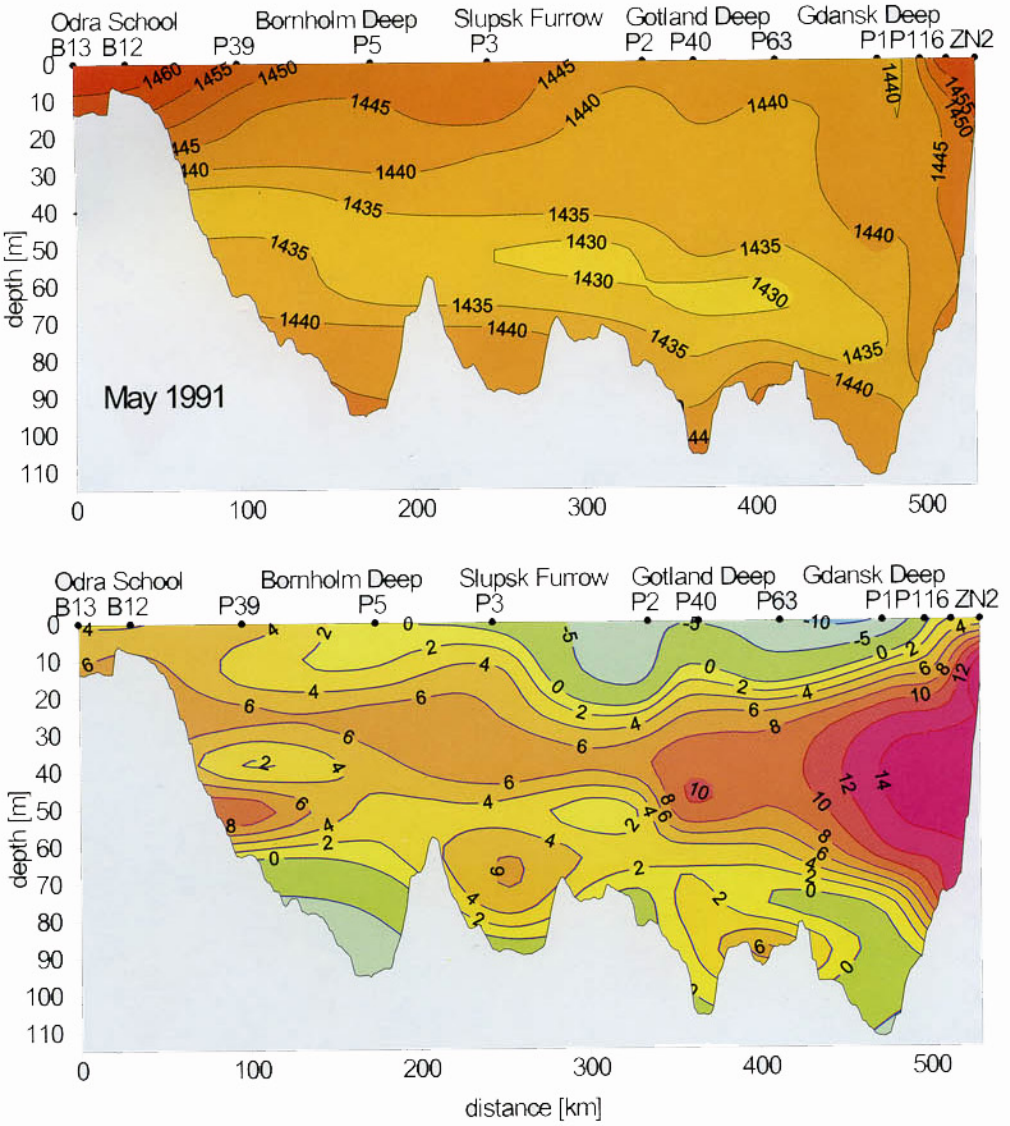


Fig. 9. The vertical sound speed distribution in May 1991 and the difference between it and the averaged distribution in May in the years 1979 – 1991.

