The influence of Vistula water on the thermodynamic and acoustic parameters of the Gulf of Gdańsk*

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Conditions for acoustic wave propagation in the Baltic Sea
Acoustic and thermodynamic parameters of seawater
Low-salinity seawater

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Abstract

The article discusses the results of investigations into the influence of water from the river Vistula on the thermodynamic and acoustic conditions in the Gulf of Gdańsk. On the basis of monthly temperature and salinity distributions averaged over 15 years, the annual variation in selected thermodynamic and acoustic parameters was determined at station ZN2 off the Vistula mouth and at station P110 in the central part of the Gulf.

In order to find the best way of calculating the area influenced by Vistula water, the spatial distributions of density, compressibility, expansion, specific heat, speed of sound and the nonlinearity parameter B/A were determined. Depending on the meteorological and hydrological conditions in a given year, the spread of Vistula water is reflected by the distributions of several parameters. Analysing a number of parameters together seems to be the most suitable way of estimating this spread. The present analysis also allows the origin of the Gulf waters to be studied. These investigations can be used to forecast conditions for the propagation

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of finite-amplitude acoustic waves in the area where Vistula water interacts with the seawater in the Gulf of Gdańsk.

1. Introduction

An acoustic wave is a disturbance of the aquatic medium due to the transmission of elastic particle vibrations. Because of the short duration of changes, the process is usually regarded as an isentropic one. Information about the spatial distribution of two basic acoustic parameters – the speed of sound and, in the case of high-intensity waves, the nonlinearity parameter B/A – is required in order to estimate the conditions of acoustic wave propagation in a given sea area. Where seawater is concerned, both parameters are complex functions of temperature, chemical composition and hydrostatic pressure (Coppens *et al.*, 1965; Sarkisov, 1993), and are modified by changes in hydrological conditions (Kozaczka and Grelowska, 1994).

The lack of systematic measurements of acoustic parameters often makes it difficult to assess acoustic conditions. However, the relationships between the thermodynamic parameters characterising seawater and temperature, salinity and hydrostatic pressure are known and experimentally confirmed, as are those between acoustic and thermodynamic parameters. The determination of the thermodynamic and acoustic characteristics of a given sea area is thus possible on the basis of hydrological measurements, which for several decades now have been carried out on a regular basis.

The Gulf of Gdańsk is an area of the Baltic Sea where constant interaction takes place between low-saline seawater and river water, the volume of which is relatively high compared to that of the Gulf waters; hence the specific distribution of acoustic and thermodynamic parameters in the Gulf of Gdańsk and its annual variations.

The article discusses the influence of the water of the river Vistula on the thermodynamic and acoustic properties of Gulf of Gdańsk water on the basis of vertical distributions, selected thermodynamic parameters (density, specific heat at constant pressure, volumetric thermal expansion, isothermal compressibility) and acoustic parameters (speed of sound, nonlinearity parameter B/A, acoustic impedance), averaged over fifteen years. Moreover, a random estimate of the range of influence of Vistula water on the thermodynamic and acoustic properties of the Gulf water was made from synoptic hydrological investigations carried out in 1994.

2. Theory

The relationship between thermodynamic and acoustic parameters has been known for a long time and can be proved by the basic Newton-Laplace formula describing the dependence of the speed of sound c on the thermodynamic parameters of water (Dera, 1983):

$$c^2 = (\frac{\partial p}{\partial \rho})_s = \frac{1}{\rho_o \beta_{T,Q}} \approx \frac{\gamma}{\rho_o \beta_T}, \tag{1}$$

where

p – acoustic pressure,
ρ – density,
ρ_o – density of the undisturbed medium,
$\beta_{T,Q}$ – adiabatic compressibility coefficient,
β_T – isothermal compressibility coefficient,
$\gamma = C_p/C_V$ – specific heat ratio,
$(\partial p/\partial \rho)_s$ – derivative at constant entropy.

Theoretical and experimental inquiries into the relationships between thermodynamic and acoustic parameters are still being carried out, since it is possible to determine the thermodynamic parameters of a medium by using acoustic methods, and vice versa.

The theoretical thermodynamic basis of the experimentally observed relationship between the nonlinearity parameter of a liquid and the speed of sound were worked out by Hartmann and others. Hartmann (1979) attempted to show theoretically the physical basis for the empirically observed relation between the nonlinearity parameter of liquids and the reciprocal of the speed of sound. Under the assumption that the intermolecular potential energy is the dominant factor in determining the speed of sound and its derivatives, Hartmann showed that the nonlinearity parameter B/A, Rao's acoustic parameter and the Grüneisen parameter were related to each other in a simple manner. In the process of developing various relations, he assumed that the speed of sound was fundamentally a function of volume and depended on temperature and pressure only in as much as these variables influenced the volume.

Sharma (1983) showed that the isochoric temperature derivative of the speed of sound was the dominant factor, exerting a significant influence on the thermo-acoustic properties. On that assumption, the relations obtained by Hartmann were modified. Sharma concluded that Beyer's nonlinearity parameter B/A, Rao's acoustic parameter, that of Carnevale and Litovitz, and the Grüneisen parameter were not independent but related to each other through the isochoric temperature coefficient of the acoustic speed and expressed the same physical quantity.

Endo (1982, 1984) paid special attention to the nonlinear properties of seawater. He determined values of the nonlinearity parameter B/A by applying two methods. In both cases the starting point was the isentropic equation of state, where pressure is expanded in a Taylor series about its equilibrium value in terms of the density and entropy:

$$\begin{aligned} p &= p_o + (\frac{\partial p}{\partial \rho})_{s,\rho=\rho_o}(\rho - \rho_o) + (\frac{\partial^2 p}{\partial \rho^2})_{s,\rho=\rho_o}\frac{(\rho-\rho_o)^2}{2!} + ... \\ &+ (\frac{\partial p}{\partial s})_{\rho,s=s_o}(s - s_o) + ... \end{aligned} \quad (2)$$

Because the propagation of an acoustic wave is an isentropic process ($s = s_o$), eq. (2) can be written as

$$p - p_o = A(\frac{\rho - \rho_o}{\rho_o}) + \frac{B}{2}(\frac{\rho-\rho_o}{\rho_o})^2 + ... \quad (3)$$

where coefficients A and B are defined in the following way:

$$\begin{aligned} A &= \rho_o(\frac{\partial p}{\partial \rho})_{s,\rho=\rho_o} = \rho_o c_o^2, \\ B &= \rho_o^2(\frac{\partial^2 p}{\partial \rho^2})_s, \rho = \rho_o. \end{aligned} \quad (4)$$

The ratio of coefficients B/A is called the nonlinearity parameter of the medium. In his calculations Endo (1984) used:

1) the dependence given by Beyer (1960) linking the B/A parameter with thermodynamic parameters and the speed of sound:

$$\frac{B}{A} = 2\rho_o c_o(\frac{\partial c}{\partial p})_T + \frac{2c_o\alpha T}{C_p}(\frac{\partial c}{\partial T})_p, \quad (5)$$

where

α – is the thermal expansion,

T – the absolute temperature,

C_p – the specific heat at constant pressure;

2) an exclusive dependence between the B/A parameter and thermodynamic parameters, which he derived himself (Endo, 1982):

$$\begin{aligned} \frac{B}{A} &= (k_T - 1) + (\gamma - 1)[2k_T - 1 - \frac{3}{\alpha\beta_T}(\frac{\partial \beta_T}{\partial T})_p] + \\ &+ (\gamma-1)^2[k_T + 1 + \frac{1}{\alpha}[\frac{1}{T} + \frac{3}{\alpha}(\frac{\partial \alpha}{\partial T})_p + \\ &- \frac{3}{\beta_T}(\frac{\partial \beta_T}{\partial T})_p - \frac{1}{C_p}(\frac{\partial C_p}{\partial T})_p]], \end{aligned} \quad (6)$$

where $k_T = [\partial(1/\beta_T)/\partial p]_T$.

There was good agreement between the values of B/A obtained using these two methods for seawater of salinity 25–40 psu, temperature 0–35°C and for variations of hydrostatic pressure in the 0–80 MPa range. Differences between corresponding values did not exceed ± 2%.

Klusek (1990) investigated the seasonal variation in the speed of sound distributions in the Gulf of Gdańsk. On the basis of salinity and temperature data from 1957–1970 he selected five periods characterised by a similar shape of the vertical speed of sound distributions. Then, on the basis of averaged data, he determined the speed of sound field distributions at the surface and at selected vertical cross-sections typical for each period.

3. Material and methods

The influence of Vistula water on the thermodynamic and acoustic properties of the Gulf water was examined by applying the results of hydrological investigations, *i.e.* temperature and salinity measurements, in the Gulf of Gdańsk.

The annual variations in thermodynamic and acoustic conditions were investigated at two stations – ZN2 (54°23′N, 18°57.5′E) at a depth of 15 m situated off the Vistula mouth and P110 (54°30′N, 19°06.8′E) at 72 m depth in the central part of the Gulf – on the basis of measurement data from 1979–1993 published in ICES papers. The averaged vertical temperature and salinity distributions for individual months were determined for this purpose. From these data, in turn, the averaged vertical distributions of the thermodynamic parameters in eqs. (1) and (5) were calculated, as were the acoustic parameter distributions.

The following relationships were used in the calculations:

1) equation of state for seawater for calculating density (Millero *et al.*, 1981);
2) an empirical relationship for the specific heat at constant pressure (UNESCO, 1983);
3) an empirical relationship for the expansion and isothermal compressibility (Chen *et al.*, 1976).

The adiabatic compressibility coefficient $\beta_{T,Q}$ and the isothermal compressibility coefficient β_T in eq. (1) are linked to each other by the formula

$$\beta_T = \gamma \beta_{T,Q}. \tag{7}$$

In the case of seawater $1.00 \le \gamma \le 1.02$, which in practice means that both compressibility coefficients are approximately equal, *i.e.* $\beta_T \approx \beta_{T,Q}$.

4) an empirical relationship for the speed of sound (UNESCO, 1983; Gill, 1982);
5) the nonlinearity parameter B/A on the basis of eq. (5) using the empirically determined parameters there;

6) the acoustic impedance of the medium for a plane wave as the product of density and speed of sound.

In addition, the range of influence of Vistula waters was estimated on the basis of hydrological investigations in the Gulf of Gdańsk carried out in April, July and November 1994. For this purpose, graphs of the distributions of the parameters examined at the water surface and in planes parallel to it at depths of 5 and 10 m were plotted using SURFER software. The vertical distributions of each parameter at profiles from the Vistula mouth in the direction of the centre of the Gulf of Gdańsk were determined as well.

4. Results

4.1. Annual variations in thermodynamic and acoustic properties of the Gulf of Gdańsk

The variations in the averaged values of each parameter at depths of 0, 5, 10 and 15 m at stations ZN2 and P110 were determined in order to assess the influence of the Vistula on the thermodynamic and acoustic properties of Gulf of Gdańsk water, the annual variations in these parameters. Figs. 1–6 show the annual variations in the thermodynamic parameters, and Figs. 7–9 illustrate the variations in the acoustic parameters at both stations.

