Changes in Conditions of Acoustic Wave Propagation in the Gdansk Deep as an Effect of Climate Changes in the Baltic Sea Region

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Type of paper: Research paper

ABSTRACT

The article presents the results from a research project investigating acoustic climate changes in the Gdansk Deep based on data extending from 1902 to 2019. This part of the southern Gotland Basin, is rarely discussed in the scientific literature.

The speed of sound in the seawater is a function of temperature, salinity, and depth. In such shallow sea as Baltic Sea, the impact of depth is not substantial. The other two factors shape the hydroacoustic conditions. In the upper layer of seawater, the dominating factor is heat exchange at the water-atmosphere interface. The observed climate warming is reflected in the water temperature rise, which results in an increased speed of sound in the upper water layer. After years of sporadic salty inflows from the North Sea, the frequency of the phenomenon has increased since 2014. As a result, the salinity at the bottom exceeds values typical for that area.

Keywords: Baltic Sea, sound speed in Baltic Sea, climate change influence on hydrological and hydroacoustic conditions in Baltic, saline water inflows from North Sea to Baltic

1. Introduction

Climatic changes in the Baltic Sea region and their environmental impact have been the subject of detailed studies for a number of years (Omstedt, 2017, Raisanen, 2017). Since the late 1990s regional climate models (RCM) have been refined, at first by individual countries from around the Baltic Sea, and since the year 2000, for the Baltic region as a whole as part of international projects. Initially they covered Scandinavia (Christensen et al., 2001) but succeeding models were expanded to include larger areas of Europe, among others, PRUDENCE (Christiansen et al., 2007), ENSEMBLES (van der Linden & Mitchell, 2009) or EURO-CORDEX (Jacob et al., 2014).

Research on climate change and its impact is carried out in all the countries of the Baltic Sea region. In order to bring together the results of these studies, in 2008 an international team of authors prepared a publication entitled *Assessment of Climate Change for the Baltic Sea Basin* (BACC Author Team, 2008). Seven years later *Second Assessment of Climate Change for the Baltic Sea Basin* was published (BACC II Author Team, 2015), which made use of new data collected since the first assessment. The two BACC publications deal with both past, as well as potentially future climatic changes in the Baltic Sea region and their environmental impact.

Detailed analysis of climate changes in the Baltic Sea region during the period of 1958-2009 was presented in the work by Lehmann et al. (2011). The authors pointed to a number of significant changes and trends in the region's climate. The specific period of global warming, which started about 1980 and continues until the present day, is also visible in the catchment area of the Baltic Sea. Detailed studies of climate variability and its impact on the Baltic Sea area in the years 1958-2009 demonstrated that the warming is connected with large-scale changes in atmospheric circulation over the North Atlantic. Both number and movement paths of deep cyclones had changed significantly, in accordance with the shift to the east of the North Atlantic Oscillation. A change in the season of strong winds was observed. During the period of 1970-1987 the winds dominated in the autumn (September to December), while in the years between 1988 and 2007, they dominated in the winter and early spring (January to March). Since the late 1980s, the winter season (December to March) in the Baltic Sea area was usually milder with reduced ice cover and higher temperatures of surface waters of the sea, particularly evident in the northern parts of the Baltic Sea. There was then, as there is now, a tendency of increased cloud coverage and precipitation in the regions exposed to westerly winds.

In the work *Second Assessment of Climate Change for the Baltic Sea Basin* (BACC II Author Team, 2015)2, Markus Meier collected data on anticipated climate change in the Baltic region for the years 2069 – 2098, comparing it with the data from the period of 1978-2007 and employing projection methods based on various numerical models. The forecast anticipates a 2-3°C water temperature increase of the surface water layer, and a 0-2°C increase in the deep water layers. The temperature increase will result in a drastic decrease of ice cover. Salinity in the top layer will fall due to substantial river discharge. However, according to one of the models, the transport of salt to the deep layers of the Baltic will remain unchanged.

In addition to creating numerical climate change models, other research methods which allow for climate change evaluation based on a combined indicator are being developed. The winter Baltic climate index WIBIX 1659-2002 proposed by Hagen and Feistel is derived, for the winter months (January-March) on the basis of air pressure difference anomalies between Gibraltar and Reykjavik, sea level anomalies in Landsort, and maximum Baltic ice cover. The WIBX index value points to a dominating type of climate, continental or maritime. Determining the power spectrum of the index for the period of 1659-2002 allowed for distinguishing five significant quasi-cycles of climate change: 2.3, 3, 6, 8 or 14 years (Hagen, 2005).

Recently, marine research has undergone considerable progress, connected with growing numbers of measurement stations, as well as the possibility of unrestricted access to meteorological and hydrological data bases for the scientific community. Measurement equipment is constantly improving, and numerical models are constantly upgraded thanks to the consideration of phenomena occurring in coastal zones, especially concerning the interaction between the land and the sea. As a result, development in the knowledge of such phenomena as the impact of large scale atmospheric circulation on the Baltic climate, and the dynamics of the Baltic Sea, is taking place. The development of physical oceanography is described in depth in the work by Omstedt et al. (2014).

Changes in natural conditions of the Baltic Sea, due to climate change as well as anthropogenic factors, are of crucial importance for development of biological life in the sea (Margonski, 2016). Marine organisms of the Baltic are particularly impacted by salinity and the halocline, temperature and the thermocline, oxygen, and light (Ojaveer, 2017).

The Baltic is not a typical sea, being of a semi-enclosed character and having a limited water exchange with the North Sea, which takes place solely through the Danish straits. As a result, the Baltic is a sea of low salinity and layered water structure. The upper layer is characterized by seasonal changes in water temperature and a low salinity of about 7 PSU in the south Baltic. The temperature of that layer depends on seasonal heat exchanges at the water-atmosphere interface. The bottom layer is much more saline – depending on the distance from the Danish straits, the salinity varies from 30 PSU to 10 PSU. The deep water layer is separated from the surface waters by a thin layer characterized by a clear-cut jump in salinity (halocline) and density (pycnocline). Despite the fact, that the halocline constitutes a barrier between the surface and the deep water, dynamic processes cause vertical mixing and transportation of salt into the upper layers of the Baltic. The salt is needed since the Baltic Sea is the catchment area of numerous European rivers and has a positive mass balance. Every single second the Baltic is on average supplied by over 15, 000 tons of freshwater from rivers and atmospheric precipitation, which mixes through the halocline with the deep water producing typical Baltic salinity (Radtke et al., 2019; Matthäus, 2006).

Water exchange with the North Sea and enrichment of the deep water layer with oxygen is of particular importance for the renewal of Baltic waters. It is also the subject of interest of Umgiesser (2016). It was observed that the saline waters from the North Sea reach the Bornholm Basin and the Slupsk Furrow in a continuous manner. These are the so called baroclinic inflows which are forced by the density difference between the Baltic and the North Sea waters. However, the volume of water transported in this manner is low and not sufficient for rejuvenating the Baltic Sea ecosystem (Mathaus, 1994), which requires large inflows to equalize the Baltic salt balance and ventilate the depths.

Major barotropic inflows are driven by the difference in sea levels from the Kattegat and the Arkona Basin. The inflows usually occur during the period of strong winds in the autumn and winter. They require a specific barometric system and atmospheric circulation: at first long-lasting easterly winds which stimulate the outflow of surface waters from the Baltic and lower the sea level, followed by a sudden reversal of the wind direction to a westerly one causing a compensatory water inflow through the Danish straits (Matthäus, 1996; Mohrholz et al., 2015). The duration and intensity of the westerly winds determine the inflow size.

The history of saline water inflows into the Baltic Sea, from the first reports until the year 2006, along with a description of atmospheric and hydrological conditions which accompany them was presented by Matthaeus (2006). In the past, five to seven inflows per decade were observed. In the years 1960-1980 the inflows occurred every three to four years, but in 1984 the phenomenon stopped occurring, resuming only years later in 1993 (Matthäus, 1994) and 2003 (Feistel et al., 2003). The situation experienced a significant change after 2014. In February and March of that year, two consecutive inflows occurred with the respective volumes of 140 km^3 and 200 km^3, with a succeeding record high inflow following in the winter of 2014 (Nausch et al., 2015). It is estimated that 320 km^3 of highly saline water from the North Sea poured into the Baltic (Mohrholz et al., 2015), being the third greatest of all the observed inflows. The only inflows exceeding it in size occurred in the winters of 1922 (258 km^3) and 1951 (225 km^3) (Fischer & Matthäus, 1996). The inflow observed in 2003 was only half as large. Successive major Baltic inflow events (MBI) occurred in the years of 2015, 2016 and in December 2018 (Nausch et al., 2019).

The inflow classification considers the volume of water which moved through the Belts and the Sound. Minor sized inflows are described as those under 100 km^3, moderate inflows 100-200 km^3 and major ones 200-300 km^3. Fisher & Matthaus (1996) defined the term of “major Baltic inflow event (MBI)”. According to their definition, the major events included only barotropic inflows which after 1984 had not been observed for over a decade. Lehmann & Post (2015) introduced the term “large volume changes (LVC)” to describe large inflows of water based on mean sea level. LVC does not always have to lead to MBI. The difference between MBI and LVC is that during LVC the water that enters the Baltic may be of relatively low salinity, while MBI is always associated with transport of water of high salt content, which is able to replace the bottom layer waters in the deep basins of the Baltic Sea.

The discrepancy between the frequency of major Baltic inflow (MBI) and low volume change (LVC) events, as well as the fact the Baltic salinity did not demonstrate any decisive trend despite significant reduction in the MBI number since 1980 (Matthaeus, 2006) captured the attention of Morholtz (2018) and convinced him to introduce a new classification of barotropic inflows. He proposed to take into account the inflows of shorter duration which also transport a large mass of salt into the Baltic Sea : DD1 – an inflow of saline water through the Drogden Sill in the Sound of at least one day, DS1 – saline water inflows through the Sound and at least a half-day long inflow through the Darss Sill, and DS5-inflows through the Darss Sill that last at least 5 days, roughly equivalent to MBI.

A barotropic inflow is a short duration phenomenon, which is accompanied by a substantial sea level difference between the Kattegat and the Arkona Basin. The phenomenon is employed in a new auxiliary method of determining the moment of inflow onset. The method is based on remote, satellite based observation of sea level anomalies (Stramska, 2019).

Recent studies based on the most up-to-date numerical models project a slightly increasing frequency of MBI events, along with warming climate and increasing sea level, in the transitional zone between the Baltic and the North Sea (Schimanke et al., 2014; Hordoir et al., 2015).