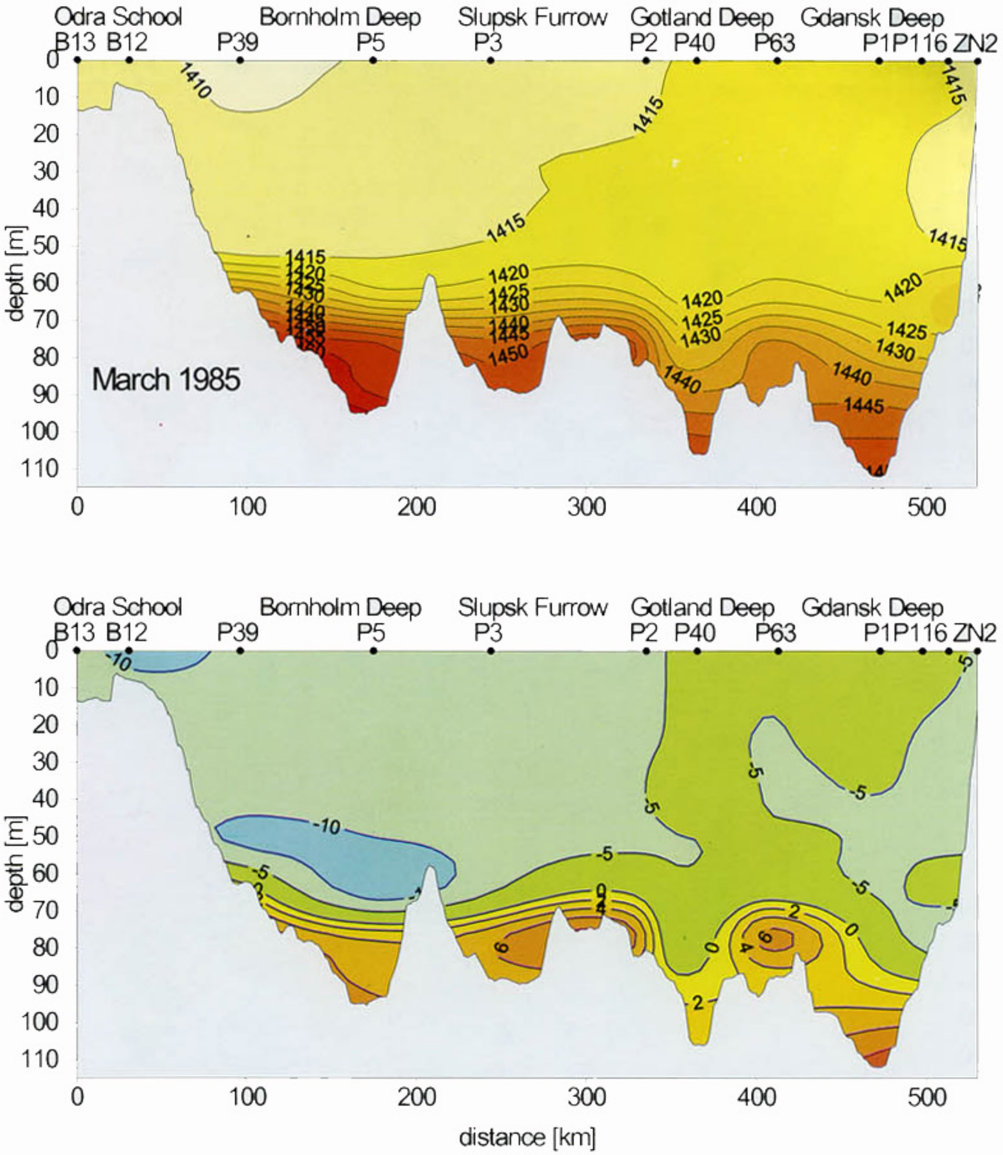


Fig. 8. The vertical sound speed distribution in March 1985 and the difference between it and the averaged distribution in March in the years 1979 – 1991.