The annual cycle of hydrological conditions at station ZN2, off the Vistula mouth, is very different from that typical of the Gulf of Gdańsk. This is particularly evident in the surface layer. The surface water temperature in the spring-summer period, from March to September, is from 0 to 5°C higher than the temperature at a depth of 5 m, while from November to March it is from 0 to 2°C lower than the temperature at 5 m. The surface salinity varies from 2.5–6 psu during the year, the lowest values, about 3 psu, being recorded in spring from March till June. The influence of the Vistula is less significant at greater depths, where the salinity varies from 7 to 8 psu, the lowest values being recorded in June (at 5 m $<$ 7 psu).

Station P110, situated in the central part of the Gulf of Gdańsk is significantly less affected by Vistula water in that the salinity at 0 and 5 m is lower in the last months of spring (May–June). Nevertheless, this is high in comparison to that at ZN2, where the lowest averaged value at the surface is about 7.1 psu. Temperature changes in the uppermost layer at P110 are close to typical for this layer in the southern Baltic. In comparison to the surface water temperature at P110, that at ZN2 is higher by 0–5°C from March till September, owing to the inflow of warmer Vistula water, which warms up faster because of its smaller volume. The opposite effect, *i.e.* the lower temperature of the surface water in autumn and winter close

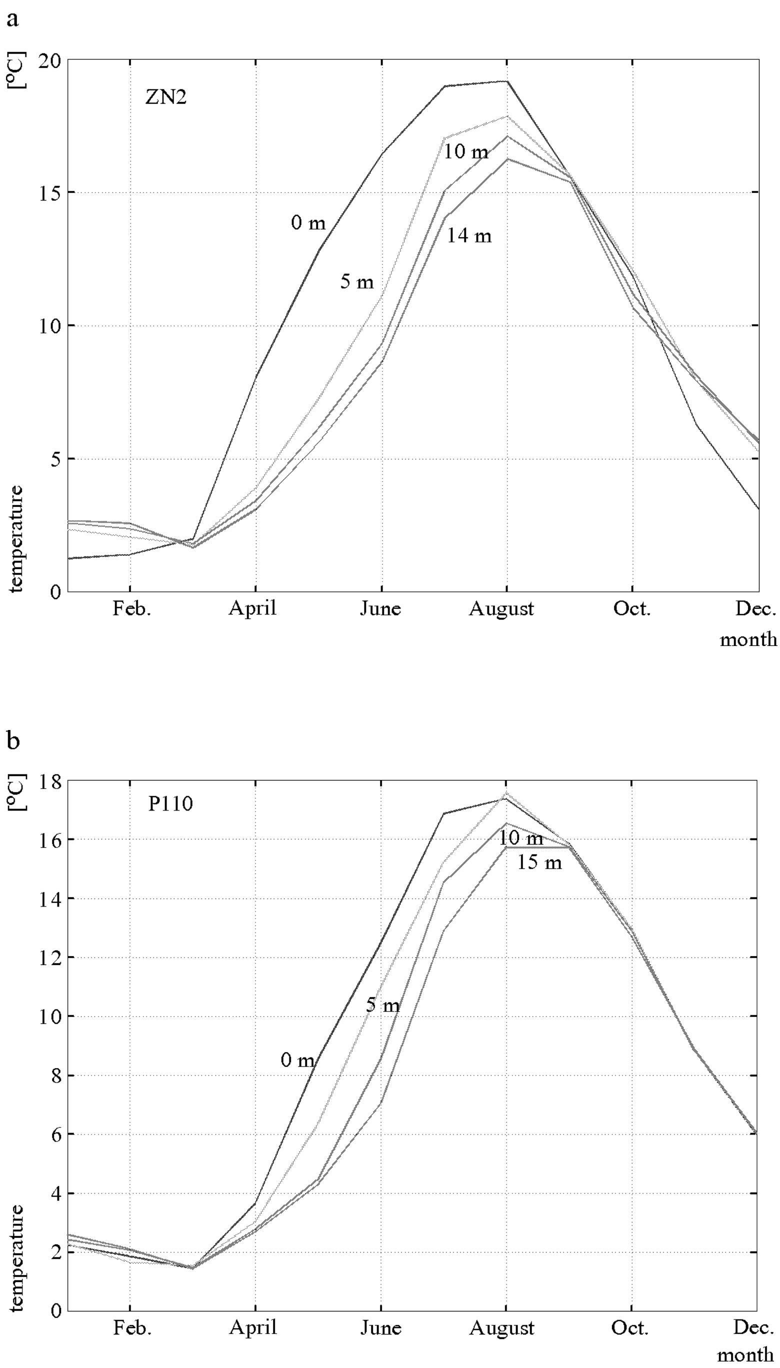
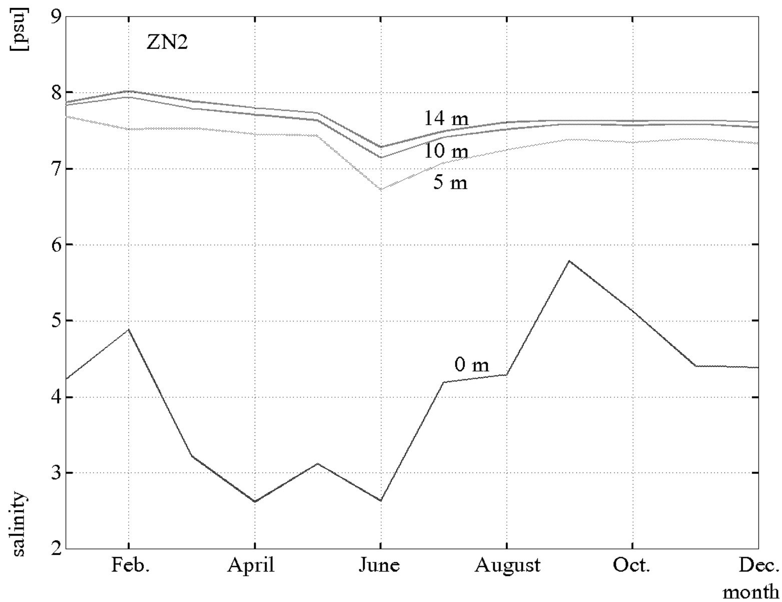


Fig. 1. Annual variation in seawater temperature at stations ZN2 and P110 at depths of 0, 5, 10 and 14 (15) m

a



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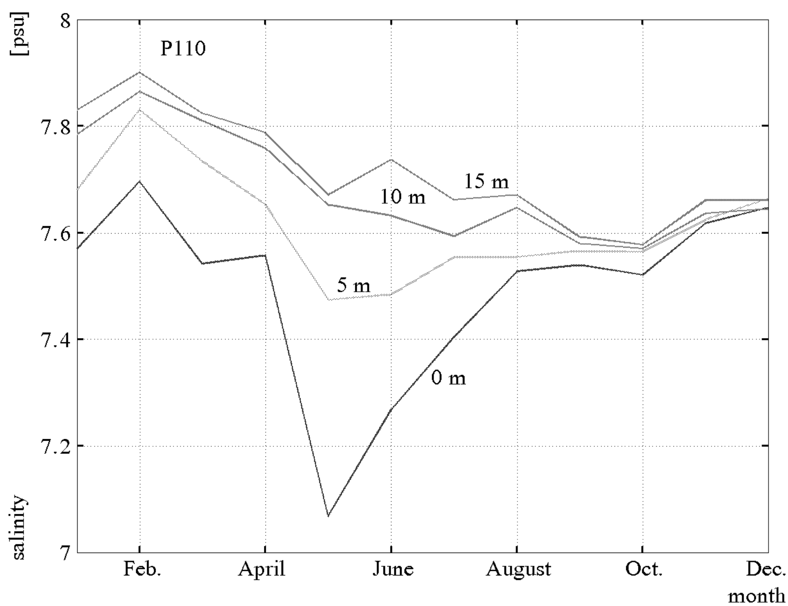


Fig. 2. Annual variation in salinity at stations ZN2 and P110 at depths of 0, 5, 10 and 14 (15) m

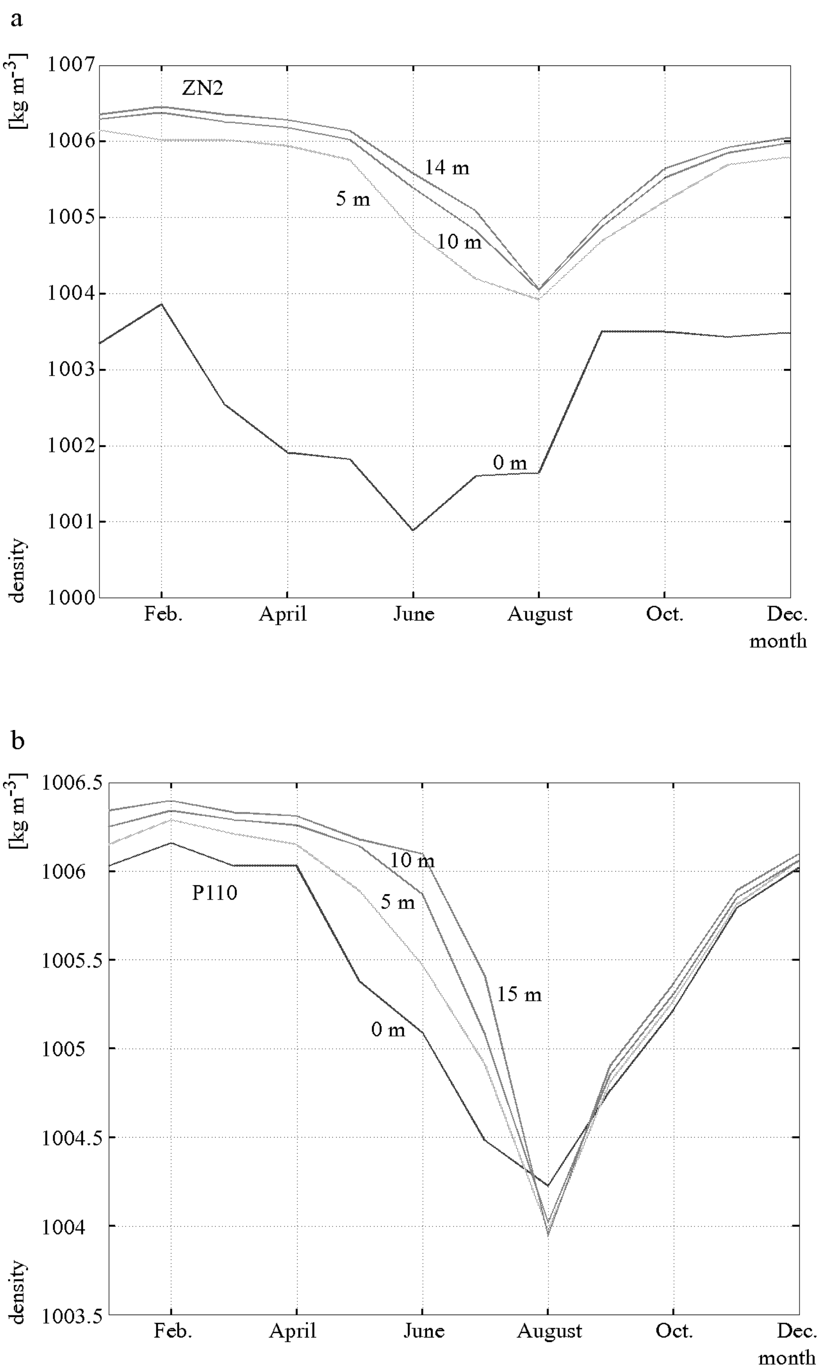
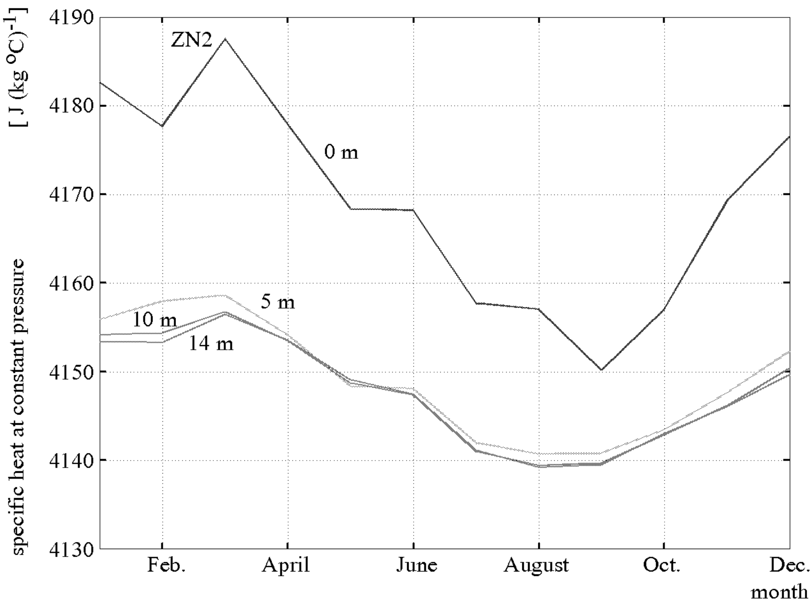