One of the rather rarely addressed physical oceanographical aspects of the Baltic Sea is the impact of changes in hydrological conditions on acoustic wave propagation. The observed substantial changes in spatial distribution of hydrological parameters in the Baltic result in an altered speed distribution of acoustic waves, which in turn shapes the conditions of acoustic wave propagation. Of course, conditions of acoustic wave propagation in any sea depend on a variety of factors, among the most important being, aside from the area of sound speed, the shape and type of the bottom sediments, as well as water depth (Blondel, 2009). In the case of a shallow sea environment, these factors cause the phenomenon of multi-path propagation, as well as reflection and dispersion of acoustic waves on water body boundaries (van Walree, 2013). However, geo-acoustic parameters of the bottom may be considered to be determined when compared to changes of hydroacoustic parameters caused by changes in hydrological parameters.

There are a number of reasons behind the interest in acoustic wave propagation. The principal one is to gain knowledge of the sea environment through acoustic methods (Wille, 2005, Serebryany, 2018, Przyborski, 2016), remote observation of marine flora and fauna (Martin, 2019), and assessment of climate change, especially based on temperature changes of the World Ocean (Darrell et al., 2007; Miziuno et al., 2016). Another one is the accuracy of depth measurement, seabed mapping or imaging of objects located beneath the water surface or at the bottom using acoustic methods (Savini, 2011; SeaBeam, 2000; Grelowska et al., 2017).

The phenomenon of refraction is caused by changes in the sound speed along the acoustic ray trace. The curving of the acoustic ray is the cause of errors in determining distance, for example (Witos-Okrasinska et al., 2018).In order to obtain accurate indications of multi-beam echosounders or side scan sonars, it is necessary to have knowledge about the distribution of sound speed during measurements and enter the appropriate corrections (Grelowska et al., 2018). Another area, for which acoustic conditions have even greater significance is the dynamically developing field of underwater communication (Kochanska, 2020; Nissen, 2016). In this case, information about the depth of the axis of the underwater channel, or determination of the path of the direct acoustic ray from the transmitter to the receiver, without reflections from the borders of the water environment, is of crucial importance. Another aspect, which requires knowledge of acoustic field distribution is the assessment of acoustic disturbance propagation. This issue became of particular significance after the introduction of the Marine Strategy Framework Directive, which requires conducting of systematic research of the environment of European seas and protecting the well-being of natural environment (HELCOM, 2018; HELCOM, 2019; Sigray et al., 2015; Mustonen et al., 2019, Humprey et al., 2019). In order to properly assess the acoustic disturbance generated by ocean engineering objects, operating ships, active sonars, and other sources of underwater sound, it is necessary to have information about the conditions of acoustic wave propagation in a given area (Kozaczka, 2018). In a situation when underwater research makes use of a new generation of hydroacoustic equipment developed based on the theory of non-linear acoustic wave propagation, it is also necessary to have information about the spatial distribution of the parameter known as the nonlinear parameter B/A, whose value also depends on the hydrological conditions (Grelowska et al., 2015, 2017).

The Bay of Gdansk constitutes the southern part of the Gdansk Deep, also sometimes referred to as the Gdansk Basin, which in turn forms a part of the Gotland Basin. In numerous works dealing with phenomena of the Baltic Sea, the main Baltic profile is taken into consideration: the Arkona Deep, the Bornholm Deep, the Slupsk Furrow, the Gotland Deep, and the Gulf of Bothnia. The data on the Gdansk Deep remains rather scarce.

This article describes changes in the hydrological conditions of the Bay of Gdansk which reflect the changes occurring in the southern Baltic and their impact on changing hydroacoustic conditions. Current data is presented with the background of the data from the period of 1902-2019.

2. Materials and method

The study made use of hydrological databases from the HELCOM collection which is available on the web site of the organization, as well as from the Polish Chief Inspectorate of Environmental Protection and our own research. Our own research was carried out in the spring-fall period from aboard s/y Freija - a 12 meter marine research vessel. Accurate positioning of the measuring unit on the navigational maps was ensured by a 12 channel GPS receiver equipped with a Garmin GPS 17x sensor of exact location, with the system accuracy of 3 m. Research safety was ensured by information obtained from the automatic identification system (AIS) and radar. Sound speed measurements were taken using a CastAway CTD instrument, its compact construction allowing for efficient conducting of sound measurements at specific depths. The instrument was also integrated with a GPS receiver facilitating cataloguing the collected profiles through their automatic assignation to individual fragments of the studied body of water. In comparison to the popularly used measuring modules, the transmission of the data recorded in the internal memory of the device is possible without the need to connect external cables, since it may be performed through the integrated, internal Bluetooth module. The instrument is capable of providing profiles to the depth of 100 meters. Based on the measurement of depth, temperature, and salinity, the software calculates the speed of sound using the Chen-Millero empirical formula. The accuracy of salinity, depth and temperature measurement is respectively 0.01 PSU, 0.01 m and 0.05°C, with a sampling frequency of 5 Hz. The instrument is equipped with a six-electrode conductivity cell sensor and fast thermistor with a response time of less than 200 ms, which allows for obtaining very accurate measurements of high resolution. The instrument is lowered to the bottom under its own weight and the resolution varies between 0.15-0.53 m depending on the speed of descent. The speed of sound values are determined based on information on vertical distribution of temperature and salinity using the Chen – Millero equation (Fofonoff, 1983).

3. Results

The processes occurring in the Gdansk Deep reflect the sum of phenomena taking place in the Baltic Sea, while the values of hydrological and hydroacoustic parameters depend on local conditions. The top surface layer is characterized by a salinity of 7.37 PSU and a temperature of 11.12°C (mean values at the surface determined for the entire year for the period of 1902-2019). The lowest surface water temperature of -0.27°C at the salinity of 7.61 PSU was recorded on January 24, 1963, and the highest, 23.57°C at the salinity of 7.20 PSU, on August 4, 2018. During that measurement, the water temperature was 24.88°C at the depth of 2.5 m - a record high in the history of measurements in that region. The lowest surface water salinity in the Gdansk Deep region in the period of 1902-2019 was 5.7 PSU at the water temperature of 12.48°C, as measured on April 29,2009, and the highest 8.13 PSU at the water temperature of 0.77°C on April 9, 1970.

The averaged salinity for the period of 1902-2019 in the deep water layer at the depth of 100 m is 12.003 PSU, and the average temperature 5.75°C, whereas the average values determined for the 50 year long period of 1960-2010 are 11.702 PSU in salinity and 5.71°C in temperature.

For the years 2008-2019 somewhat different average values were obtained. The salinity at the surface was 7.22 PSU, water temperature in February was 3.67°C at a salinity of 7.35, while in August the temperature reached 20.35°C at 7.18 PSU in salinity. At the depth of 100 m, the salinity was 12.18 PSU and the temperature 6.73°C.

Even this initial comparison signals the tendency of changes in both layers of the Baltic in the Gdansk Deep region: an increase of the surface water temperature both in the coldest and the warmest months accompanied by decreased salinity, as well as an increase of 0.48 PSU in salinity and 1.02°C in temperature at the depth of 100 m.

Based on archival data collected by HELCOM since 1902, it may be concluded that the lowest recorded water temperature in the Gdansk Deep region of -0.29°C at the water surface and a salinity of 7.48 PSU, was recorded on February 24, 1963, and the highest of 24.88 C at a salinity of 7.24 PSU (at the depth of 2.5 m) – was reported on August 4, 2018. The record high salinity at the bottom was connected with the largest inflow of saline water in the history of the Baltic since 1880 (Morholtz, 2018), which took place in November and December of 1951. On July15, 1952 it amounted to 15.59 PSU, with the inflow water temperature of 7.2°C. The maximum water temperature at the bottom of 9.45°C at the salinity of 11.59 PSU, was observed on November 20, 2002 and was connected with the warm inflow which directly preceded the cold MBO of 2003.

The speed of sound, which determines the accuracy of the underwater observation methods employing elastic waves, depends on both temperature and salinity. The complex spatial structure of temperature and salinity fields causes spatial changes in the distribution of the sound speed. In the upper layer, where salinity fluctuations during a year remain low over a period of years, the sound speed changes are directly proportional to changes in the temperature. The situation in the deep water layer is more complex, as an increase in salinity may be accompanied by a rise in water temperature, with both of these factors causing an increase in the speed of sound. Quite frequently, winter inflows are observed when along with increasing salinity the water temperature drops by as much as a few °C. In such as a situation, the impact of both factors is counteractive.

The speed of sound depends on the temperature and salinity, as well as, to a much lesser degree in the case of a shallow water, on depth. The range of changes in the speed of sound in the region of Gdansk Deep are presented in Table 1.

Table 1. Speed of sound in the region of Gdansk Deep for extreme values of hydrological parameters.

Surface					
Date	Depth, m	T, °C	S, PSU	c, m/s	Comment
	0	**11.12**	**7.37**	**1460.7**	1902-2018 Average
1963-02-24	0	**-0.27**	7.61	1411.3	Minimum temperature
2009-04-29	0	12.48	**5.70**	1463.7	Minimum salinity
2018-08-04	0	**23.57**	7.20	1500.8	Maximum temperature
2018-08-04	2.5	**24.88**	7.20	1504.3	Maximum temperature
1970-04-09	0	0.77	**8.13**	1417.1	Maximum salinity
Bottom					
	100	**5.75**	**12.003**	**1446.4**	1902-2018 Average
1963-08-11	100	**1.30**	10.75	1424.4	Minimum temperature
1990-06-24	100	5.53	**6.95**	1439.0	Minimum salinity
2002-11-20	100	**9.45**	11.59	1460.9	Maximum temperature
1952-07-15	100	7.20	**15.59**	1456.9	Maximum salinity

Due to the distance from the Danish straits, saline water inflows reach the Gdansk Deep with a certain delay. For instance, the inflow which took place in January 1993, gave the highest salinity value in the Gdansk Deep on June 29, 1993 - 12.160 PSU at the temperature of 5.06°C. However, the next inflow of December 1993 (Nehring, 1995) raised the salinity level in the Gdansk Deep to 13.01 PSU at the temperature of 5.28°C (April 1994), while the cold inflow of March 1994 (Nehring, 1995) changed the salinity at the bottom of the Gdansk Deep to 13.05 PSU at the temperature of 4.339°C (the lowest since 1989).

Waters of the untypical, warm, late summer inflow of the year 2002 (Feistel, 2013 b) were observed in the Gdansk Deep at the end of October of that year. The event was marked by an increase of the bottom temperature of over 2°C at the salinity of 11.69 PSU. The water from that inflow remained in the Gdansk Deep until February 2003 (S = 11.65 PSU, T = 9.00°C), after which it was displaced by cold water mass from the succeeding inflow of January 2003, which was classified as MBI (Feistel, 2003). As early as in March of that year, the temperature decreased to 5.88°C and the salinity increased to 12.49 PSU. The highest salinity value of 13.23 PSU was recorded on June 30, 2003 with the water temperature of 4.40°C.

Symptoms of the MBI which took place in December 2014 were observed in the Gdansk Deep in February 2015. – the increase in water temperature at the bottom from 5.95°C to 7.90°C at the salinity of 12.77 PSU. The highest salinity value of 14.292 PSU was recorded in March 2015. It was at the time the highest value documented since 1980.

