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The Effect of Dynamics of Sea Level in Southwest Baltic Sea and Kattegat Strait on a Hydrochemical Mode in Deep-Water Horizons and Fishery Productivity

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Abstract—The features of the long-term dynamics of various indicators of a hydrochemical mode in deep-water areas of the Baltic sea were considered. Influence of the content of the dissolved oxygen and salinity of water as major ecological factors for the efficiency fishery productivity was characterized. The comparative analysis of long-term dynamics sea levels surfaces in a southwest part of the Baltic sea and in strait Kattegat was made. It was shown that inflow of water mases in many respects depended on the sea level difference between these areas from the North Sea possessing the raised salinity and the higher content of the dissolved oxygen. The principal reasons capable to lead to occurrence of the most intensive intrusion of the North Sea waters were analysed.
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INTRODUCTION

One of the characteristic features of the Baltic Sea is its considerable isolation from the open ocean because the Danish straits are narrow and shallow [1]. Significant amount of fresh water river runoff, which is on average 433 km^3, amid slow water exchange with highly saline water of the Atlantic and the North Sea leads to significant desalination of the Baltic aquatorium. This is more typical for the central and eastern regions. The complete exchange of the entire water mass of the sea takes not less than 27 years [2, 3].

The salinity and oxygen concentration in bottom layers of the Baltic Sea mostly depend on the periodic inflow of the transformed North Sea waters into the southern and central parts of the sea. Increasing salinity and growth of dissolved oxygen benefits the marine ecosystem and its biological productivity [2, 4–7]. The intense and prolonged inflow improve the environmental conditions for the reproduction of organisms with oceanic origin increasing the yield of commercially valuable fish: Baltic cod (*Gadus morhua callaris L.*) and flatfish (*Pleuronectes flesus L.*, *Platessa platessa L.*, *Limanda limanda L.*) [8, 9]. So, the study of long-term variability of hydrochemical and hydrological regime of the Baltic Sea in order to identify the factors leading to an intense flow of North Sea waters or the absence of significant advection is an important scientific and practical problem.

The aim of the present study is to analyze the impact of the dynamics of the sea levels surfaces in the southwest of the Baltic Sea and the Kattegat Strait on the intensity of water exchange, hydro-chemical regime in the bottom water and fishing productivity.

FEATURES DETERMINING THE HYDROCHEMICAL MODE OF THE BALTIC SEA

The content of dissolved oxygen is among the most important factors determining hydrobiological mode of an ecosystem. Oxygen supply of the two main water masses of the Baltic Sea, surface and bottom, is carried out by various sources. The content of dissolved oxygen in the surface layer of the sea is determined by the processes of absorption of oxygen from the atmosphere and its production in the process of photosynthesis. In the deep layer due to the difficulty of vertical water exchange, the oxygen intensity from the surface is very limited. The main source of aeration is the advection of North Sea waters through the Danish straits. This source operates constantly but the power of the offenses and the degree of aeration of various zones of the deep layer is uneven. During the periods

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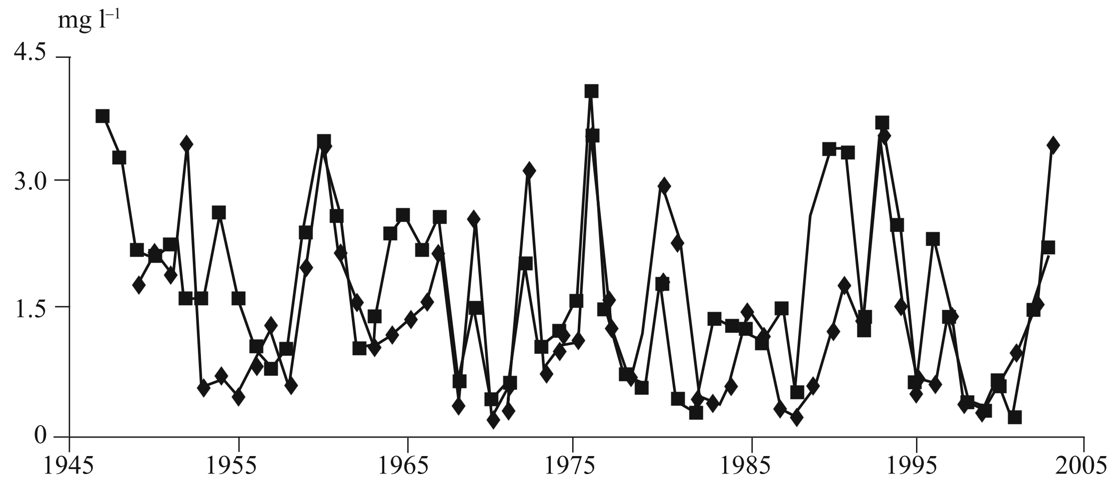