Fig. 3. Annual variation in seawater density at stations ZN2 and P110 at depths of 0, 5, 10 and 14 (15) m

a



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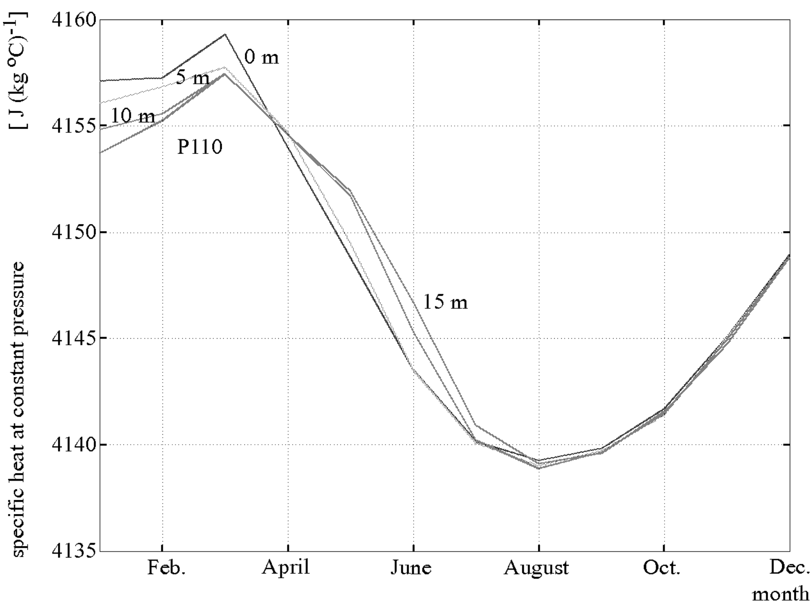


Fig. 4. Annual variation in specific heat at constant pressure of seawater at stations ZN2 and P110 at depths of 0, 5, 10 and 14 (15) m

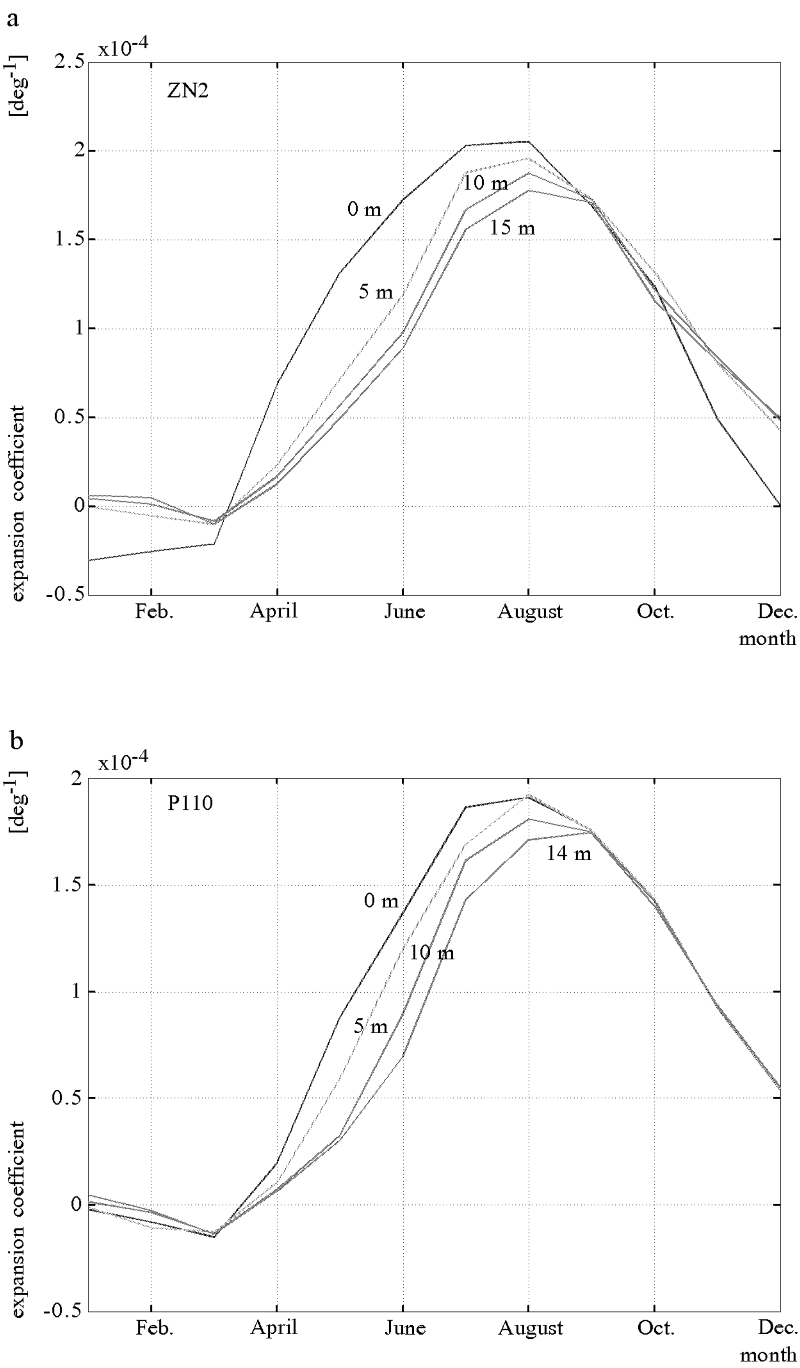


Fig. 5. Annual variation in the seawater expansion coefficient at stations ZN2 and P110 at depths of 0, 5, 10 and 14 (15) m

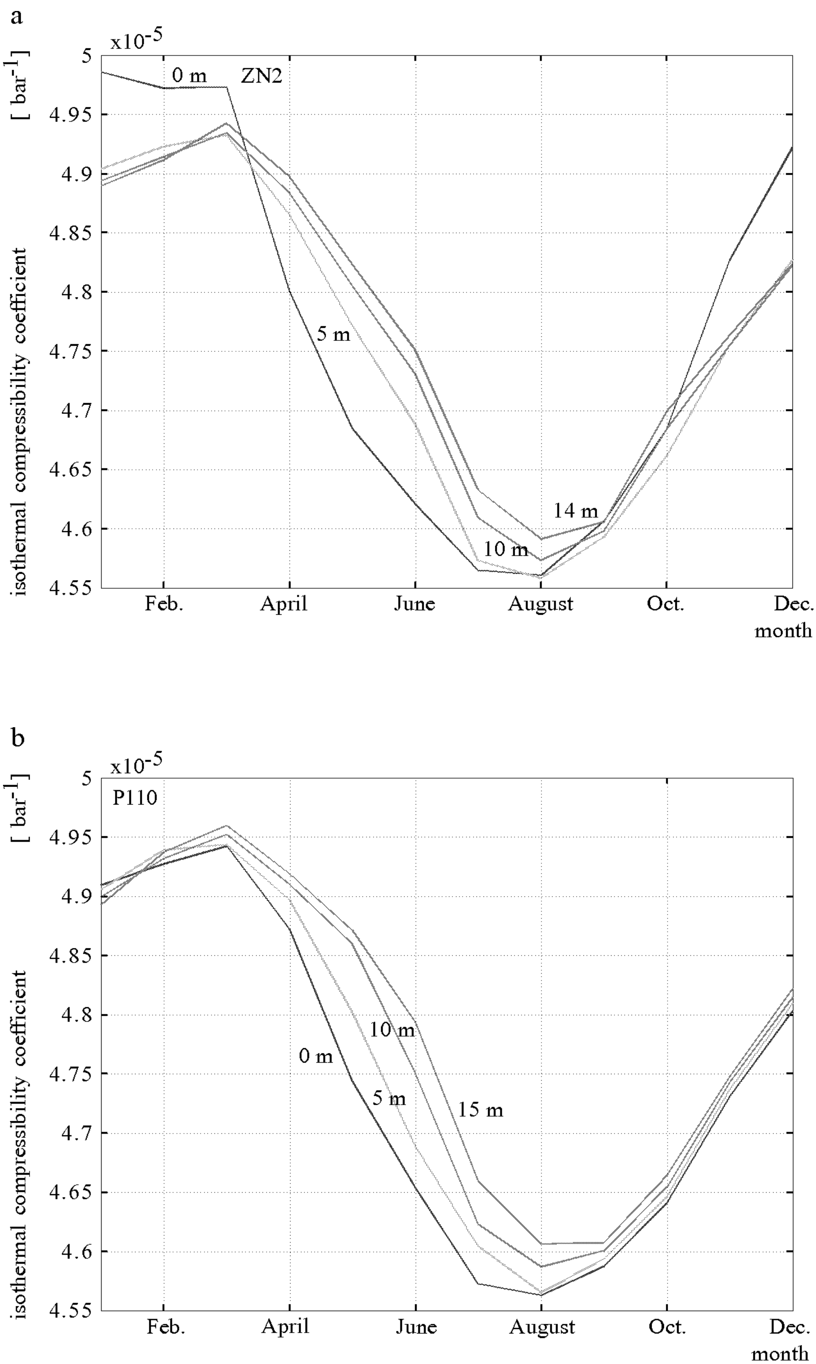


Fig. 6. Annual variation in the seawater isothermal compressibility coefficient at stations ZN2 and P110 at depths of 0, 5, 10 and 14 (15) m