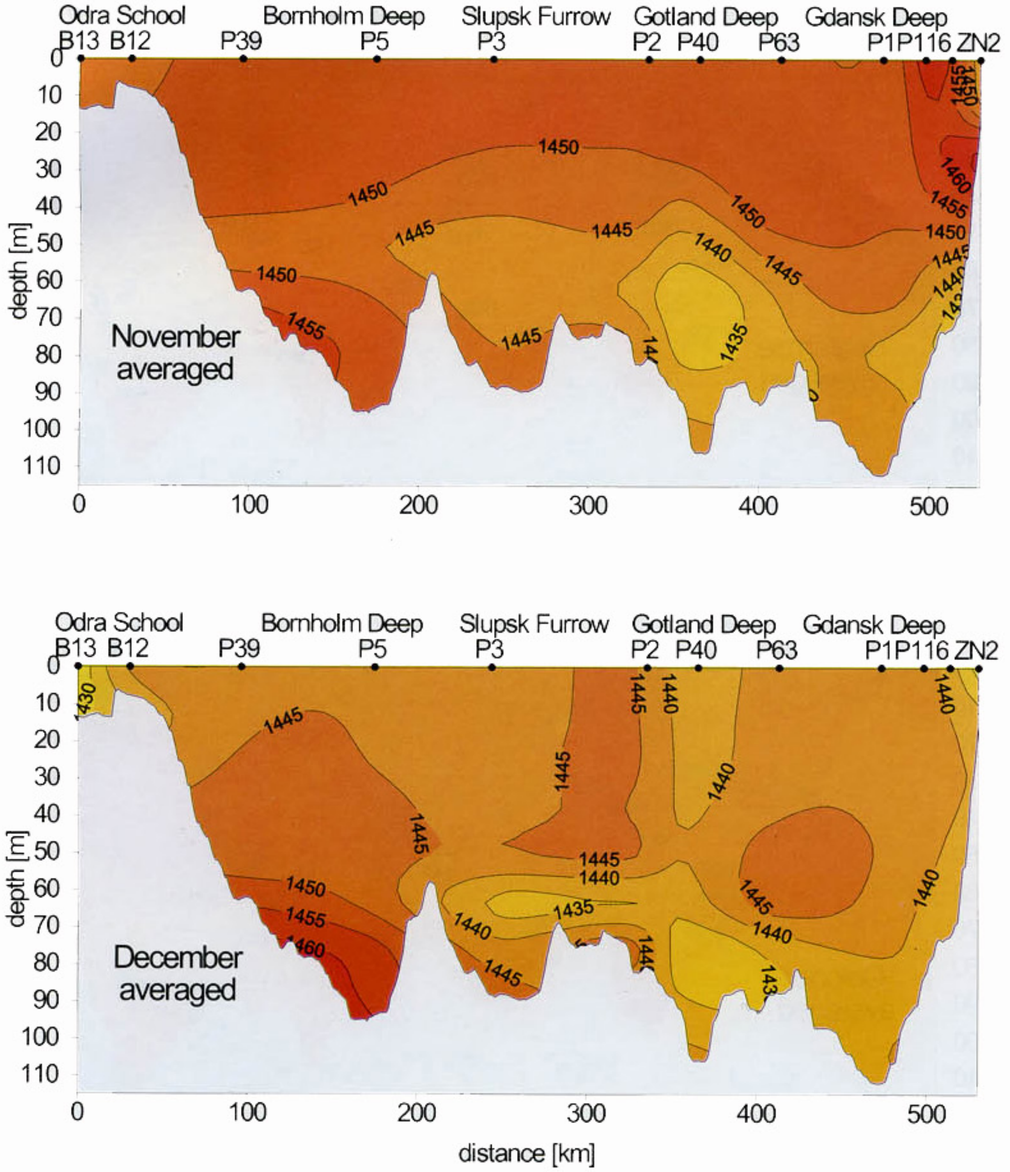


Fig. 7. The averaged vertical sound speed distribution in November and December in the years 1979 - 1991.