Fig. 1. Long-term dynamics of annual values of dissolved oxygen content in bottom waters of the Bornholm (♦) and Gdansk (■) Deeps.

of weak inflow of North Sea waters the oxygen near the bottom can completely disappear and appearance of hydrogen sulfide in the bottom layers of deep-sea trench becomes quite possible [2, 10, 11].

Interannual variability of dissolved oxygen and salinity in the bottom layers is primarily determined by the intensity of North Sea water intrusion. Secular changes of annual average values of oxygen concentrations in the bottom layer of the main basin of the Baltic Sea are presented in Figs. 1 and 2. Data for the period from 1946–1953 to 1979 were taken from ref. [2], from 1980 to 2000 and from 2001 to 2003 were taken from materials of AtlantNIRO [9, 11, 12].

In the Bornholm Deep, at the depth of 80 meters, dissolved oxygen is exposed to considerable interannual and long-term variability. High concentrations of oxygen (more than 3.5 Mg l^{-1}) were observed in middle of 1952, 1960, 1976, 1993 and 2003. Minimum values (less than 0.3 mg l^{-1}), when oxygen is virtually absent, were observed in 1970, 1988 and 1999. Periods of lower concentrations of oxygen are short and are usually not accompanied by the appearance of hydrogen sulfide.

In the Gdansk Deep at the depth of 100 m fluctuations in the concentrations of oxygen are also marked. There are three basic steps of increasing concentration of dissolved oxygen to levels exceeding the 3.5 mg l^{-1}. The first period falls upon the years from 1946 to 1948, and also in 1976 and 1993. Minimum values of annual concentrations of oxygen (less than 0.5 Mg l^{-1}) were typical for 1970, 1982 and for the period from 1998 to 2001. Generally, from the second half of 1940th up to 1970 the aeration of the bottom layer tended to decrease, from 1988 to 1994 there was a short-term upward trend in the oxygen content, yet, at the end of 1990 oxygen concentration decreased dramatically, and in 2001 the minimum concentration of 0.2 mg l^{-1} for the entire period under review was achieved. Nevertheless, the complete absence of oxygen in relation to the average annual values was not observed.

In the Gotland Deep at the depth of 240 m the amplitude of the dissolved oxygen was minimum, and hasn't exceeded 3 mg l^{-1} for the reviewed period. Since the early up to the middle of 1950th the concentration of dissolved oxygen did not fall below zero mark and fluctuated around the values of 1.5–2 mg l^{-1}. Since 1956 the oxygen content has been sharply reduced, and there was the first period of his absence accompanied by the appearance of hydrogen sulfide (negative values in Fig. 2 correspond to concentrations of hydrogen sulfide). Considerable concentration of hydrogen sulfide 1.2 mg l^{-1} was registered in 1961. However, in 1962 reducing conditions were replaced by oxidation, and oxygen content reached the level of 2 mg l^{-1} again. During the next 15 years the concentration of oxygen in the bottom layer ranged up to rather wide limits remaining generally above zero. For example, in 1969 the contents of hydrogen sulfide exceeded 2 mg l^{-1} but the following year free oxygen with concentration of about 2 mg l^{-1} appeared. By 1978 the period of relatively high oxygen content was completed and the second, a longer period of its complete absence began accompanied by a steady trend of increasing of hydrogen sulfide concentration. The maximum concentration of hydrogen sulfide was achieved in 1988 and reached 4.8 mg l^{-1}. It is clear that in such circumstances the existence of highly