After 2014, the situation in the Gdansk Deep changed significantly. The inflow of 2014 classified as the third largest MBI (Morholtz, 2015) led to a water exchange in the region and initiated a period of definite increase in the salinity of the deep water layer in the Gdansk Deep. Following 2014, no events classified as MBI have taken place, but saline water systematically enters the Baltic maintaining the salt content in the Gdansk Deep at levels which had not been seen earlier. Presented in Table 2 are the selected months of the period between 1980 and 2019, in which the salinity at the bottom exceeded 13 PSU. In addition, the table contains a few cases of somewhat lower salinity to provide a more comprehensive picture of the occurring phenomena. the salinity or the temperature at the bottom were the highest.

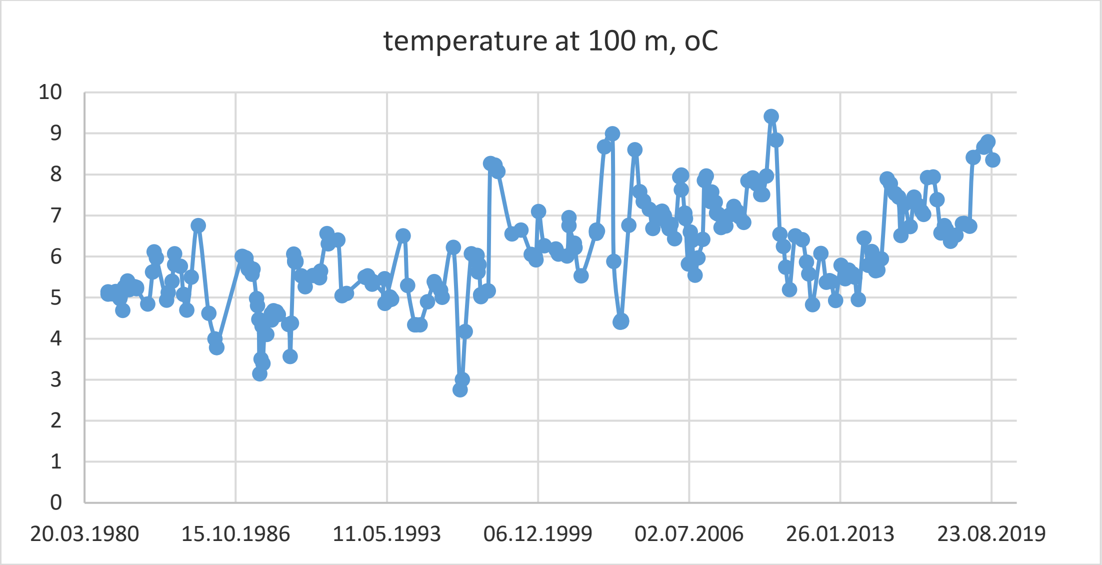
Table 2. Months in which the salinity or temperature at the bottom of the Gdansk Deep were the highest

Date	Temperature, ^{o}C	Salinity, PSU	Sound speed, m/s
2016-04-08	7.453	14.318	1453,1
2019-04-21	8.89	13.22	1460.7

3.1. Deep water layer

Salinity in the Gdansk Deep had remained lower than 12 PSU for many years. Inflows of water from the North Sea only occasionally resulted in the salinity increasing above 12 PSU. In the period from 1980 to 2015 there were only a few such cases. The first of them was the salinity level of 12.377 PSU recorded in March 1983. After a pause of nearly ten years, following two large inflows, the salinity once again broke the barrier of 12 PSU, reaching the value of 12.160 PSU in June 1993, and in the spring and summer of 1994 it even climbed over 13 PSU. It should be noted that the two inflows of 1993 brought cold water into the Baltic Sea. At the turn of 1997 and 1998, a mass of warm water of over 8°C in temperature and salinity exceeding 13PSU reached the Gdansk Deep. After a few years long period of stagnation, there was an in-pouring of saline water mass, recorded as the January 2003 inflow, which was preceded by the warm inflow of 2002. The inflow increased the salinity in the Gdansk Deep to 13.406 PSU. After that, once again there was an over a decade long period with no events which would provide a major rejuvenation of deep water in the Gdansk Basin. The inflow of December 2014 provide the Gdansk Deep with water of record high salinity of 14.217 PSU and a temperature of 7.786°C. Since that moment, a period of systematic transport of saline water into the Baltic Sea began, which was also evident in the Gdansk Deep. In 2015 and 2016 two MBI events which systematically replenished the salt content in the Gdansk Deep were observed (Naumann, 2019). In April 2016 the highest salinity level of 14.318 PSU was recorded. In the years that followed, barotropic inflows of medium intensity took place, supplying the Gdansk Deep to such an extent that the salinity did not fall below 12 PSU.

Attention should be paid to a certain anomaly regarding the temperature of the inflow water. Let us compare the properties of the saline water at the bottom of the Gdansk Deep in the two time segments of 1981-2000 and 2001-2019 (Fig.1).



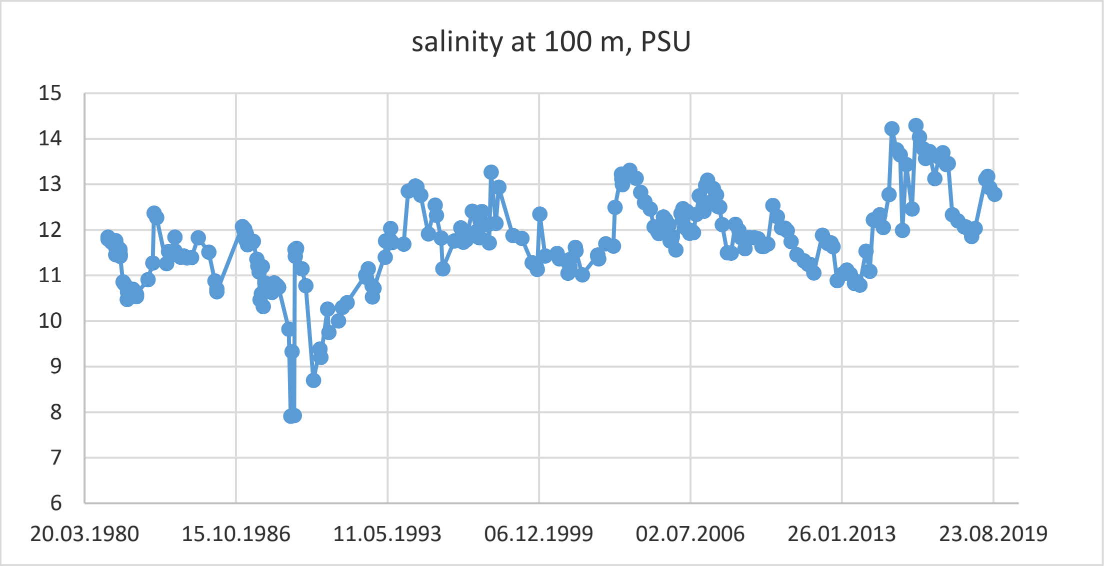


Fig. 1. Temperature and salinity in the Gdansk Deep at the depth of 100 m in the years 1981-2019

The difference between hydrological parameters in both of the periods is not large. A significant increase in both the salinity and the temperature is observed after the year 2000. The average temperature at the depth of 100 m for the entire period of 1981-2019 amounted to 5.95°C and the salinity to 11.74 PSU.

In the two-decade long period of 1981-2000, a single event of warm, saline water inflow was recorded in November 1997. As a consequence, the salinity of the water exceeded 13 PSU and the water temperature climbed over the 8°C mark. In other cases, the temperature did not exceed 7°C, and the salinity, even after the water inflow of 1993, did not reach the value of 13 PSU. The average salinity at the depth of 100 m for the period of 1981-2000 amounted to 11.35 PSU, and the temperature to 5.29°C.

The period of 2001-2019 is characterized by a markedly higher temperature of the deep water layer (the average value of 6.75°C is 1.46°C greater than in the prior period) and a decidedly higher salinity (the average value of 12.21 PSU being 0.86 PSU greater than in the preceding two decades). The high salinity value is connected with intensive transport of saline water in a number of inflows classified as MBI events (FM96) in 2003, 2014, 2015, 2016, 2017, as well as a series of DS5 and DS1 classified inflows. Attention should be paid to a significant increase in the water temperature of the deep layer. The only event which significantly lowered the temperature was the inflow of 2003, which brought a mass of 4.41°C temperature water into the Gdansk deep . All the other saline water inflows did not cause the water temperature to drop below 5.5°C, but instead brought in water masses of 8-9°C in temperature. Following the inflow of January 2010, which caused the temperature of the bottom water layer water to increase to 9.41°C, the period of decreasing deep layer water temperature came to an end. Its value oscillated from 5 to 6.5°C up to the end of 2014. The inflow of December 2014 caused an increase in the salinity to 14.22 PSU and initiated a period of in-flowing warm, saline waters which has continued until the present day. The salinity at the bottom has values between 12 to 14.29 PSU and is accompanied by high temperatures ranging from 6.5 to 9°C.

The speed of sound values varied in accordance with the changes in temperature and salinity, as shown in Fig.2.