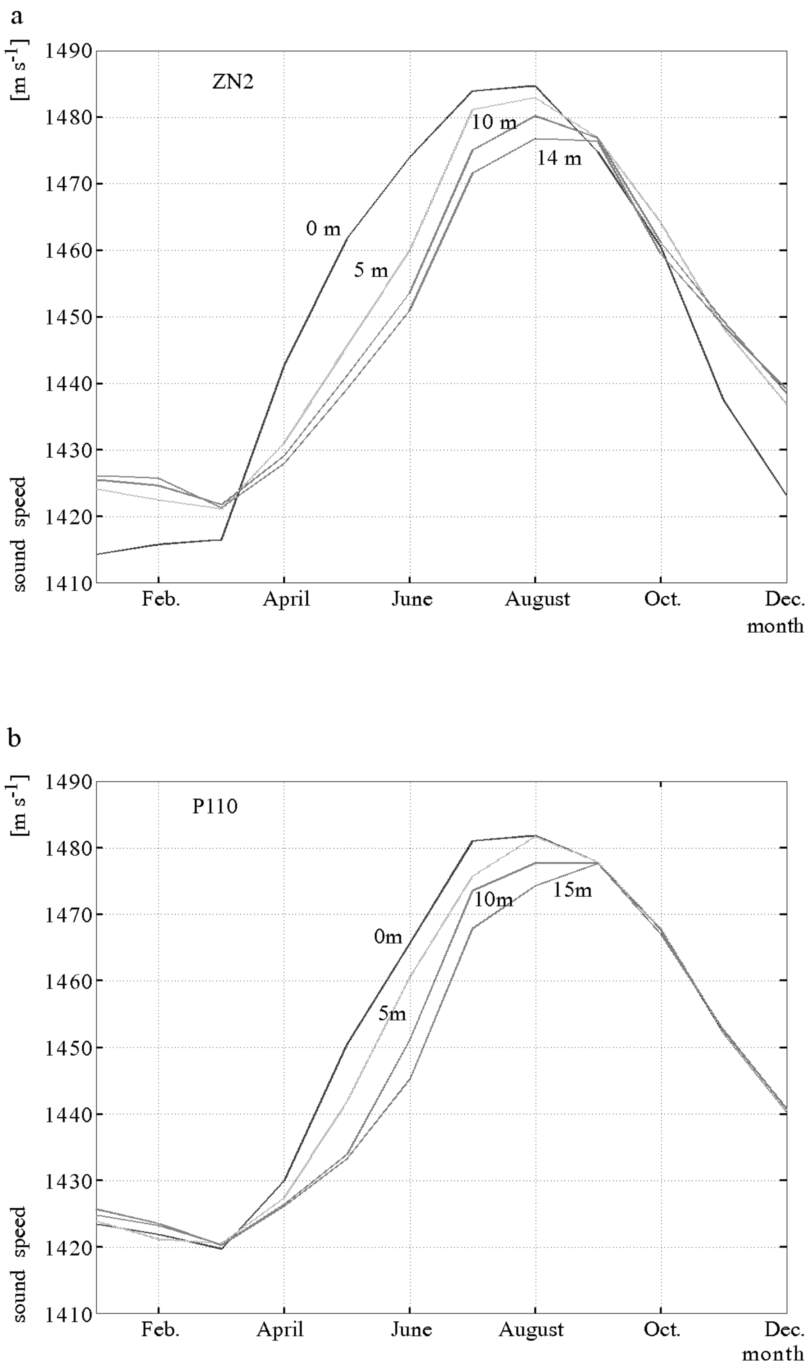
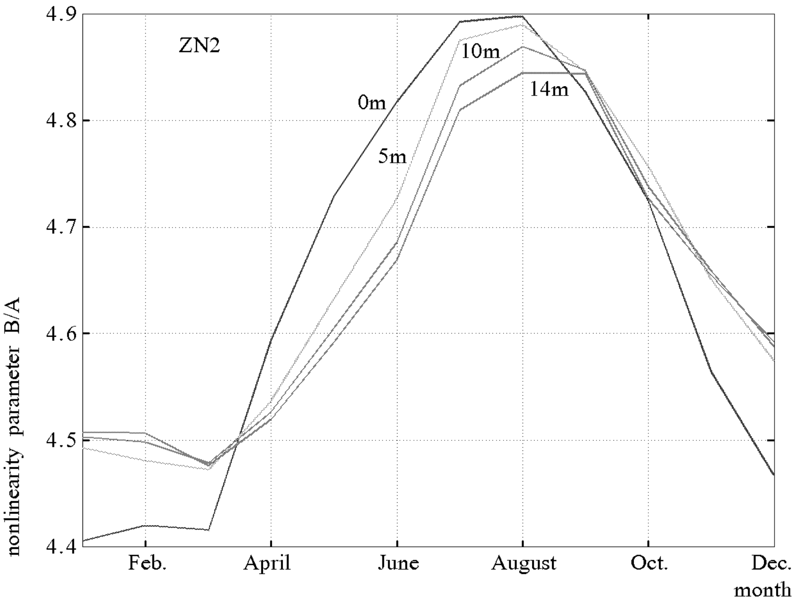


Fig. 7. Annual variation in the speed of sound at stations ZN2 and P110 at depths of 0, 5, 10 and 14 (15) m

a



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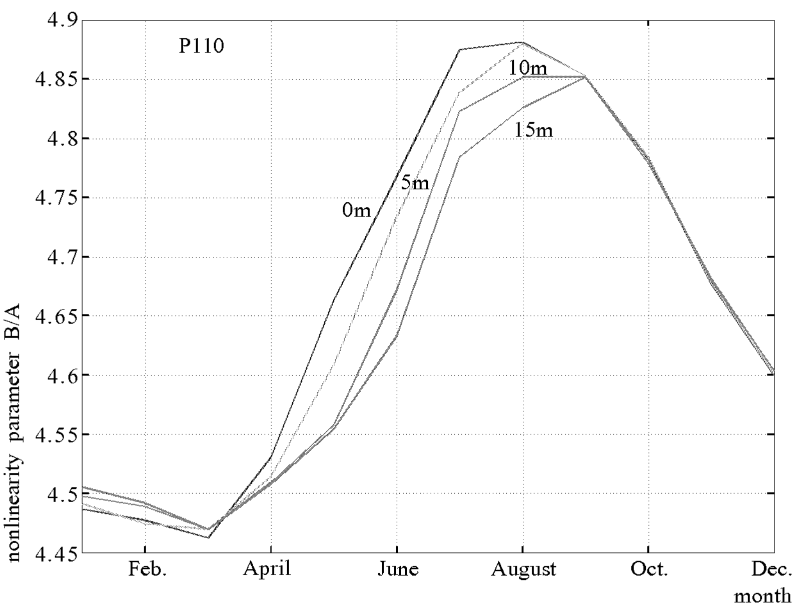

Fig. 8. Annual variation in the nonlinearity parameter B/A at stations ZN2 and P110 at depths of 0, 5, 10 and 14 (15) m

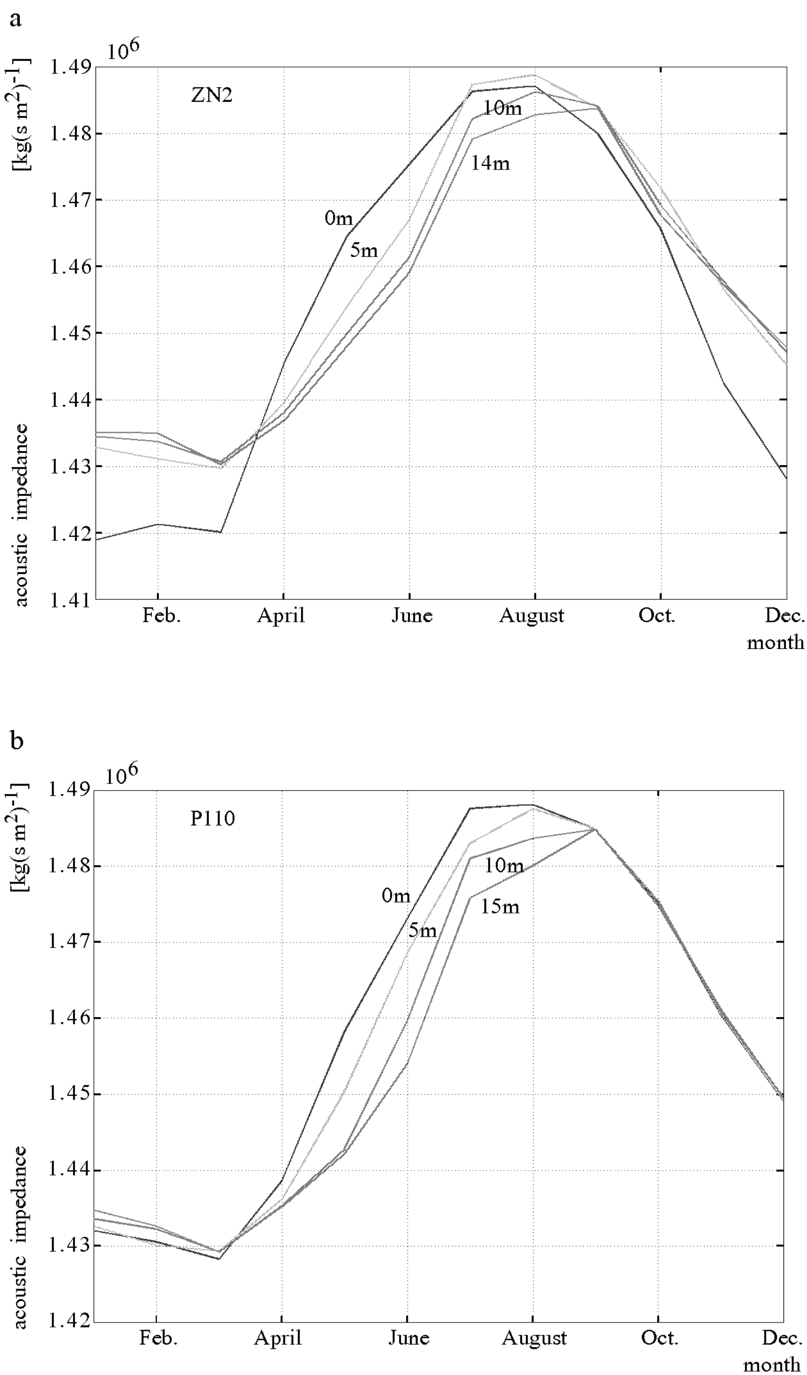

Fig. 9. Annual variation in acoustic impedance at stations ZN2 and P110 at depths of 0, 5, 10 and 14 (15) m

to the Vistula mouth is due to the faster cooling of the river water because of its lower heat capacity.