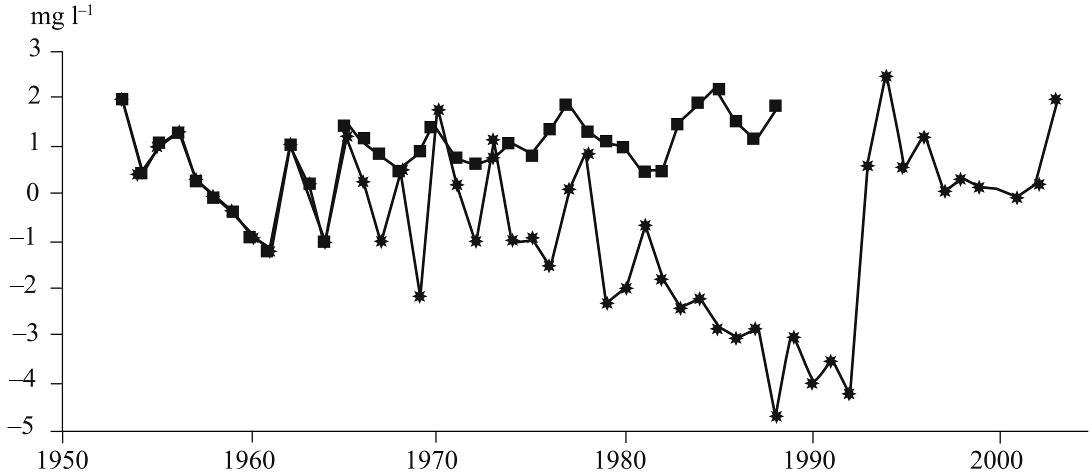

Fig. 2. Long-term dynamics of annual values of dissolved oxygen contents in the bottom (■) and intermediate (✱) layers of the Gotland Deep. Negative values correspond to concentrations of hydrogen sulfide.

organized life is impossible. Until 1993 the content of hydrogen sulfide in the Gotland Deep remained extremely high and ranged from 3 to 4 mg l^{-1}. But in 1993 reduction conditions were rapidly changed by the oxidation, and in 1994 the concentration of oxygen reached the absolute maximum for the entire reporting period and amounted to 2.6 mg l^{-1}. However, the next 8 years the reduction of aeration of the bottom layers, up to complete disappearance of free oxygen was observed, and only in 2003 its concentration increased to 2 mg l^{-1} again.

On the whole, the longest period of absence of strong inflow of the North Sea water masses into the Baltic Sea was completed to the year 1993. In 1993 significant increase in salinity in the Bornholm Deep was registed, and in 1994 the salinity in the Gdansk and Gotland Deeps increased greatly. After 1997 all deep-sea trench the significant increase in heat storage of the deep waters due to advection of warm waters from the North Sea in September 1997 was marked. In autumn of 2001 and 2002 the inflow was less intensive. Oxygen regime in the Southern and Central parts of the Baltic Sea in the second half of 1980 up to the end of 1990 can be characterized as extremely unfavorable for the existence of the benthic fauna in spite of short periods of improvement. In 1999–2000 water area of the Baltic Sea occupied by the water with hydrogen sulfide was the largest during the preceding 16 years. In 2003 there was a significant improvement of abiotic conditions for the existence of organisms in the deep and bottom layers through intensive and continuous inflow of the winter North Sea waters. According to various estimates the volume of inflow from the North Sea was about 100 km^3, which is comparable to the most intensive inflows, with half of the inflowing partially transformed water having degree of salinity of more than 17 ‰ [10]. In the early summer of 2003 the concentration of oxygen in the bottom layer of the Gotland Deep exceeded 3.5 mg l^{-1}. Such high concentrations in the layers of 200 m deep in the Gotland Deep were previously observed only twice: in 1930 and in May 1994, [9, 13, 14]. In general, changes in the gas regime in the bottom layers due to advection of 2003 were very significant: in 2003, as compared with 2001, areas with hydrogen sulfide content decreased almost 3-fold.