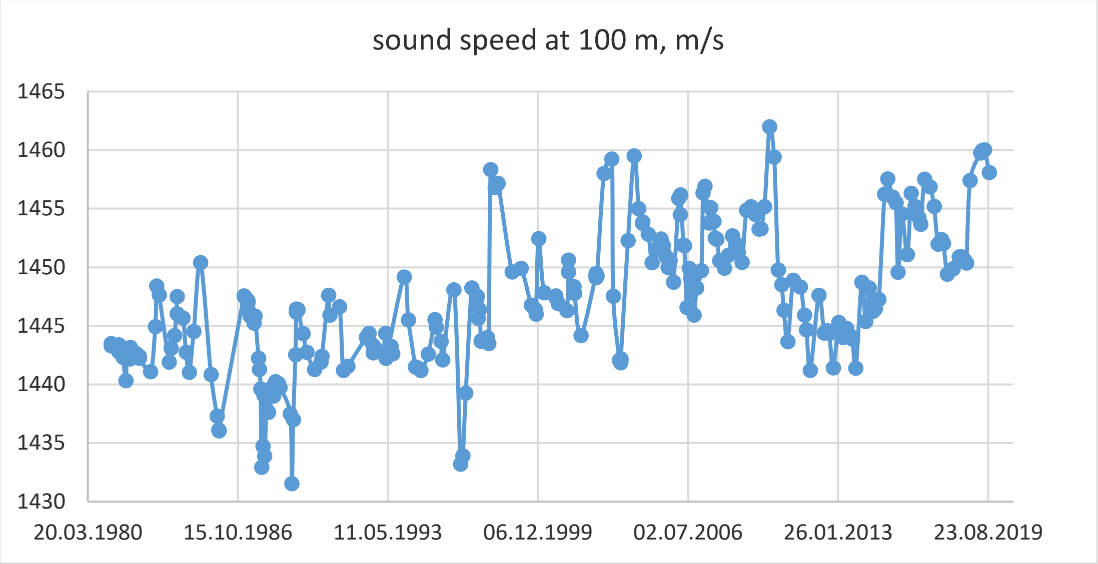
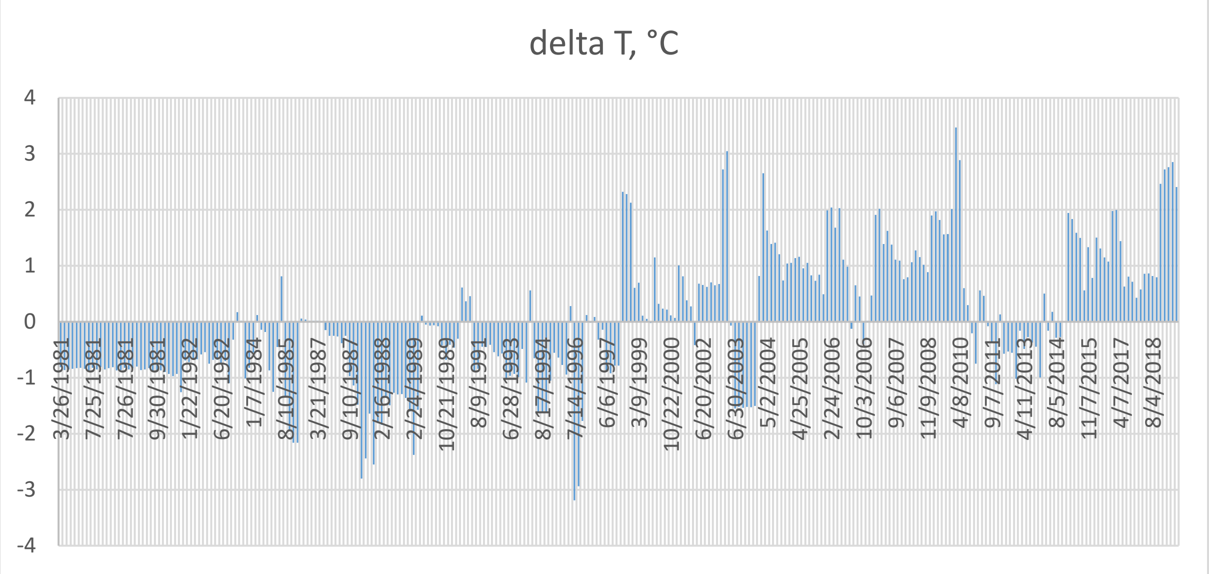


Fig. 2. Speed of sound in the Gdansk Deep at the depth of 100 m in the years 1981-2019

Relative standard deviation of temperature, salinity, and speed of sound at the bottom of the Gdansk Deep in the years of 1981-2019 is presented in the illustrations below.



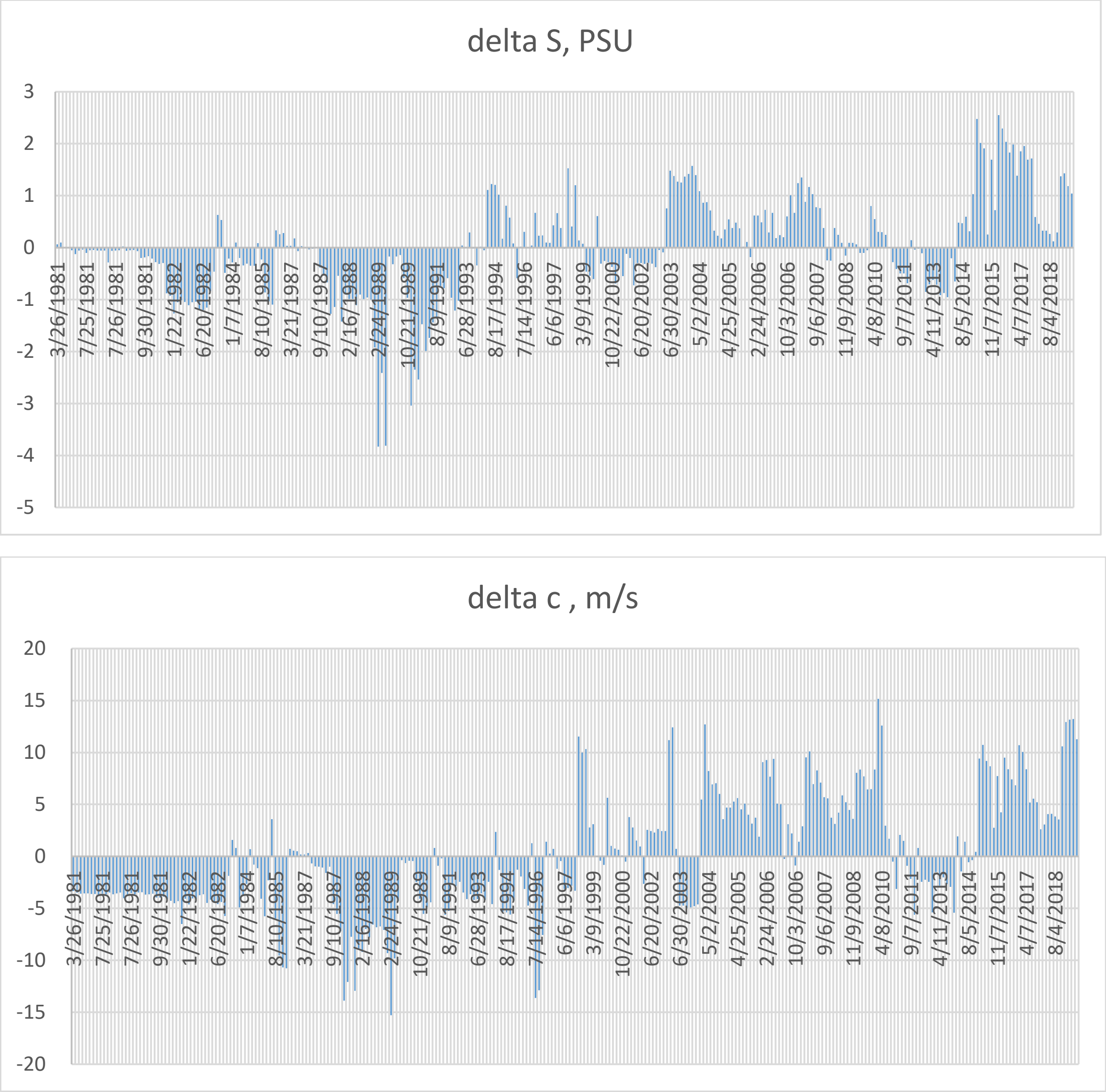


Fig. 3. Relative standard deviation of temperature, salinity and speed of sound at the bottom of the Gdansk Deep in the years of 1981-2019; average temperature value T = 5.95°C, average salinity value S = 11.74 PSU, average speed of sound value c = 1446.82 m/s

Change in the deep water layer characteristics in the analyzed forty year period is clearly noticeable. In the 1980s and the 1990s, which were a period of stagnation when the Gdansk Deep housed cool water of very low salinity. In the years of 1994-1998 a number of moderately sized inflows took place, which added to the increase in salinity but did not raise the water temperature. Only the 1998 warm water inflow, exceeding 8°C in temperature, raised the water temperature in the Gdansk Deep and initiated the period of high water temperature which, with just two exceptions, continues until the present day. The first exception was the cold inflow, classified as an MBI, having a water temperature of 4.41°C and a salinity of 13.16 PSU, which reached the Gdansk Deep in July 2003. However, directly after it, a surge of warm water began entering the Baltic raising the bottom water temperature, which, as soon as in February 2004, reached nearly 9°C (8.60 PSU). The next pause when the water temperature had moderate values, little different from the average value, was the period which began after the warm water inflow at the start of 2010 (T = 9.42°C, S = 12.54 PSU) and lasted from June 2010 till the end of 2014. During that time, the water temperature changed from 5 to 6.5°C and the salinity from 11 to 12

PSU. Since the warm water inflow, which reached the Gdansk Deep at the beginning of 2015, there has been a continuous uninterrupted period in which the temperature and salinity of the deep water layer have taken on values which are markedly greater than the 40 year average. These hydrological anomalies have an impact on the speed of sound values which, since November 1997, have been greater than the average value at the bottom with two exceptions connected with the periods of lower temperature mentioned above.

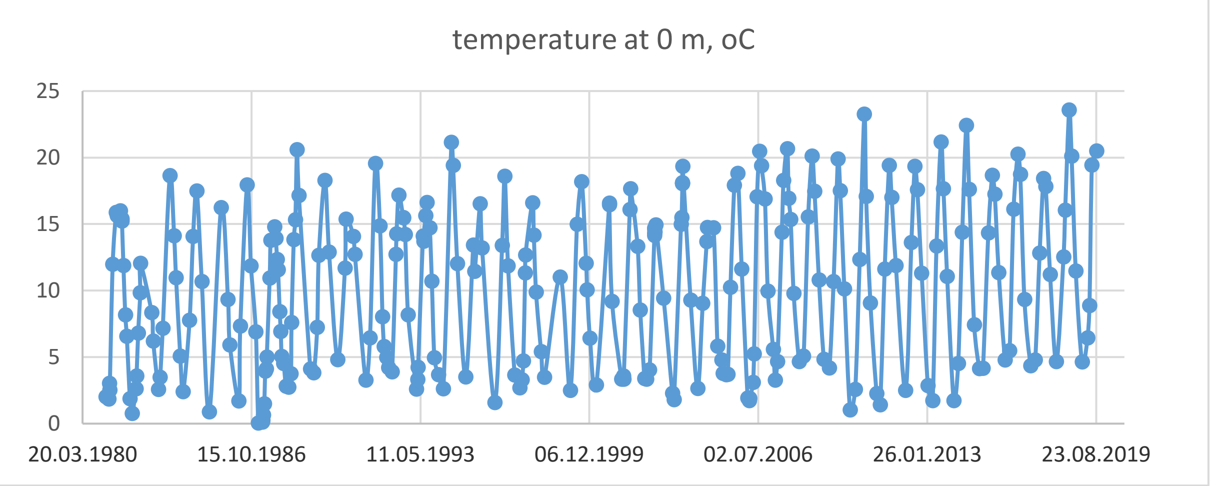
3.2. Water surface

Hydrological conditions of the surface water layer depend to a substantial degree on the changes in air temperature, as well as on the inflow of freshwater in the form of precipitation and river water discharge. The average salinity for the years 1980-2019 amounts to 7.37 PSU which is the same as the average salinity since the year of 1902. However, when the period between 1980 and 2019 is taken into consideration, then significant changes become apparent.

Table 3. Hydrological and hydroacoustic parameters of the water surface, average values with no division by season.