The influence of the Vistula's waters is evident in the annual variations in the thermodynamic and acoustic parameters. At the surface at station ZN2 the parameters significantly dependent on temperature, *i.e.* the expansion of seawater (rises with temperature) and its compressibility (decreases with temperature) take, relative to seasonal temperature variations, higher or lower values than the corresponding ones at 5 m depth and at the surface at station P110. The vertical distributions of acoustic parameters, *i.e.* the speed of sound, the nonlinearity parameter B/A and the acoustic impedance, are similar; they are not typical of the southern Baltic or of the Gulf of Gdańsk at sites more distant from the Vistula mouth.

Parameters significantly dependent on both salinity and temperature – density and specific heat are among the ones under consideration here – are discriminants of Vistula water only at the surface at ZN2. The density of the surface water off the Vistula mouth is < 1004 kg m^{-3} the whole year round (the minimum of the averaged values is 1001 kg m^{-3} in June). The density at greater depths at ZN2 is similar to that in the 0–15 m layer at station P110, varying from 1006–1006.5 kg m^{-3} in the winter months to 1004 kg m^{-3} in August.

The specific heat of fresh Vistula water entering the Gulf of Gdańsk ranges annually from *ca* 4150 J kg^{-1} deg^{-1} to over 4185 J kg^{-1} deg^{-1} and is higher than in deeper water by 10–27 J kg^{-1} deg^{-1}; the same applies to the specific heat of the water at station P110 in the 0–15 m layer.

4.2. The influence of Vistula water on the distributions of selected thermodynamic and acoustic parameters

The investigations of the Vistula's influence on hydrological phenomena in the Gulf of Gdańsk, the range of influence of its waters and how this is reflected by the distribution of individual acoustic and thermodynamic parameters were carried out under different hydrological conditions, on the basis of measurements conducted in April, July and November 1994.

The extent of the Vistula's influence was estimated from thermodynamic and acoustic distributions at the water surface and in planes parallel to it at depths of 5 and 10 m, and from distributions in vertical planes at selected profiles, determined by pockets of Vistula water come across during r/v 'Baltica's' cruises in 1994. Their positions are shown in Fig. 1 in Grelowski and Wojewódzki (1995).

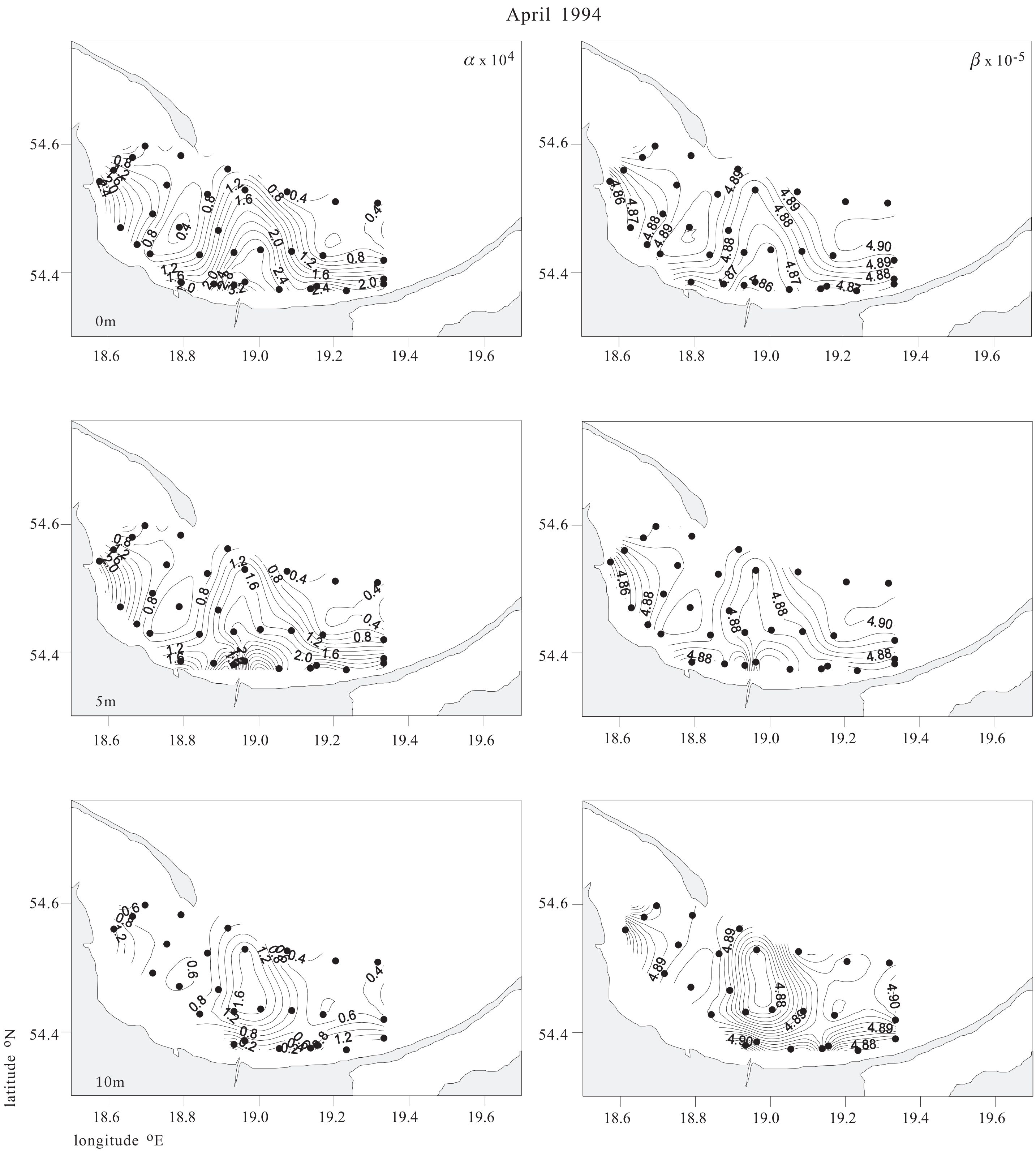

Fig. 10. Compressibility and expansion at depths of 0, 5 and 10 m (April 1994)

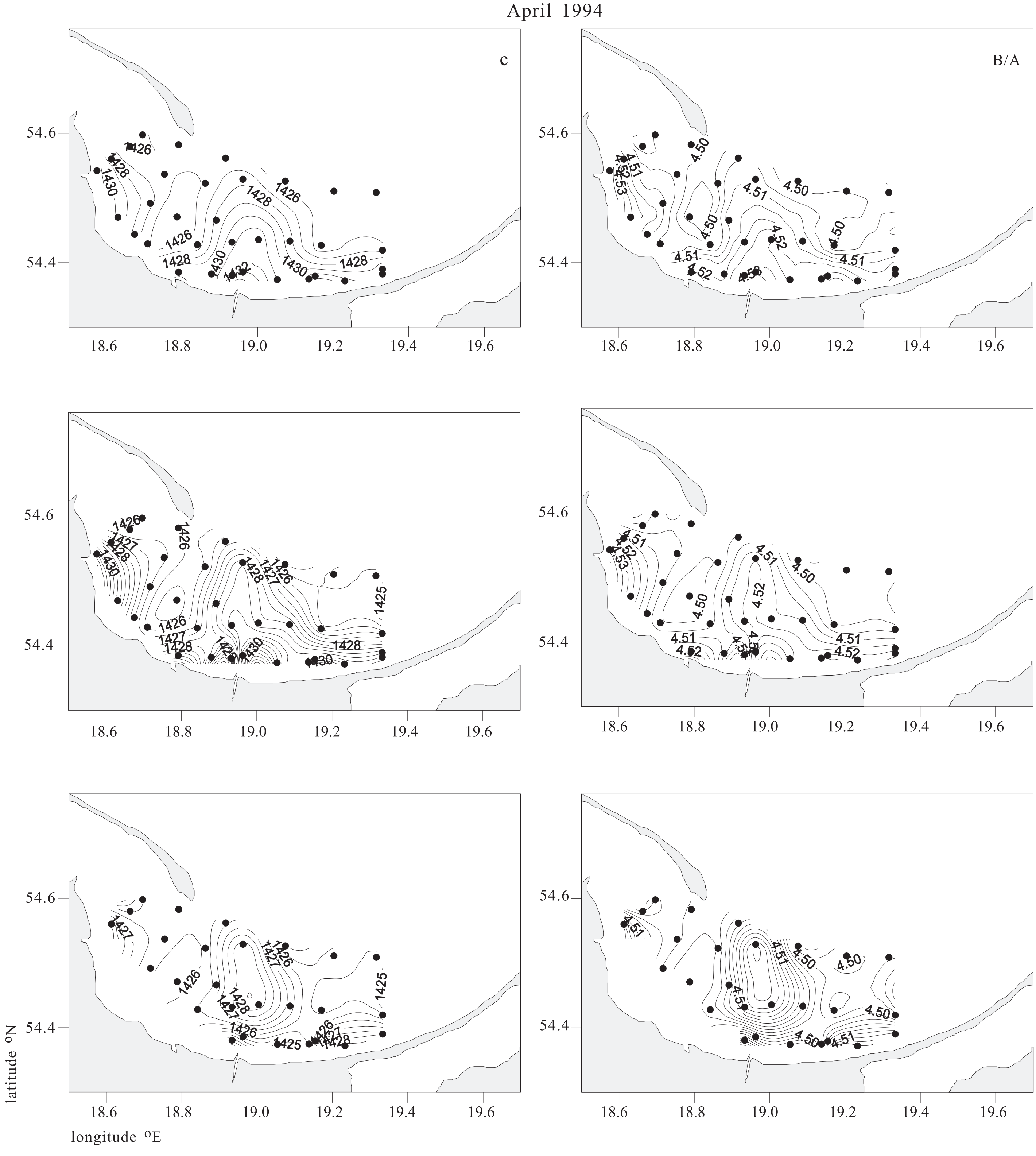

Fig. 11. Speed of sound and the nonlinearity parameter B/A at depths of 0, 5 and 10 m (April 1994)