In the ensuing years, as it is shown in Fig. 3, the largest increase in the area of bottom layers with the presence of hydrogen sulfide was observed in 2007 and 2008. In 2009 the area of hydrogen sulfide zone decreased owing to another sufficiently strong inflow of the North Sea waters.

Fig. 4 shows the long-term dynamics of values of the water area in the Baltic Sea with the presence of hydrogen sulfide and the deficit (O_2 < 2 mg l^{-1}) of dissolved oxygen. These characteristics can be regarded as a generalized indicator of the oxygen regime of bottom layers. The most significant increase in the area of hydrogen sulfide zone was observed in the early 1980s, as well as from the beginning of the XXI century. A ten-year period from 1999 to 2009 can be distinguished, when the number of areas with a deficit of dissolved oxygen, and, in particular, the presence of hydrogen sulfide, was considerably higher than the standard for the entire period under review.

Thus, the concentration of dissolved oxygen, hydrogen sulfide and the magnitude of salinity in the deep

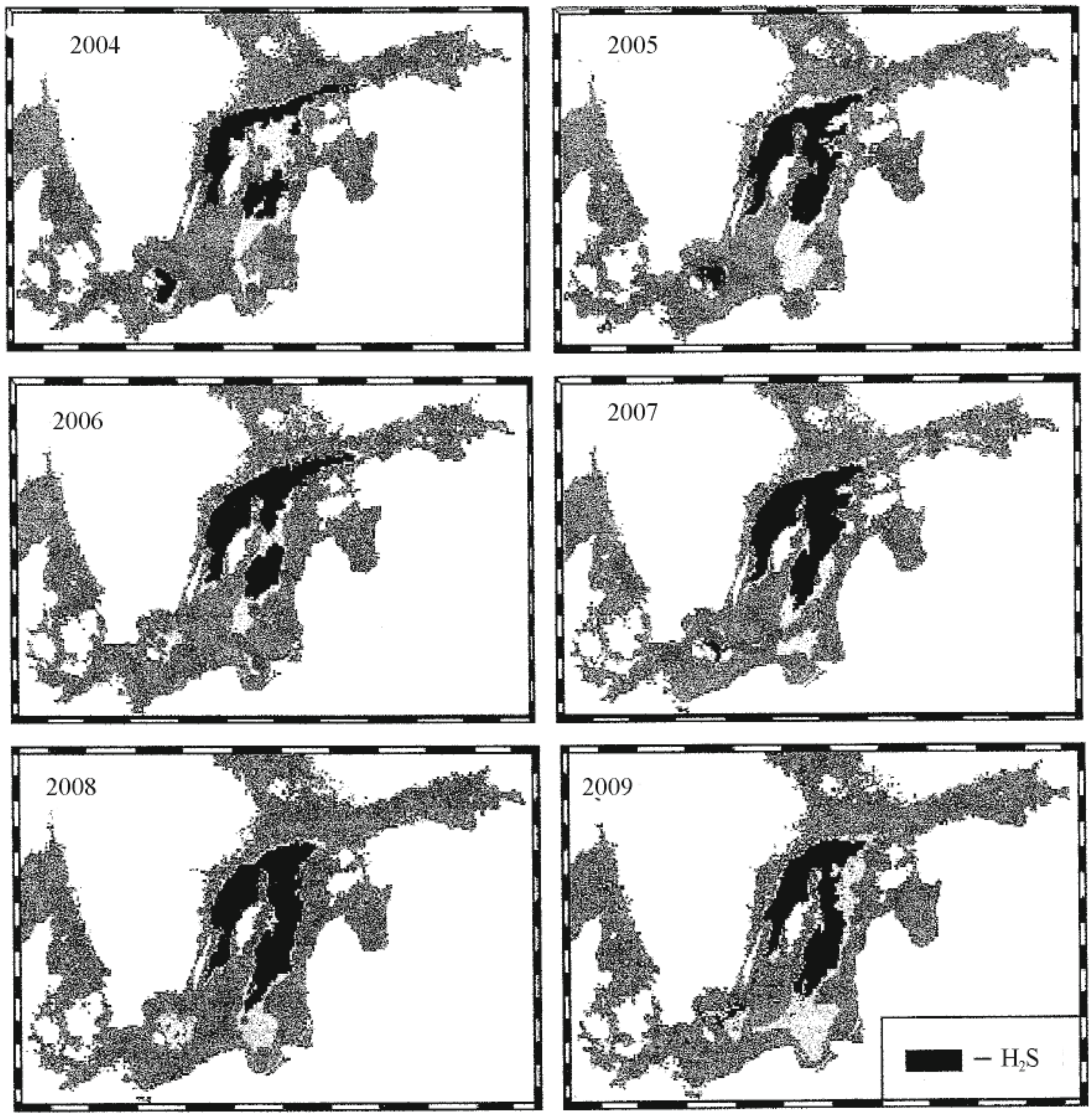

Fig. 3. Dynamics of zone locations in the deep layers of the Baltic Sea with hydrogen sulfide from 2004 to 2009 [13].

and bottom layers of the Baltic Sea are highly variable characteristics through time and space. Biological productivity and the extent of the sea bottom fauna spreading, the most important commercial fish, in particular, greatly depend on the data values of hydrochemical parameters of the marine environment.

HYDROCHEMICAL MODE OF BOTTOM LAYERS AND FISHING PRODUCTIVITY

Dominant position in the Baltic Sea fish fauna is occupied by species genetically related to the Atlantic Ocean fauna, some of which have adapted to the life in brackish waters and thus were able to significantly expand their range. The latter include the important commercial pelagic fish, i.e. bathypelagic species, such as Baltic herring (*Clupea harengus membras L.*), sprat (*Sprattus sprattus balticus L.*) and dominant bottom-living species, such as the Baltic cod (*Gadus morhua callaris L.*), flatfish, which are flounders (*Pleuronectes flesus L.