Period	T, °C	S, PSU	c, m/s
1981-2019	10.301	7.331	1455.7
1981-2000	9.357	7.423	1452.4
2001-2019	11.355	7.228	1459.4

The averaged surface water temperature was approximately 2°C lower and the salinity nearly 0.2 PSU higher than in the period before. In the years between 1981-2000 the summer season water temperature exceeded 20°C only twice, with the highest recorded water temperature of 21.15°C. Between 2001 and 2019 there were ten cases of the water temperature exceeding 20°C, with the highest value being 24.88°C. In the winter season in the first of the periods in question, the water temperature was lower than 1°C on four occasions, with the lowest value being 0.04°C. After the year 2000, the water temperature did not fall below 1°C even once, with the lowest recorded value of 1.027°C. The speed of sound which depends on a combination of temperature and salinity, exceeded 1490 m/s eleven times in the period following the year 2000, with the record high of over 1500 m/s recorded in 2018. In the period of 1982-2000, the speed at the surface exceeded 1490 m/s only twice.



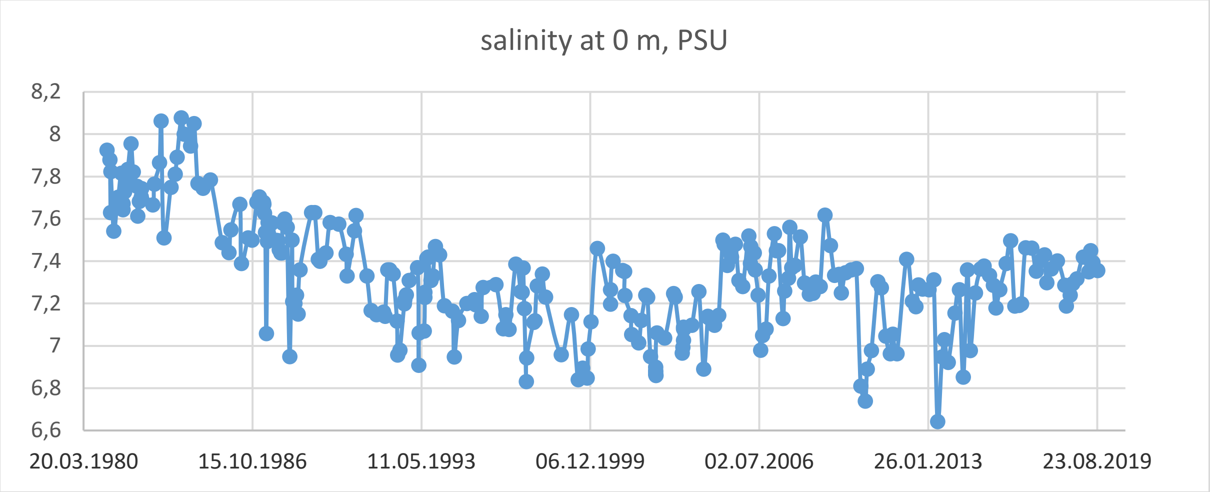


Fig. 4. Surface water temperature and salinity changes in the period of 1981-2019

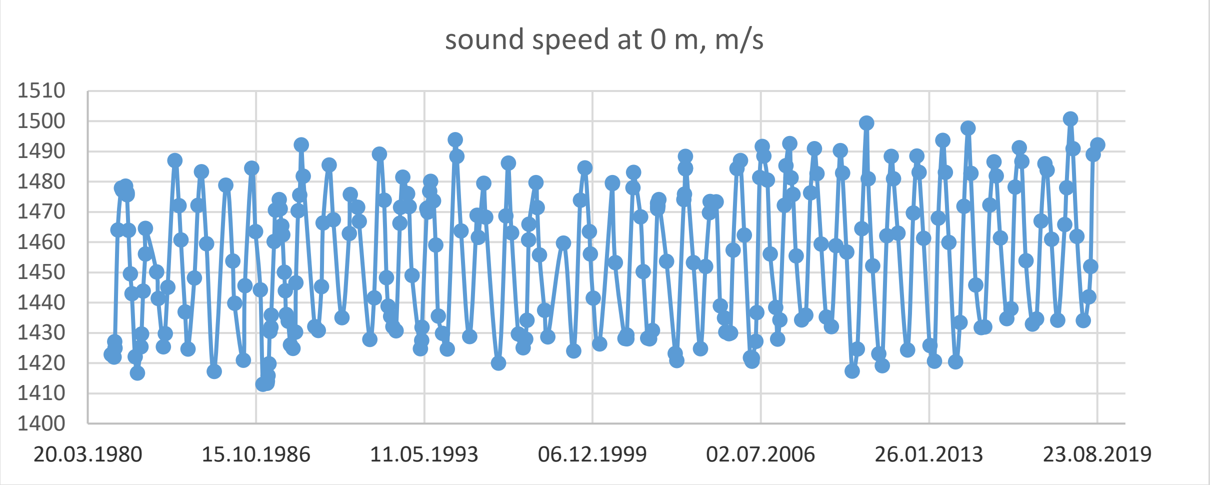


Fig. 5. Speed of sound changes in surface water in the period of 1981-2019

3.3. Vertical distribution

The Baltic is a shallow sea which is unique in its density and thermohaline structure. The water entering the Baltic from the North Sea is of greater salinity and also often of higher temperature than the deep water layer and, thanks to its greater density, creates a bottom density current which moves along the Baltic depths. In the Gdansk Deep region, the conventional density σ adopts the average values of approximately 9 kg/m^3 at the bottom, and following an intensive inflow, the values may exceed 10 kg/m^3. At the surface, in the winter period, the conventional density σ is 5 to 6 kg/m^3, and in the summer season, at high water temperature, it may even fall lower than 3 kg/m^3 (Fig. 6). The quantity called σ is defined by

$$\sigma = 1000\left(\left({}^{\rho}/_{\rho_m}\right) - 1\right),$$

Where ρ/ρ$_m$ is the specific gravity, ρ$_m$ is the maximum density of pure water, ρ$_m$ = 999.975 kg m^{-3} (Gill, 1982).

Heating of the upper water layer in the spring-summer period causes the creation of a minimum in the vertical distribution of temperature, and as a consequence an underwater acoustic channel at a depth of about 60 meters (Fig. 7).

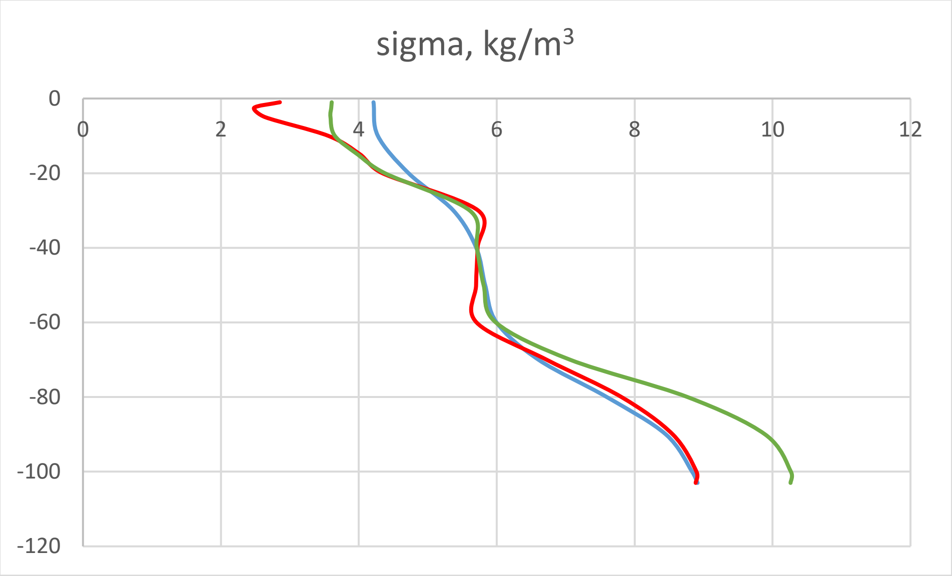
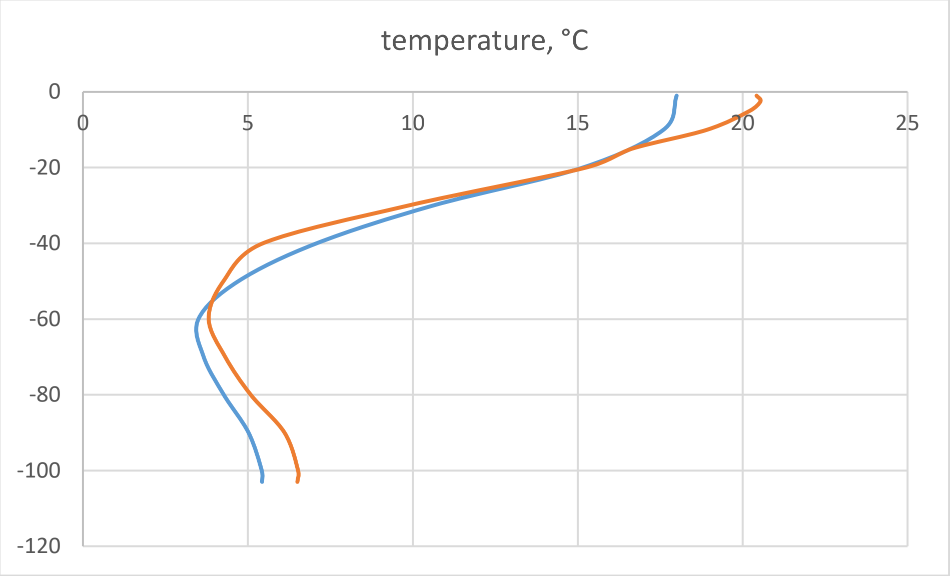


Fig. 6. Conventional density σ in the Gdansk Deep region in August: blue – averaged for the period of 1960-2010, red – August 2018, green – August 2016