December, the distributions are not significantly diversified and the value of the sound speed is relatively considerable. The minimal value is higher than 1445 m/s in the region of the Bornholm Deep, higher than 1440 m/s in the environment of the Gdańsk Deep, and only in the surroundings of the Gotland Deep it is lower than 1435 m/s. In December the sound speed in the deep water layer in the Bornholm Deep increases significantly and at the depth below 60 m reached values greater than 1450 m/s, which comes to about 20 m/s more than in March and to about 10 m/s more than in September in the upper part of the area considered. The value at the bottom exceeded the average in March by about 5 m/s and the average in September by about 10 m/s.

5. Acoustical anomaly in the southern Baltic

In the previous chapter an attempt was made to characterize the acoustic climate of the southern Baltic. It was based on the averaged sound speed distributions. The next step in the search for the specific features of the Baltic treated as a complex environment of sound propagation was to find out how does the particular synoptic sound speed distribution differ from the averaged one. To get the answer, several synoptic distributions established in different seasons are compared with the averaged distribution.

Differences in the winter distribution depend predominantly on two main factors: the anomaly high or low temperature of air and the volume of the inflow of saline water from the North Sea. Both of these factors are reflected in the sound speed distribution in March 1985. During that year the averaged temperature of water in the upper layer at the depth of 10 m was 0.32°C, that is by about 1.16°C lower than the averaged temperature in March at the same depth. The consequence was reflected by the decrease of the sound speed from 5 to 10 m/s in the whole cross-section, with the exception of the areas close to the bottom of the deeps. There, as a result of the inflow which increased the salinity to 16.1 PSU (avg. 15.49 PSU) and the temperature to 7.44°C (avg. 6.42°C) at the Bornholm Deep, the established values were greater by up to 4.92 m/s than the averaged ones. The distribution for March 1985, as well as the difference between it and the averaged distribution (Fig. 3), are shown in Fig. 8.

The situation typical for May (see Fig. 4) could be regarded as the distribution representative for the spring. The influence of the warm winter of 1991 on the acoustical conditions in the next season was confirmed by the distribution pattern in May 1991 presented in Fig. 9. In this case, the middle area of the decreased sound speed is bordered by the isoline 1435 m/s. Only in the northern part of the considered area occurred the residue volumes of water in that the sound speed was below 1430 m/s. In contrast to that, the values at the surface were lower by up to 10 m/s than the average ones. It indicates that the heat delivered from the atmosphere during that spring was smaller than usually. Also in deeps, especially at the Bornholm Deep, the sound speed in the deep water layer was below the average values by up to 10 m/s. It was an effect of the lower salinity at the Bornholm Deep caused by the lack of inflow of saline water in the preceding autumn.

An example illustrating a summer with the generally positive anomaly of the acoustical conditions is the August of 1991 (Fig. 10). Only at the depths of about 20 – 30 m values below the average ones appeared. It could be the consequence of the negative anomaly near the surface, which was observed in May of that year (Fig. 9). In the deep water in the area of the Bornholm Deep decreased values of the sound speed were observed as a continuation of the situation in the spring.

The above presented examples of the positive and negative anomaly in the whole volume of the southern Baltic or in a part of it were chosen from among those which differed most distinctly. It allows to assess the range of changes of the sound speed in particular seasons.

6. Impact of local morphological and hydrological conditions on the sound speed distribution

Difficulties in specifying the acoustical conditions of the southern Baltic are increased by the appearance of short-term local phenomena changing considerably the sound speed distribution in certain areas [6, 19, 28]. Examples of such phenomena can be seen in the upwelling near Rozewie; the influence of the Vistula waters on the acoustical conditions is visible in the Gulf of Gdańsk.