* and *Liman*da *limanda L.*), plaice (*Platessa platessa L.*) and large sand dabs, which are turbot (*Rhombus maximus L.*). As moving from west to east species diversity noticeably reduces. There are more than 100 species of marine fish in the Skagerrak Strait where salinity is about 25%, 75 species in the Kattegat Strait with the salinity of 20 ‰, 27 species in Bornholm basin, and no more than 20 species in Finland and the Gulf of Bothnia [14].

Baltic cod and flatfish in the spawning period greatly depend on the salinity of the water and on the content of dissolved oxygen. In this regard, their spawning areas in the Baltic Sea are located in the bottom layers of deep-sea trench with increased salinity and a more constant water temperature, necessary for the development of pelagic fish. However, the lack of oxygen in the deeper layers leads to a restriction of spawning habitat. A water area suitable for the normal development of cod larvae is in average of about 27% of the total area of high seas [4, 15]. The main spawning grounds of the west Baltic cod are located in Arkonskaya depression to the north of Rügen Island and in Mecklenburg Bay, in the Bay of Kiel, as well as in Little Belt Strait. Spawning takes place in February-March in the western areas and in March-April in the Arkonskaya depression. The Eastern Baltic cod spaw in the Bornholm Deep, Slupsk Trough, Gdansk and Gotland Deeps (Fig. 5). According to ref. [5], the greatest density of eggs is typical for Bornholm Deep. Here the inflow of saline North Sea waters and, accordingly, aeration of bottom spawning layers happens more frequently than in the eastern and north-eastern regions of the sea. In general, the appearance of the maxima number of eggs and larvae of cod is associated with periods of advection of North Sea waters. In periods of stagnation, i.e., easing the water flow, the quantity of eggs and larvae reduces and mortality of embryos increases. On average, during the years of aeration the number of calves under 1 m2 from the surface is two times higher than in the years of stagnation, while the number of larvae is the more than three times higher [5, 15, 16].