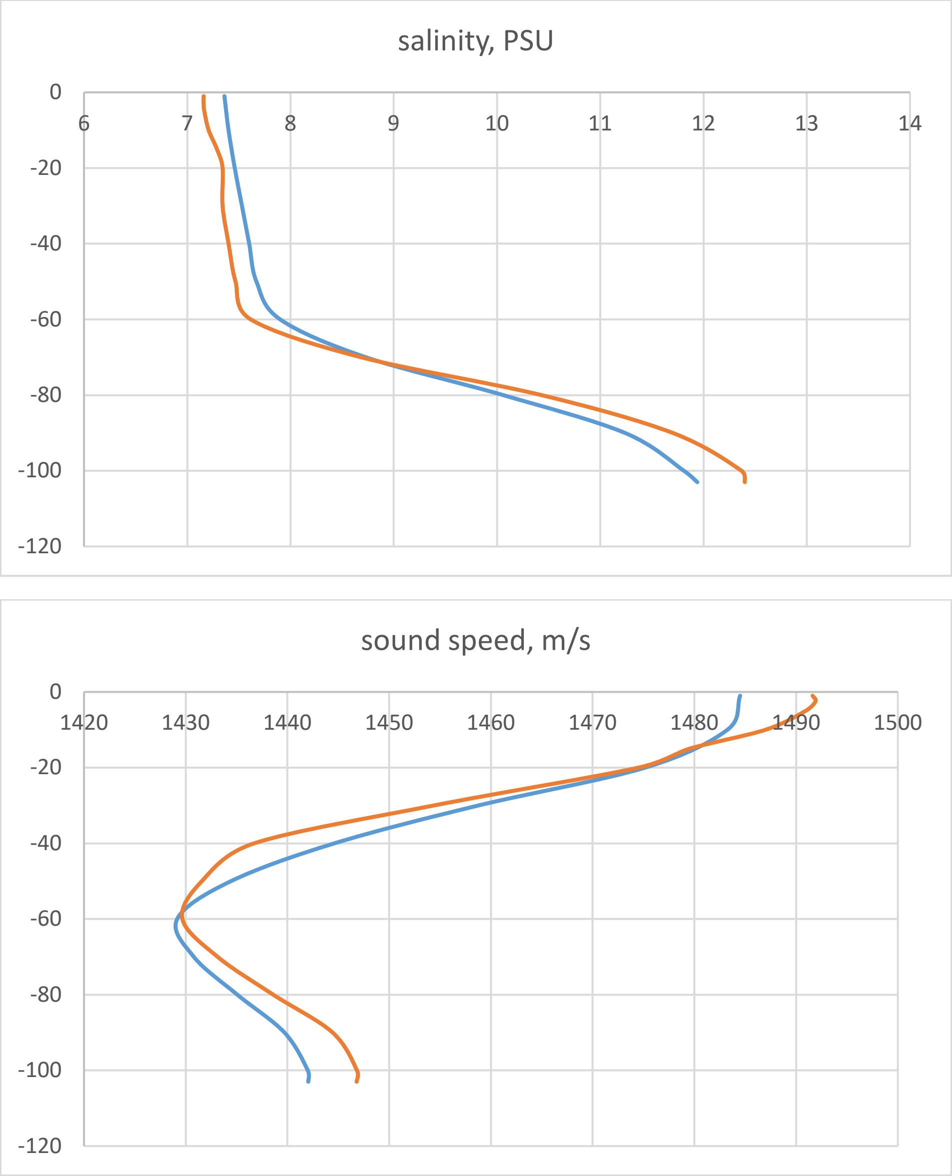


Fig. 7. Vertical temperature, salinity and speed of sound distributions in the Gdansk Deep region (blue – averaged for the period of 1960-2010, orange – averaged for the period of 2010-2019)

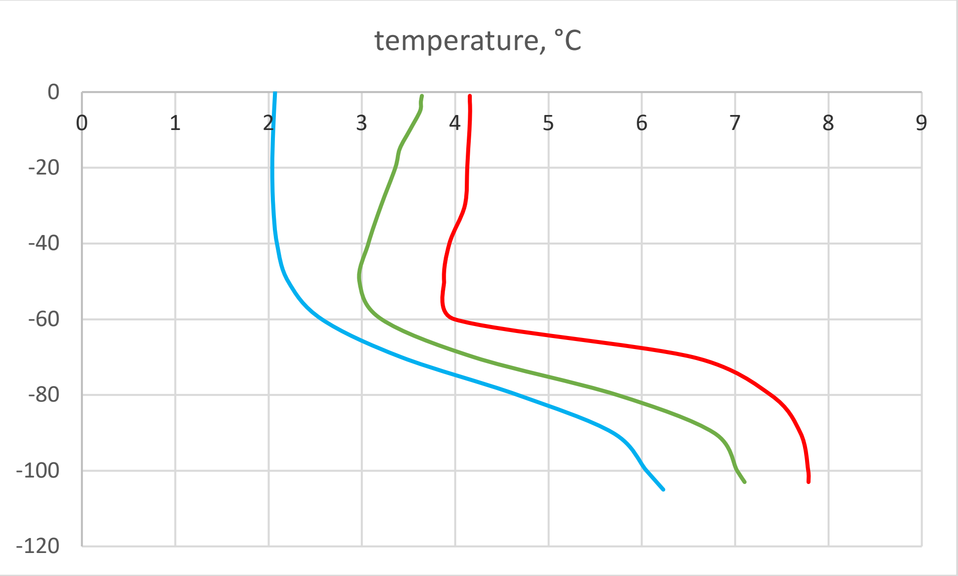
The phenomenon of underwater acoustic channel formation is also observed in two other locations in the world: the north-east region of the East China Sea [(Song, 2018) and the Yellow Sea (Lee, 1992). However, in their cases, the mechanism is completely different. The variability of the sound speed field is caused by internal wave interference and strong currents. The scale of the phenomena is also much smaller. For instance, the temperature difference between the water surface and the acoustic channel axis in the East China Sea is approximately 3°C, while in the Gdansk Deep it is over 15°C. The sound speed difference between the surface and the acoustic channel axis in the East China Sea amounts to approximately. 7 m/s (Song, 2018) while in the Gdansk Deep it exceeds 50 m/s.

The diagrams presented in Fig. 7 illustrate the long-term changes in the hydrological and hydroacoustic parameters. They provide a comparison of the temperature, salinity, and acoustic wave speed values averaged for the fifty year period between 1960-2010, and the succeeding decade long period of 2010-2019 for the warmest month of the year – August. The surface water temperature increased substantially from 18.0 to 20.4°C, which confirms that global warming also has an impact on the phenomena occurring in the southern region of the Baltic Sea. The bottom water temperature also increased from 5.42 to 6.50°C, while at the same time the salinity grew from 11.94 PSU to 12.40 PSU, which signals a more intensive saline water inflow, and in comparison to the earlier period, a change in the inflow character. Presently, the inflows of high temperature, so called warm inflows, are observed. Concurrently, the salinity of the upper layer decreased and the average fell from 7.36 to 7.16 PSU. As a result, a rise in the speed of sound values at the surface and the bottom occurred, with a simultaneous increase in the difference between the speed of sound at the surface and in the acoustic channel axis from 55.8 m/s to 62 m/s, as well as in the difference between the speed of sound at the bottom and in the acoustic channel axis from 13 m/s to 17 m/s. This creates more favorable conditions for acoustic energy concentration in the acoustic channel.

Saline water inflows modify the hydrological conditions in the entire Baltic Sea, also including the Gdansk Deep, despite the large distance from the Danish straits. The December 2014 inflow, whose impact was recorded during measurements conducted in March 2015, decidedly changed the conditions in the Gdansk Deep region. This is presented on the diagrams in Fig. 8, where the data from March 2015 is compared with the averaged distributions of the fifty year long period of 1960-2010, and the decade long period of 2008-2017. The inflow transported warm water which increased the temperature at the bottom to 7.786°C and salinity to 14.219 PSU. These values are greater by 0.68°C and 1.75 PSU than corresponding mean values from the last ten years, and by 1.55°C and 2.37 PSU from the averages of the fifty year period.

At the same time, the upper water layer was over 2°C warmer than the fifty year mean temperature value and nearly 0.2 PSU less saline.

As a consequence, the speed of sound in the entire water column was substantially higher than the typical value for March. At the surface, it was 1431.9 m/s (2.4 m/s and 9.0 m/s greater than the corresponding average values for the periods of 2008-2017 and 1960-2010), at the depth of 60 m the speed was 1430.7 m/s, which exceeded the average values by 1.7 m/s and 6.1 m/s, while at the bottom it was 1454.3 m/s – exceeding by 1.7 m/s and 9.3 m/s the multi-year mean values.