The shape of the bottom near Rozewie causes in specific hydrological and meteorological conditions the occurrence of upwelling of the colder water. Data shown in the next figures illustrate the influence of upwelling on the acoustical conditions.

The consecutive graphs (Fig. 12) show the sound speed distribution measured on 28th August 1996 at stations marked in the map (Fig. 11). The distances between the stations were relatively small (about 1 – 2 km), however the distributions differed considerably. The value at the surface varied from 1451 m/s to 1474 m/s, at the bottom from 1431 to 1439 m/s. The difference between the maximal value at the surface and the minimal ones at the bottom changes from 16 m/s at the station D14 to 43 m/s at the station D17. The distance between those two stations equals 5 km.

Patterns of the vertical sound speed distribution at stations the D18, D19. D20 and D21, distant from those mentioned previously by about 3 – 10 km, were similar to each other. They all had the sound speed of about 1484 m/s at the surface and a high gradient of it within a layer ranging from 10 to 30 m with a sound speed reduction downward by about 1430 m/s.

The upwelling of the mass of cold water with temperatures of about 12°C, being lower by about 6°C in comparison to its environment (Fig. 13), was the cause of the anomaly. The vertical sound speed distribution at the cross-section along the stations marked in Fig. 11 is shown in Fig. 14. It is a phenomenon occurring sporadically, but when it happens it changes the local acoustical conditions to a considerable degree.

Another phenomenon changing the acoustical conditions in the southern Baltic to a certain degree is the inflow of the Vistula waters which influences the acoustic parameters of the Gulf of Gdańsk. This phenomena, described in detail in [19], is the subject of seasonal changes during the year. In propitious circumstances, its impact on the situation in the Gulf of Gdańsk is clearly visible, as for example in April and November 1994 (Fig. 15, Fig. 16). The situation appeared after a few windless days. The range of the impact of the Vistula waters is up to 20 km from the mouth of the river in a layer of about 15 m thickness from the surface.

7. Conclusions

The acoustical climate of the southern Baltic is difficult to describe because of the many factors influencing it. In the paper, an attempt is made to characterize the acoustical conditions in this region. The characteristics obtained offer much valuable information on the conditions of the sound propagation in the Baltic Sea, on their changes during the year and on the impact of particular physical phenomena on them. However, it must be taken into account that this picture has been created with a limited number of available data.

The averaged distributions allow to assess the general trends and to find specific features for particular seasons. The acoustical conditions in the upper layer, where the salinity is almost invariable, depend on the seasonal changes in the temperature of the water. In the winter temperature, it is nearly stable in the upper layer down to the depth of about 50 - 60 meters. Therefore the spatial distribution of the sound speed is nearly uniform at that season.

In other seasons, the temperature of the water at the surface is higher than in the deeper layers. It involves the vertical gradient of the sound speed and the appearance of the minimum sound speed in its vertical distribution approximately at the border between the upper and the deep water layer. The value of the gradient is the highest in the summer. During the year, the gradient changes seasonally in accordance with the heat exchange between the atmosphere and the seawater. The thermal conditions in the winter exert an influence on the minimal value in the vertical sound speed distribution during successive seasons, whereas the maximal value of the speed at the surface depends on current conditions in each particular season.

The impact of the inflows of highly saline water from the North Sea, causing the increase of the sound speed in the deep water layer, is usually visible in the western part of the Baltic Sea in the autumn, and in the Gdańsk Deep region in the early spring. The inflow appears as a rule in the autumn and the subsequent course of the phenomena depends mainly on when it occurs and on the volume of the inflowing water.

The differences between synoptic and average distributions demonstrate the strength of the impact that physical factors have on them and confirm the necessity of investigating acoustical conditions by hydroacoustic equipment is used in underwater research.

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