Fig. 6 shows the comparison of long-term dynamics of dissolved oxygen in the Gotland Deep and water salinity in the Bornholm Deep and the survival of Baltic cod eggs. The corresponding correlation coefficients are $r = 0.48$ and $r = 0.55$ at the confidence level of $P = 99\%$. The survival of larvae and juveniles of benthic Baltic fish directly depend on the oxygen concentration and salinity of the water [6, 7, 16, 17].

DYNAMICS OF THE EQUATION SURFACE AS A FACTOR OF HYDROCHEMICAL REGIME FORMATION OF THE BOTTOM LAYERS

Currently, the mechanism of water exchange in the Danish Straits, according to many scientists [1, 2, 8, 12, 13, 17], is the following. There is a two-layer system of currents near the Danish and Kattegat Straits. In the surface layer desalinated, due to significant river runoff, the water flows in the direction to the North Sea, forming the output current. The saline North Sea waters penetrate into the near-bottom layers of the Baltic Sea (inlet flow). Such system of currents is considered to be normal for the area at low wind speeds (up to 5 m s^{-1}). Cyclones from the North Atlantic going to the east and north-east are accompanied by strong western winds. This leads to conversion of the current system in the straits, and inlet flows are observed in all layers. In such cases huge amount of salt water encroach into the Baltic Sea during storms. Thus, in November-December 1951 about 200 km^3 of North Sea waters passed through the Straits [14]. So, the water exchange between the Baltic Sea and the North Sea, being highly variable feature, may indicate the nature and direction of the interaction of water masses of the seas. Large-scale variability of atmospheric processes developing over the North Atlantic and European territory of the continent, leads to fluctuations in the levels of the Baltic and North Seas. Water flows in the straits appearing under such conditions play an important part in water exchange. Due to the river-flow there appears a constant stream of fresh water of varying intensity directed to the North Sea.

The main specific features in the interannual variability of water inflow into the Baltic Sea are as follows [13, 14, 18]. Since the beginning of the XX century until 1920, and since 1940 till 1950 significant increase in the fresh air component of the water cycle is registed with the highest values of inflows during the latter period, when the peaks occurred at the beginning of the century exceeded by 150–200 km^3 $year^{-1}$. In the early 1970s the inflow values showed maximum level several times, almost extreme levels, but the increase of inflow wasn't traced. During the period of 1920–1940, the intensity of the inflow was low. The next periods of lower inflows were observed at the end of 1950 and at the middle of 1980s – early 1990s. The most significant decrease in the intensity of the inflow of the North Sea waters into the Baltic Sea in XX century was in early 1990's. Spectral analysis of the inflow component of the water exchange reveals that the most intense period of the variability corresponds to 56 years. Periods 22, 18 and 3.4 years are also distinguished. With regard to the purpose of this study the discussion of long-term level oscillations is very reasonable in view of the fact that the magnitude difference in the levels of the Baltic and North Seas may depend on the direction of water flow in the area of the Danish Straits. This in turn determines the conditions for the entry of the North Sea waters into the Baltic Sea, which greatly influence the hydrochemical and hydrobiological modes of the sea.

For a comparative analysis of the dynamics of the surface levels eight of the most representative recording stations out of the most available were chosen (Fig. 7). The coordinates of the points are as follows: Esbjerg