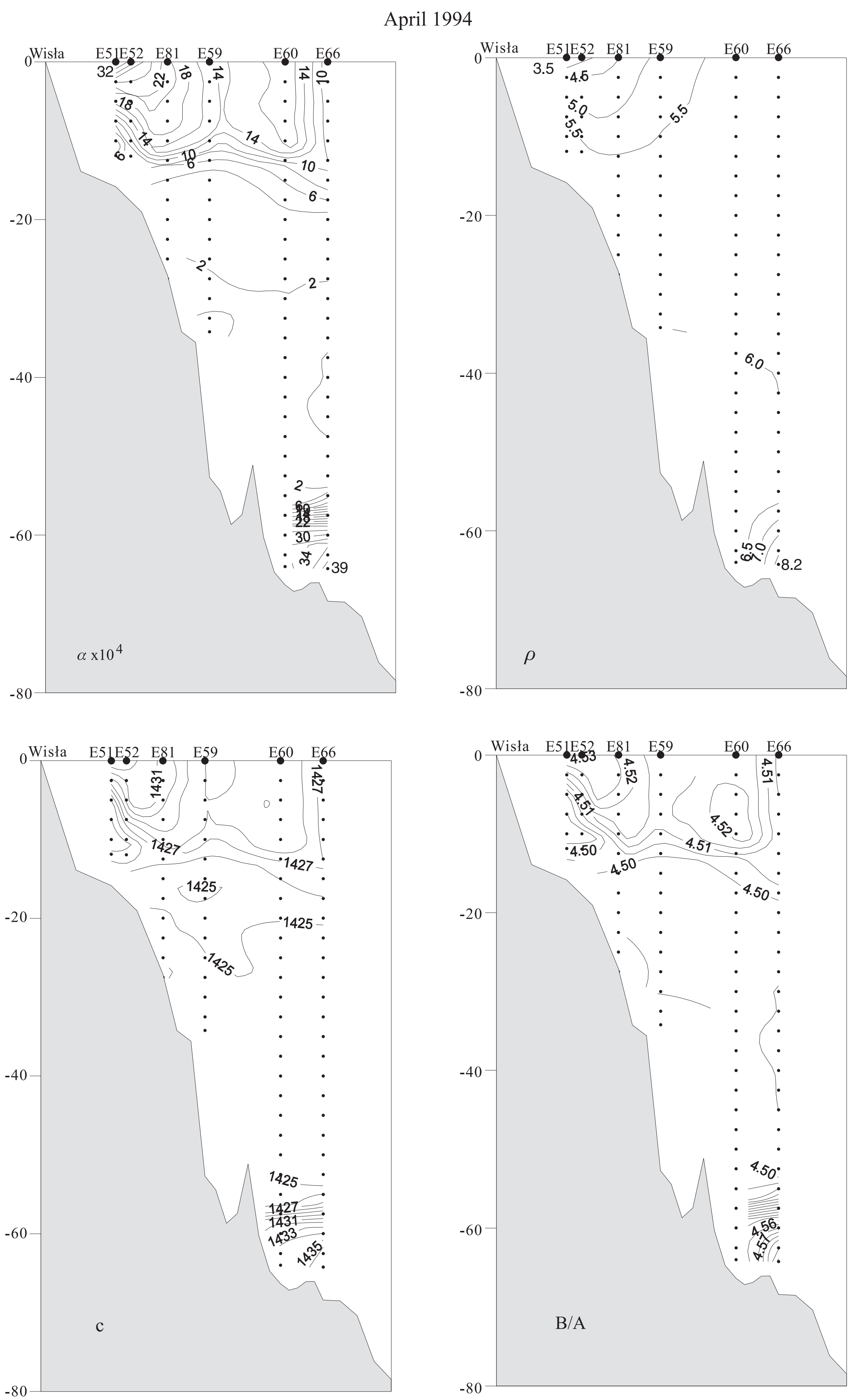

Fig. 12. Vertical distribution of expansion, density, speed of sound and the nonlineary parameter B/A in a profile extending northwards from the Vistula mouth

April 1994

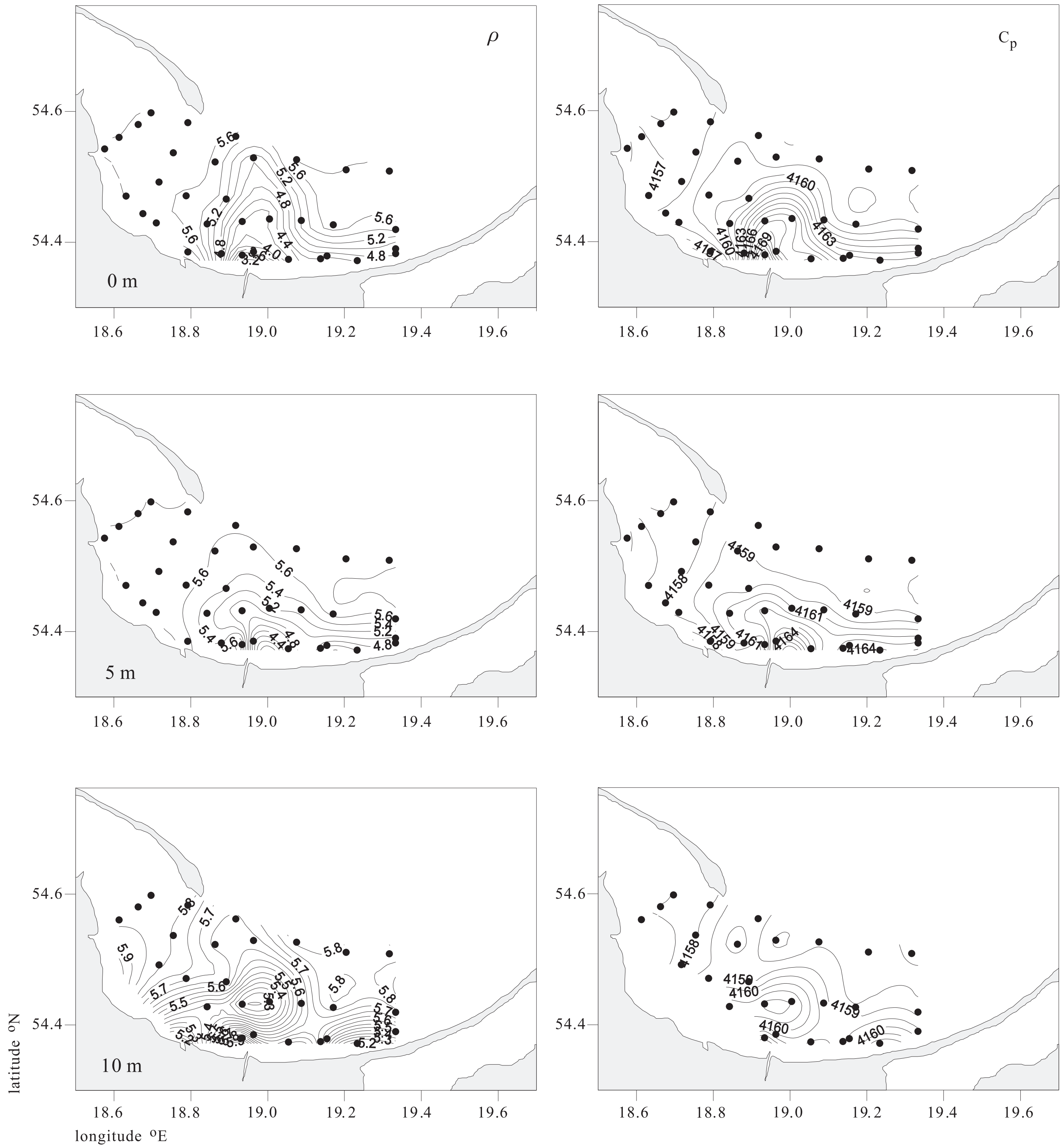

Fig. 13. Distribution of density and specific heat at depths of 0, 5 and 10 m (April 1994)

4.2.1. April

The hydrological situation of the Gulf of Gdańsk in April was characterised by an extensive area of Vistula water 12 m thick extending northwards from the Vistula mouth for a distance of about 12 NM. The influence of the warmer and less saline river water was reflected by the distributions of all parameters. The negative temperature gradient and the positive salinity gradient stretching northwards from the Vistula mouth were responsible for the configuration of the isolines of compressibility and expansion (Fig. 10), speed of sound and the nonlinearity parameter B/A (Fig. 11), illustrative of the area influenced by Vistula water. The surface distribution of the speed of sound shown in Fig. 11 is typical of early spring (Klusek, 1990).

The vertical range of Vistula water is evident in the distribution of these parameters in the horizontal cross-sections at depths of 0, 5 and 10 m and in the vertical cross-sections (Fig. 12).

The specific heat and density distributions are reflected only by the temperature gradient due to the Vistula's influence. At depths of 5 and 10 m, the increase in salinity causes the range of the limiting values of both

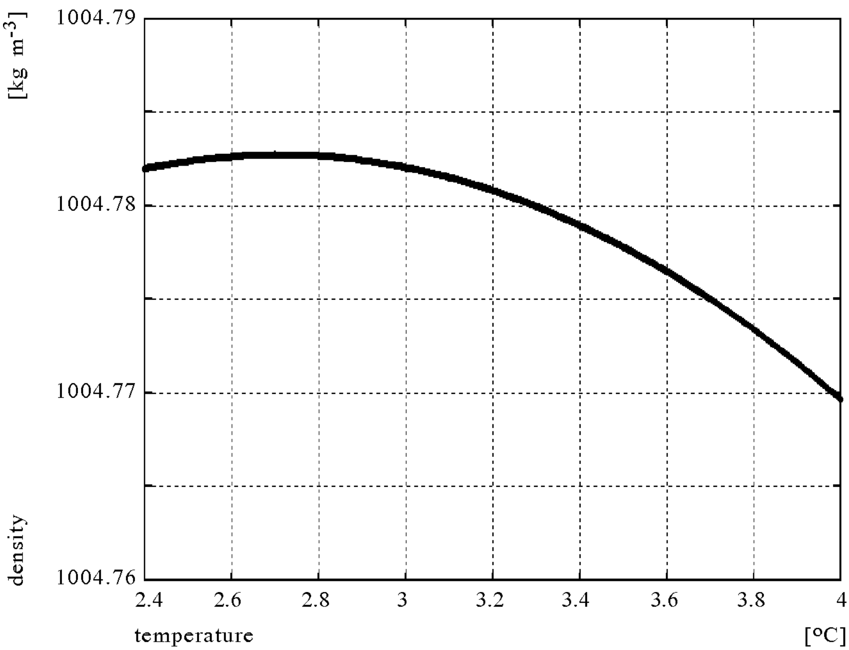

Fig. 14. Density of water of salinity 6 psu as a function of temperature

these parameters to decrease in a given synoptic situation. The density distribution at 5 m depth (Fig. 13) is especially interesting: the temperatures and salinity ranges recorded correspond approximately to the point of maximum density of seawater (Perry and Walker, 1982). In the 5 m layer the temperature changes from *ca* 3 to 4°C at salinity 6 psu. The corresponding changes in density are < 0.015 kg m^{-3}, (1.5×10^{-3} %) (Fig. 14). This causes the formation of a 0–15 m thick layer where the density is little different from that in the large area of the Gulf of Gdańsk (Figs. 12 and 13).