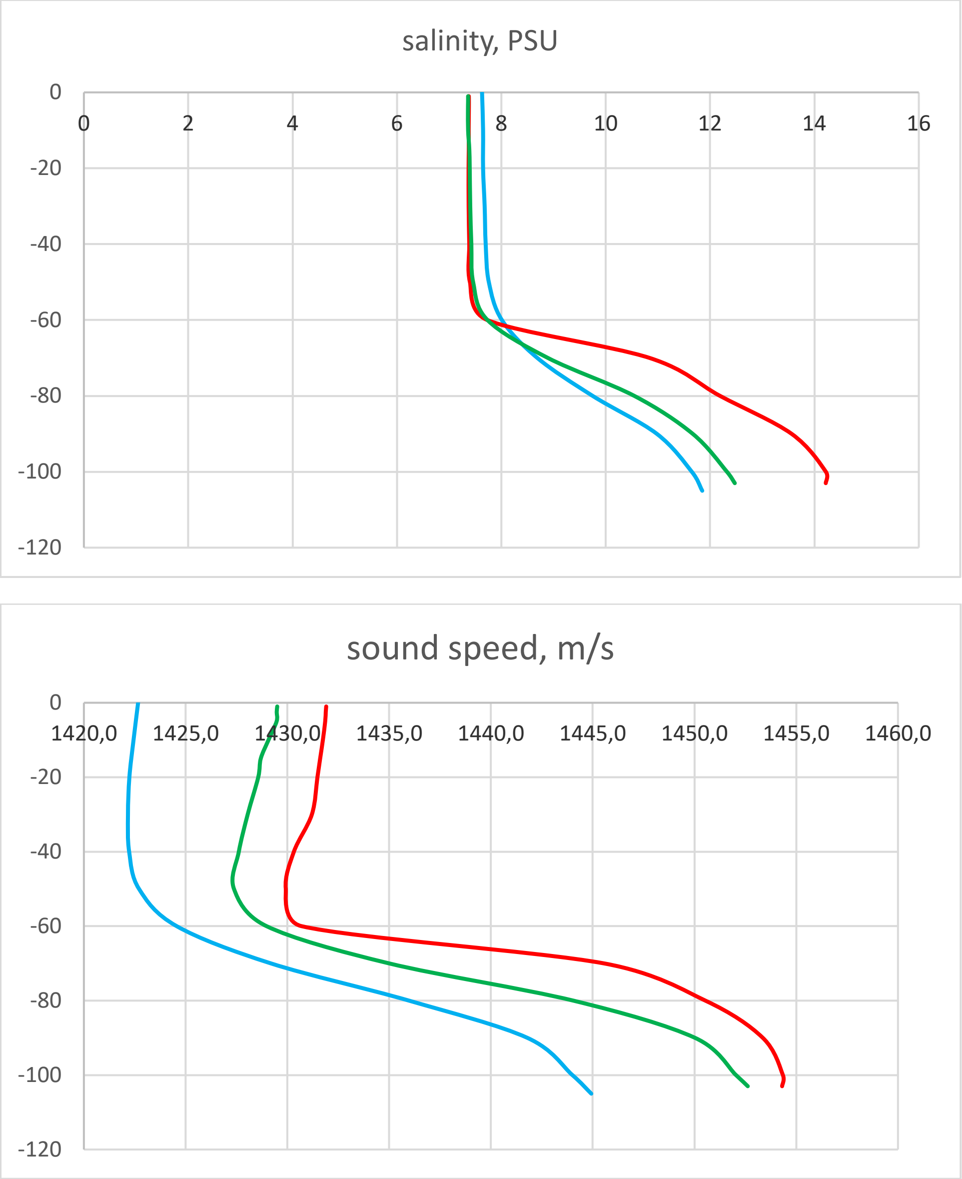
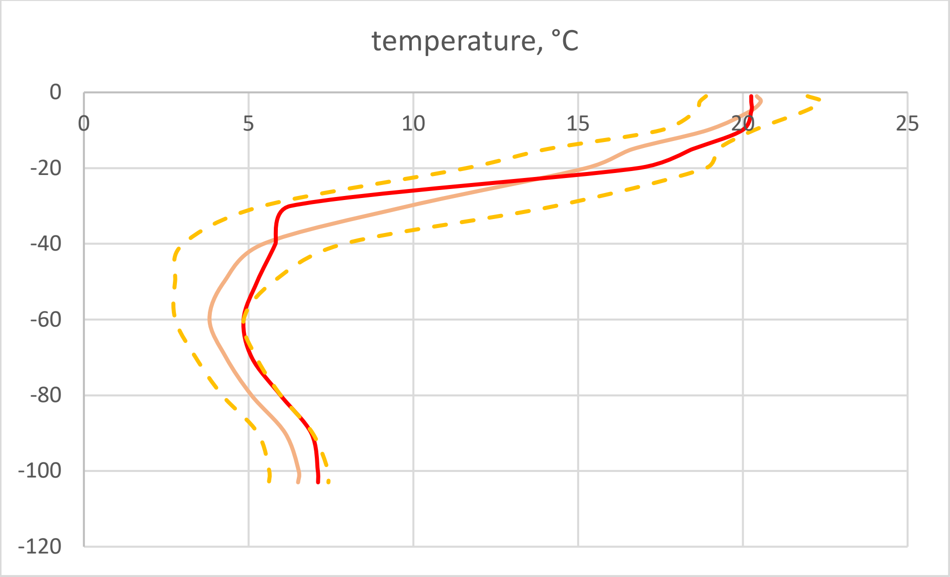
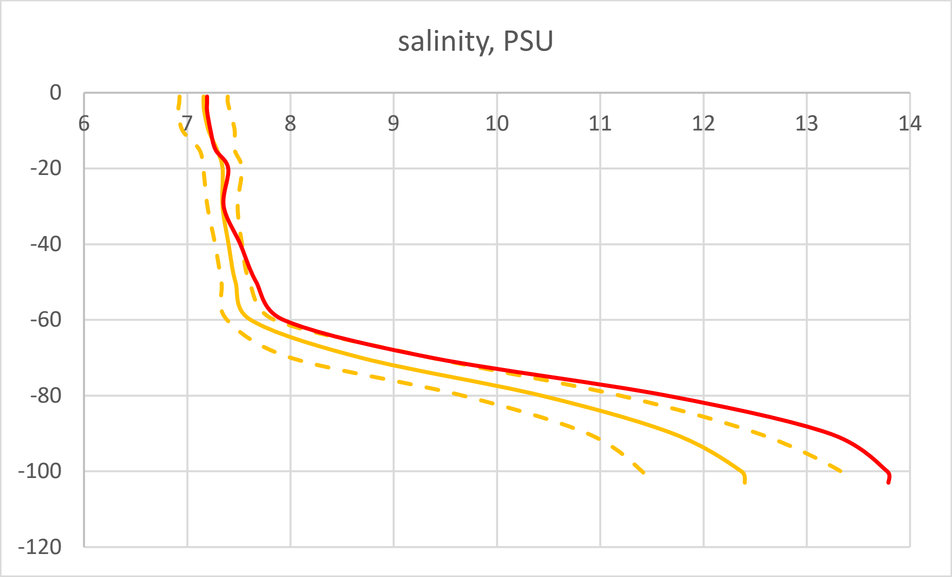


Fig. 8. Vertical temperature, salinity and speed of sound distributions in the Gdansk Deep in March 2015 (red line) in comparison with the averaged values for the periods of 1960-2010 (blue line) and 2008-2017 (green line)

Climatic anomalies, which are in fact climate change tendencies, can be observed on succeeding characteristics representing the vertical distribution of temperature, salinity, and speed of sound in the last few years. The diagrams below present the results of measurements conducted in August of 2016, 2018, and 2019 with the background of the average values for the period of 2010-2019 with the indicated confidence intervals.


temperature, °C
0
-20
-40
-60
-80
-100
-120
0
5
10
15
20
25


salinity, PSU
0
-20
-40
-60
-80
-100
-120
6
7
8
9
10
11
12
13
14

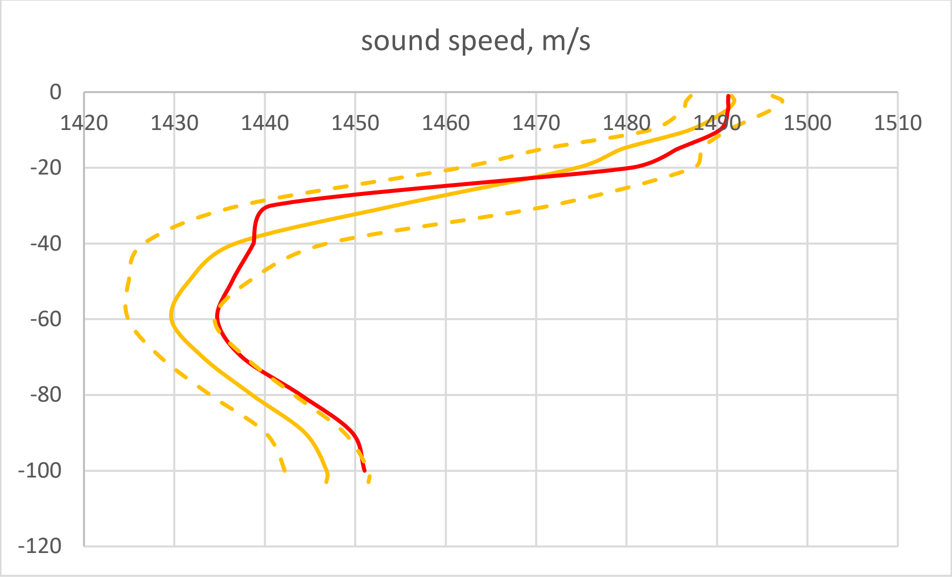
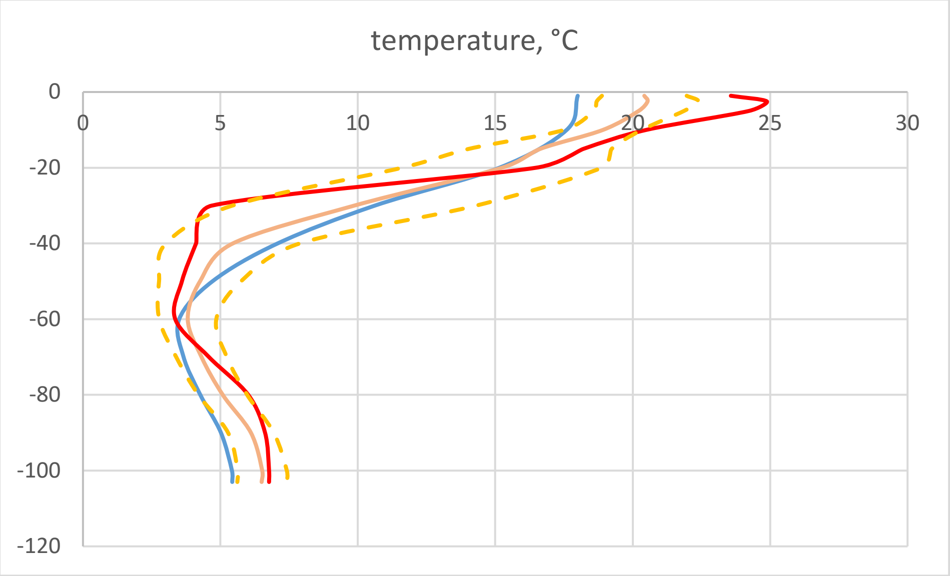
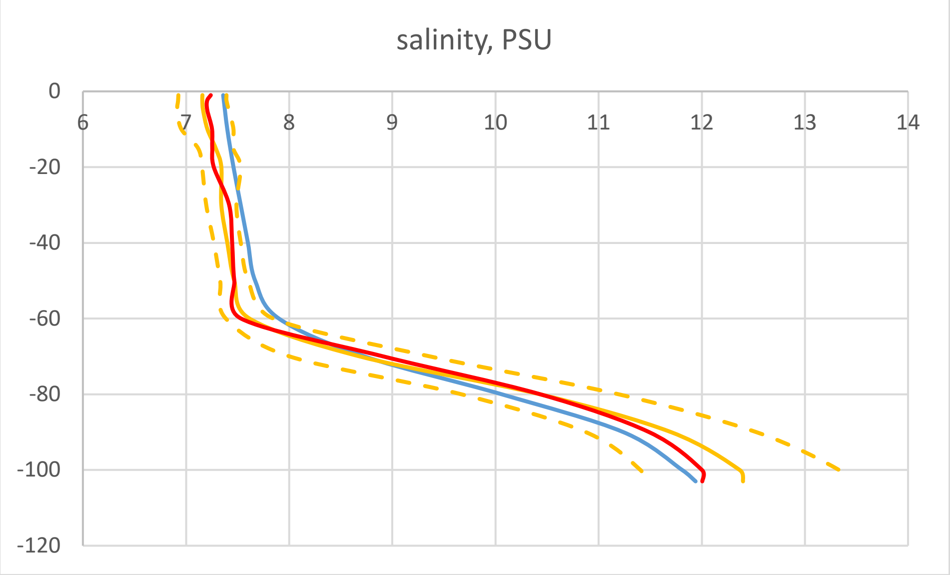

sound speed, m/s
0
-20
-40
-60
-80
-100
-120
1420
1430
1440
1450
1460
1470
1480
1490
1500
1510

Fig. 9. Vertical temperature, salinity and speed of sound distributions in the Gdansk Deep region in August 2016 (red line) in comparison with the mean value (orange line) and confidence interval (orange dashed lines) determined for the period of 2010-2019