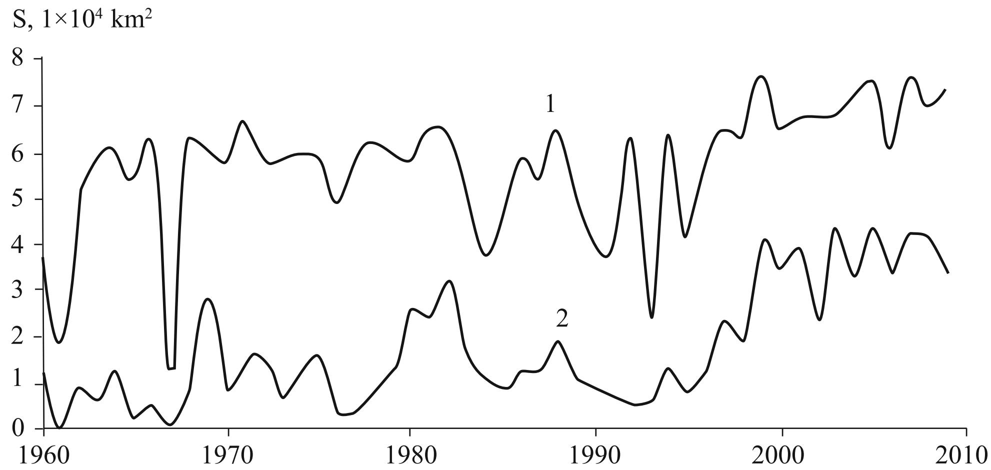

Fig. 4. Long-term dynamics of the values of the squares of hydrogen sulfide zone (1) and the zone with a deficit of dissolved oxygen (2) in the Baltic Sea [13].

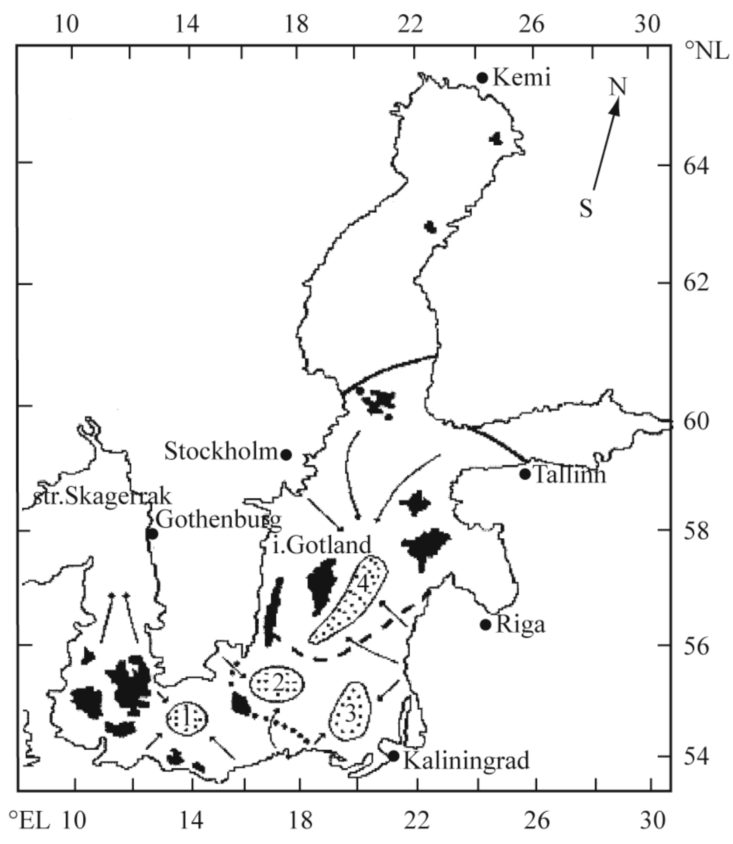

Fig. 5. The eastern boundaries of commercial stocks of bottom Baltic fish and locations of their main spawning areas (1–4) and spawning migration routs. 1 is Arkonskaya Deep; 2 is Bornholm Deep; 3 is Gdansk Deep; 4 is Gotland Deep. Strait line corresponds to the boundaries of marketable shoals of cod. Dashed line corresponds to the boundaries of marketable shoals of plaice. Short dashed line corresponds to the boundaries of marketable shoals of dab.