4.2.2. July

In July the characteristic aspect of the hydrological situation was the occurrence of a cyclonic vortex in the central part of the Gulf. The shape of the temperature and salinity isolines in the vertical cross-section (Fig. 5, Grelowski and Wojewódzki, 1995) of the profile extending northwards from the Vistula mouth confirms the upwelling of cooler water of higher salinity from a depth of 40 m towards the surface. This is evident from the distributions of the 14°C isotherm and 7.15 isohaline at 10 m depth; at the surface this is indicated by an area of cooler water (< 20°C) (Grelowski and Wojewódzki, 1995, Figs. 2 and 3).

The occurrence of this vortex was evidenced at the surface by the distribution of compressibility and expansion, as well as by the speed of sound and the nonlinearity parameter B/A (Fig. 15). The extreme values of the these parameters determine the centre of the area covered by the vortex. At the surface this determine is displaced northwards relative to the vortex centre at 10 m depth.

At this depth the vortex covers a far greater area than at the surface. Its range is readily apparent on the temperature distribution but not so much so on the salinity distribution, because it occurs in the isohaline layer, which is particularly extensive in the Gulf of Gdańsk, reaching down even to a depth of 80 m in the Gdańsk Deep. The area of waters affected by the vortex at 10 m depth is also clearly visible on the compressibility (Fig. 16) and expansion plots. Moreover, its influence on the speed of sound and the nonlinearity parameter B/A is clear. On the graph of density at 10 m depth the limits of the area occupied by the vortex are not indicated by a steep density gradient. However, its presence is betrayed by the closed isoline of the highest density ($>$ over 1500 kg m^{-3}) (Fig. 16).

In July, Vistula water can be distinguished in the Gulf of Gdańsk on the basis of the surface salinity distribution and at 10 m depth. Two areas of riverine water occurred: just off the Vistula mouth and in a narrow belt to the east.

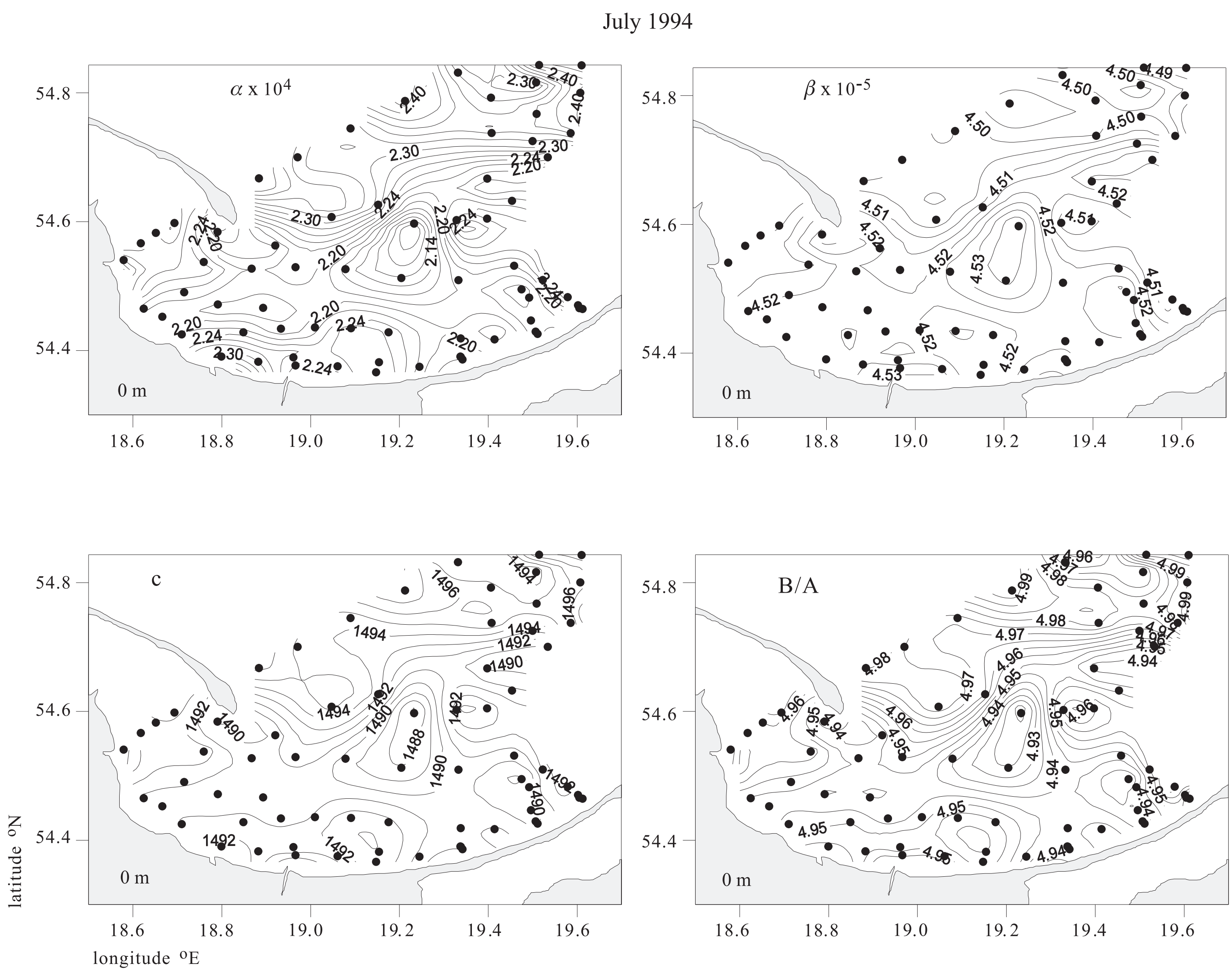

Fig. 15. Compressibility, expansion, speed of sound and the nonlinearity parameter B/A at the surface of the Gulf of Gdansk (July 1994)

July 1994

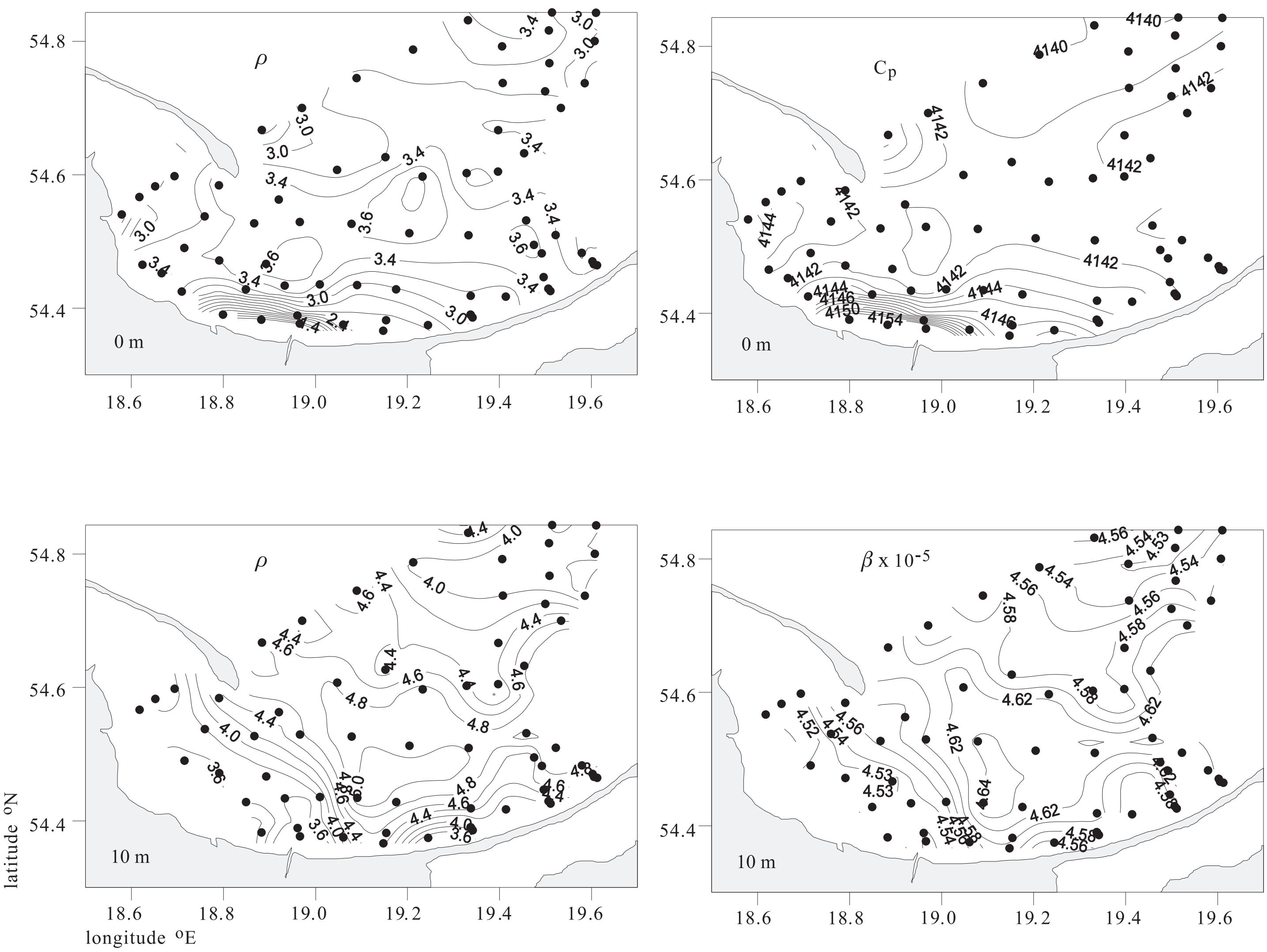

Fig. 16. Density and specific heat at the surface and compressibility at 10 m depth in the Gulf of Gdańsk (July 1994)