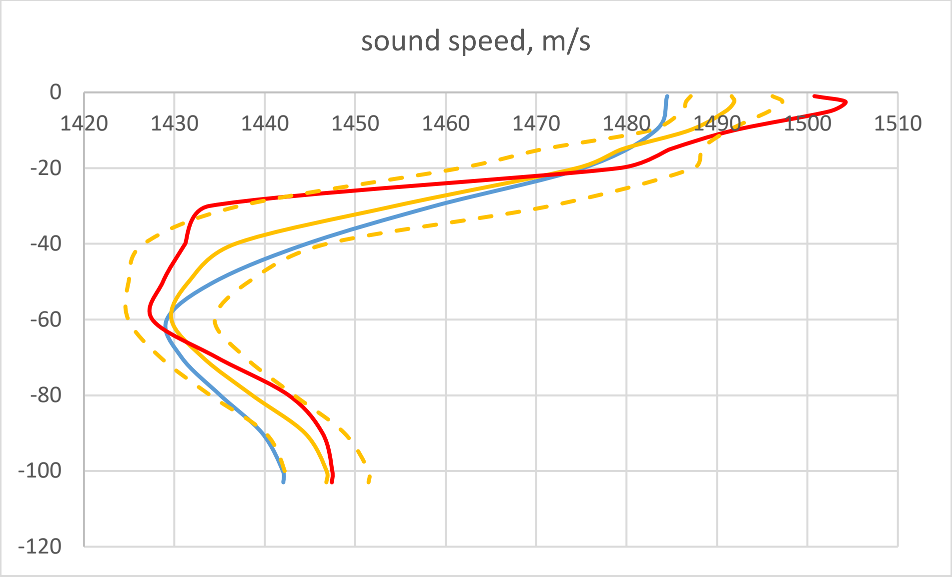
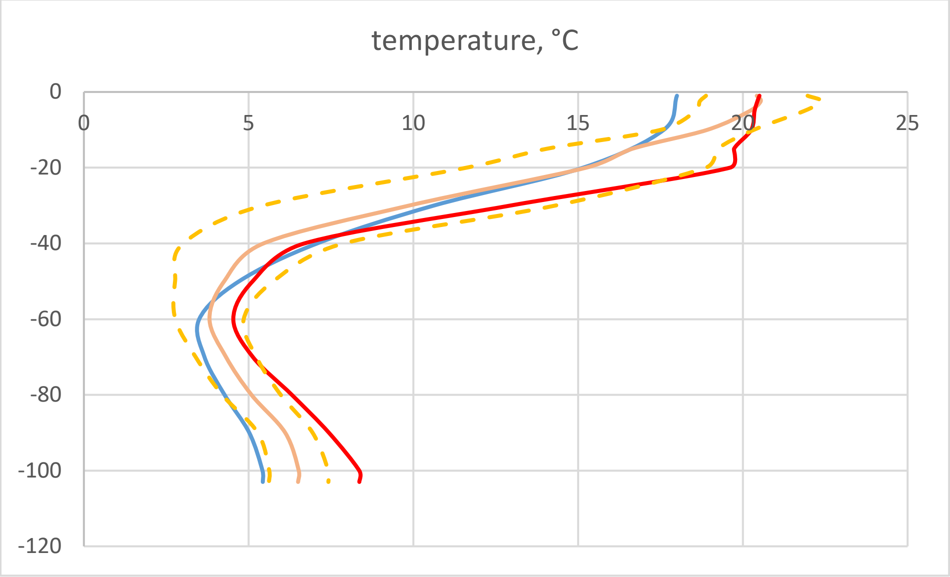
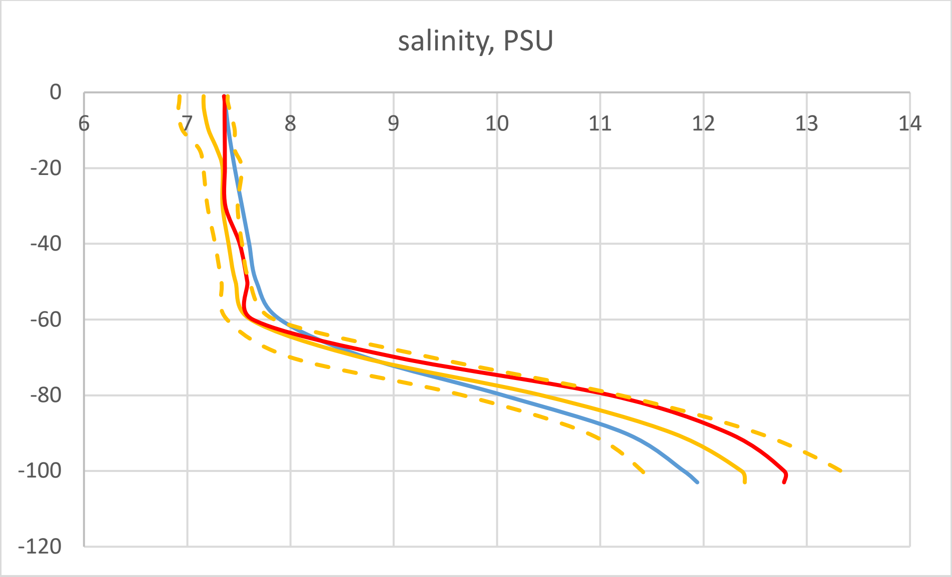


Fig. 10. Vertical temperature, salinity and speed of sound distributions in the Gdansk Deep region in August 2018 (red line) in comparison with the mean value (orange line) and confidence interval (dashed orange lines) determined for the period of 2010-2019 and the average for the period of 1960-2010 (blue line)





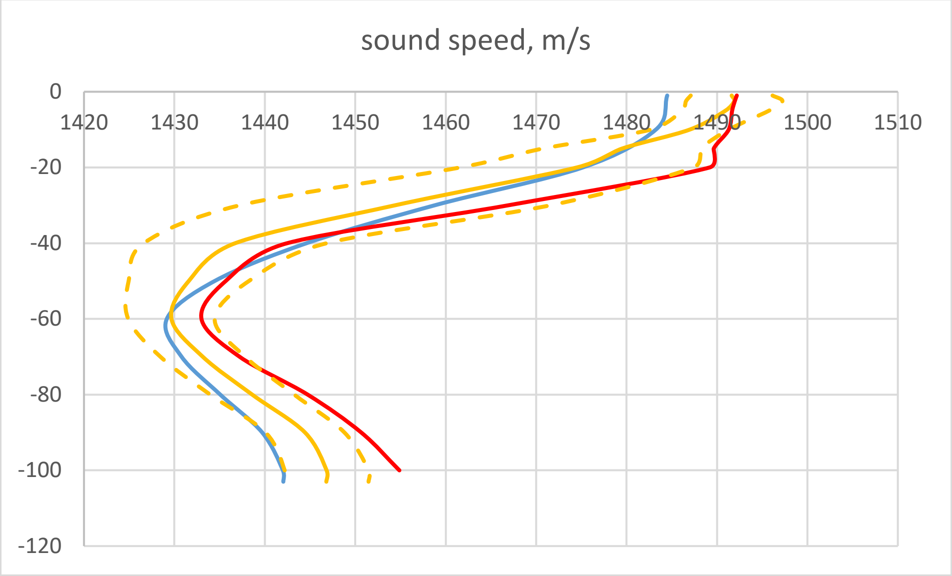


Fig. 11. Vertical temperature, salinity and speed of sound distributions in the Gdansk Deep region in August 2019 (red line) in comparison with the mean value (orange line) and confidence interval (dashed orange lines) determined for the period of 2010-2019 and the average for the period of 1960-2010 (blue line)

The upper layer water temperature, especially to the depth of 20 m, is greater than 20°C and exceeds the average values. In 2016, the temperature in the surface water layer, to 20 m depth, is greater than the average values. In the 20-40 m depth range it is slightly lower than the average for the years 2010-2019, and below 40 m it adopts values from the upper limit of the confidence interval (Fig. 9). The temperature distribution in August 2018 was analogous, with a record high value of 24.884°C recorded at the surface (Fig. 10). The following August (2019) is characterized by high temperature values throughout the entire section which substantially exceed the average multi-year values for both of the referential periods (Fig. 11). The bottom temperature was 1.86°C higher than the average for the period of 2010-2019 and exceeded the average for the period of 1960-2010 by 2.75°C.

The upper layer salinity is generally in line with the values typical for the period of 2010-2019 and somewhat lower (approximately 0.2 PSU) than in the period of 1960-2010 (Fig. 9, 10 and 11). In the deep layer the salinity is greater than the typical values for 2016 and 2019, while in 2018 it is equal to the expected value. Only in the bottom layer does it adopt somewhat lower values, however, they still remain within the confidence interval. .

As a consequence of the high temperature at the surface and the substantial temperature and salinity values in the deep layer, the speed of sound at both margins of the acoustic channels has values typical for the Gdansk Deep region.

4. Conclusions

The article presents a detailed analysis of the hydrological conditions in the Bay of Gdansk based on the phenomena occurring in its deepest region – the Gdansk Deep, and their impact on the conditions of acoustic wave propagation. The results of studies conducted in recent years are compared with the archival data collected since 1902.

Generally, the conditions in the Gdansk Deep reflect the conditions in the southern Baltic. Significant changes in both the upper and the deep layer resulting from global climatic changes can be observed.

In the last decade of 2010-2019, a substantial water temperature increase was observed, both at the water surface and in the bottom layer. The increasing air temperatures of climate change resulted in a rise of the average temperature by 2.50°C in comparison to the average for the fifty year period of 1960-2010. At the same time, we observed an increase in the average deep water temperature, at the bottom, by 1.07°C. Also, the salinity in the bottom layer in the corresponding periods increased by 0.46 PSU. The changes occurring in the deep water layer are a consequence of changes in the barometric situation in the North Atlantic, which are favorable for the development of conditions for frequent inflows of saline, high temperature water. We are witnessing a phenomenon of general change in the character of the inflows. Putting it simply, it might be stated that in contrast to the situation remaining typical for many years when saline water entered the Baltic most often in the form of cold inflows, which in the period of 1902-2019 gave the Gdansk Deep an average bottom water temperature of 5.75°C, at the present time the dominant part is played by warm inflows providing the Gdansk Deep with water with an average temperature of 6.5°C.

Starting from the 1990s we see in the Gdansk Deep region an increase in the water surface temperature which is accompanied by a decrease of the salinity value in the upper layer.

A critical juncture in the conditions present in the Gdansk Deep is the water inflow of December 2014, which reached the Gdansk Deep in the early spring of 2015. Since that moment there has been a regular inflow of saline, warm deep water resulting in the continuous presence of water characterized by high salinity and temperature.

In summary, it should be concluded that in the recent period of time the Gdansk Deep has experienced phenomena which favor deepening of the acoustic channel in the summer season, i.e. an increase in the speed of sound both in the surface and deep water layers. However, the mechanisms of these phenomena differ – at the water surface it is the heat exchange at the atmosphere-sea boundary, and in the deep water layer the saline, high temperature water inflows. These phenomena do not occur synchronously, a season of intensive inflows is not always accompanied by high air temperature. Nevertheless, both of the phenomena are characterized by a stable trend of increased temperature at the surface and at the bottom, which in consequence result in an increase in the speed of sound in these layers.

The systematic changes observed in the Gdansk Deep region reflect global climate changes.

Acknowledgments

The research was supported in part by the Ministry of Science and Higher Education, within the framework of funds for statutory activities of the Gdansk University of Technology. The publication was

prepared using HELCOM data, as well as data obtained from the Inspectorate of Environmental Protection obtained within the framework of the State Environmental Monitoring.

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