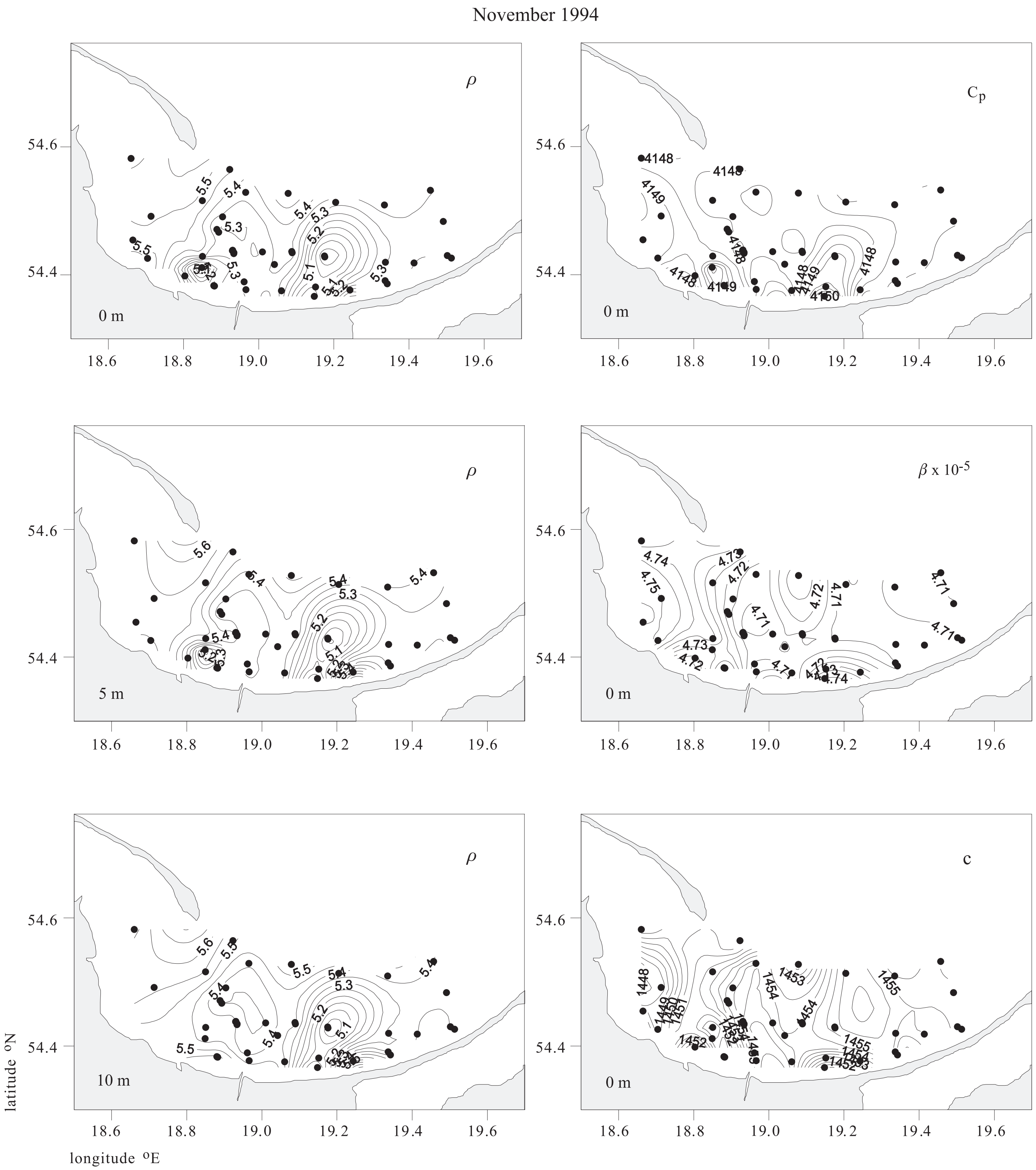

Fig. 17. Density at depths of 0, 5 and 10 m, and specific heat, compressibility and the speed of sound at the surface in the Gulf of Gdańsk (November 1994)

Less saline waters (from 6.5 to 7 psu at the surface and 6.9–7 psu at 10 m) occurred in the western part of the Gulf of Gdańsk in the basin delimited by the Vistula mouth, the tip of the Hel Peninsula and the shorelines of Gdańsk, Sopot and Gdynia.

In July, when the surface layer of water has been well warmed after a period of stable weather, Vistula water can be distinguished by its density and specific heat distributions (Fig. 16), both salinity-dependent parameters.

In summer, when weather conditions are usually stable, temperatures and salinities in the Gulf are little differentiated. Thus, thermodynamic and acoustic parameters are likewise little differentiated, so it is difficult, on the basis of their distributions, to delimit water masses or areas where hydrological phenomena occur.

4.2.3. November

There were two areas where the influence of Vistula waters was significant. The larger one was situated to the west of the Vistula mouth, the smaller one to the east. In both cases Vistula water was distinguished by salinity. The temperature variations within these areas were more complicated , and were illustrative of the basin's complex structure, which is linked to the original formation of these areas.

The water-temperature distributions at stations ZN2 and P110 averaged over the year (Figs. 1, 2) show that the temperature of inflowing Vistula water is lower than that of surface water in the Gulf in autumn. At the beginning of November this temperature difference is evident in the eastern pocket of water at short distances from the Vistula mouth. In the western pocket the temperature differentiation in the surface layer is less distinct, and Vistula water is scarcely distinguishable from the background of Gulf water.

At greater distances from the Vistula mouth, the temperature of the eastern pocket of water is much higher than that of Gulf water ($> 9.8°C$ at the surface, $> 10°C$ at 10 m depth). This anomaly testifies to the earlier formation of this part of the pocket, as the higher temperature of the less saline Vistula water in comparison to that of Gulf water is characteristic of earlier months.

Because of the temperature difference between these two pockets of Vistula water, it is difficult to determine their range from distributions of thermodynamic and acoustic parameters. The area of Vistula water is most readily apparent from its density distribution (Fig. 17).

Other parameters represent it less accurately. Their distributions are significantly dependent on temperature, so its higher values often determine the shape of isolines, unlike the salinity, which determines the limits of Vistula water. Despite a certain ambiguity in delineating the range of Vistula water, the origin of these waters can be traced by analysing the combined distributions of different parameters. In this hydrological situation, an area of lower salinity can be distinguished on the basis of distributions of density and, in part, of specific heat, whereas the cooler, inflowing water within this area is distinguished by the compressibility and expansion distributions. This area is also evident from the speed of sound and nonlinearity parameter B/A distributions.

5. Conclusions

The results of these investigations into the influence of Vistula water on the annual thermodynamic and acoustic conditions in the Gulf of Gdańsk have enabled certain characteristic aspects of sound propagation conditions in this basin to be described. They are reflected by the distributions of the speed of sound and the nonlinearity parameter B/A, and also those of the thermodynamic parameters on which the acoustic parameters directly depend. The water entering from the Vistula is visible as pockets situated close to the Vistula mouth. In synoptic investigations their position and the area they occupy depends on the hydrological-meteorological situation directly prior to measurements.

At station ZN2, off the Vistula mouth, the influence of fresh water is evident during the whole year. This is manifested in the thermodynamic and acoustic parameter distributions specific to this station, which differ from the typical values for the Gulf and is most clearly visible in the salinity distribution, which does not exceed 4 psu in the surface layer down to a depth of 5 m. The annual temperature variation in the surface layer is characteristic of Vistula water and, moreover, differs from the typical values for the Gulf. Because the water in the river bed warms up faster in the spring-summer period, the surface temperature of Vistula water is higher than that of Gulf water. On the other hand, in autumn and winter, the temperature of Vistula water is lower because it has cooled down faster. The different temperature and salinity distributions are reflected by the parameters under consideration. Temperature markedly affects the distributions of compressibility, expansion, speed of sound and the nonlinearity parameter B/A, whereas salinity influences the distributions of density and specific heat.

The distributions of all the parameters examined are helpful when analysing synoptic situations and assessing the extent of Vistula water penetration into the Gulf. Depending on the hydrological situation, which in turn depends on season and weather, the distribution of Vistula water is more clearly evident in the distributions of certain parameters. In a typical spring situation, the development of the temperature and salinity gradient gives rise to an essentially temperature – dependent gradient of parameters at the boundary between Vistula and Gulf water: compressibility and expansion, the speed of sound and the nonlinearity parameter B/A. The area covered by Vistula water is less well-defined by the specific heat and density distributions.

In summer, when the water temperature is high and little differentiated, the extent of Vistula water is better reflected by the distributions of parameters essentially dependent on salinity, *i.e.* density and specific heat.

The most complex situation occurs in the autumn, when the temperature and salinity gradients are such that the distributions of other parameters are less unequivocal. It is then that convectional mixing begins, as a consequence of which the differences between water parameters become smaller.

The results presented here illustrate certain short-term hydrological situations that have occurred. Because systematic investigations in this field are lacking, their results are comparable only with averaged distributions at selected points in the Gulf.

The distributions of acoustic parameters in the area influenced by Vistula water, the values of which differ from those typical of the Gulf of Gdańsk, indicate that this area must be investigated in order to assess the conditions for acoustic wave propagation there. Research into the variations in a range of thermodynamic and acoustic parameters seems to be justified, as combined analysis of these parameters allows the extent of Vistula water to be determined more accurately than an analysis of any one of them. It may be also useful in investigations into the origin of the Gulf's waters.

References

UNESCO, 1983, *Algorithms for computation of fundamental properties of seawater*, UNESCO Tech. pap. mar. sci., 44, 31–38, 46–50.

Beyer R. T., 1960, *Parameter of nonlinearity in fluids*, J. Acoust. Soc. Am., 32 (2), 719–721.

Chen C. T., Millero F. J., 1976, *The specific volume of seawater at high pressures*, Deep-Sea Res., 23, 595–612.

Coppens A. B., Beyer R. T., Seiden M. B., Donohue J., Guepin F., Hodson R. H., Townsend C., 1965, *Parameter of nonlinearity in fluids, II*, J. Acoust. Soc. Am., 38 (5), 797–804.

Dera J., 1983, *Marine physics*, PWN, Warszawa–Kraków, 92–119, (in Polish), [1992, Elsevier, Amsterdam–Oxford–New York–Tokyo, 357–371, (in English)].

Endo H., 1982, *Determination of the nonlinearity parameters for liquids using thermodynamic constants*, J. Acoust. Soc. Am., 71 (2), 330–333.

Endo H., 1984, *Calculation of nonlinearity parameter for seawater*, J. Acoust. Soc. Am., 76 (1), 274–279.

Gill A. E., 1982, *Atmosphere-ocean dynamics*, Academic Press Inc., Orlando, 39–43, 559–603.

Grelowski A., Wojewódzki T., 1995, *The impact of the Vistula River on hydrological conditions in the Gulf of Gdańsk in 1994*, Bull. Sea Fish. Inst., (in press).

Hartmann B., 1979, *Nonlinearity acoustical parameter B/A for liquids*, J. Acoust. Soc. Am., 65 (5), 1392–1396.

Klusek Z., 1990, *Sound propagation conditions in the southern Baltic*, Rozprawy i monografie, 1, Inst. Oceanol. PAN, Sopot, 23–29, (in Polish).

Kozaczka E., Grelowska G., 1994, *Nonlinearity parameter B/A of the low-salinity seawater*, Arch. Acoust., 19 (2), 259–269.

Millero F. J., Chen C. T., Bradshaw A., Schleicher K., 1981, *Summary of data treatment for the international high pressure equations of state for seawater*, UNESCO Tech. pap. mar. sci., 38, 99–108.

Perry A. H., Walker M. J., 1982, *The ocean-atmosphere system*, Wyd. Mor., Gdańsk, 159–161, (in Polish).

Sarkisov G. N., 1993, *Determination of the nonlinearity parameter B/A in theory of liquids*, Akad. Zh., 39 (3), 542–548, (in Russian).

Sharma B.K., 1983, *Nonlinearity acoustical parameter and its relation with Rao's acoustical parameter of the liquid state*, J. Acoust. Soc. Am., 73 (1), 106–109.