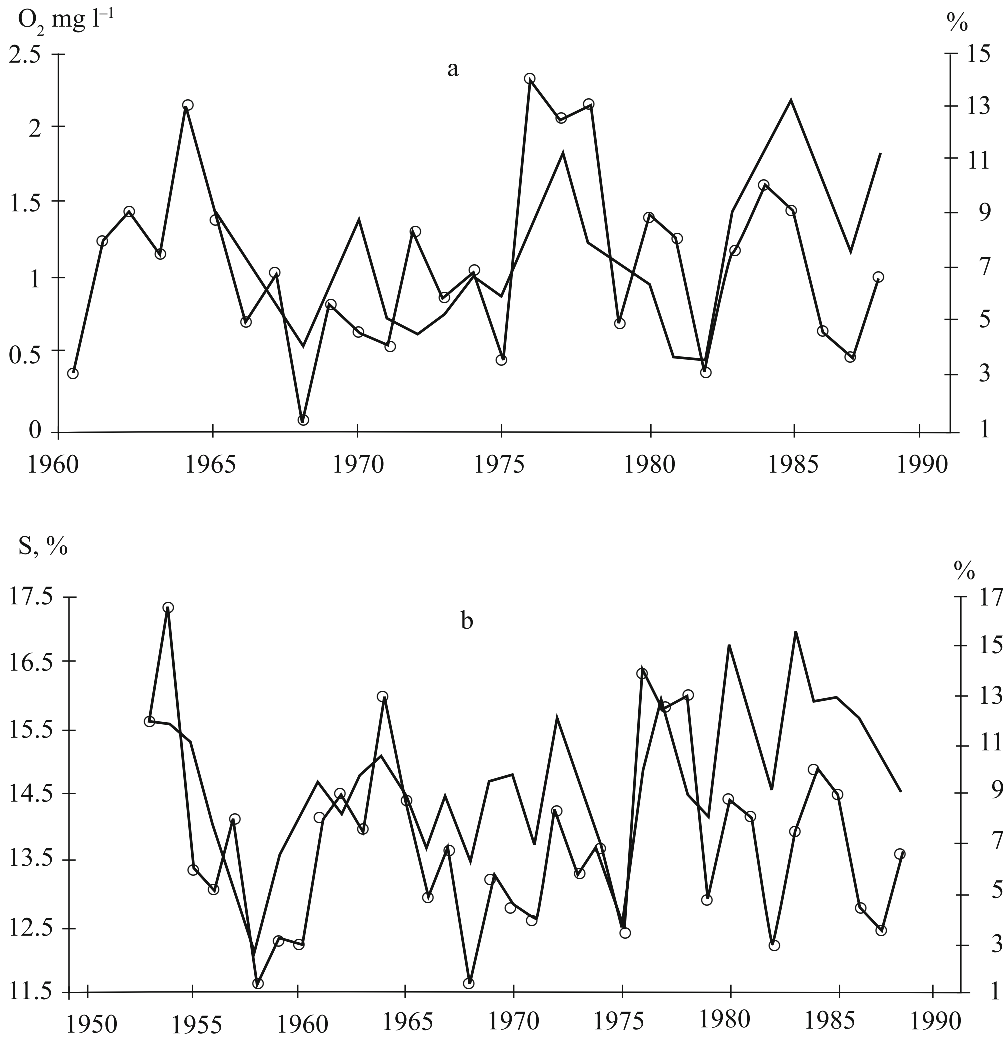

Fig. 6. Effect of long-term dynamics of dissolved oxygen at the depth of 90 m (a) and salinity of water (S) at the depth of 80 m (b) in the Gotland Basin on the survival of the eggs of Eastern Baltic cod. Ordinate axis (right) in both Figs. corresponds to the survival of the eggs, %.

58º 28' NL, 08º 26' EL; Oslo 59° 54' NL, 10° 45' EL; Smogen 58º 22' NL, 11º 13' EL; Aarhus 56° 09' NL, 10°13' EL;Gedser 54º34' N, 11º56' EL, Kobenhavn 55° 41' NL, 12° 54' N; Kungholmsfort 56° 06' NL, 15° 35' EL and Vladislavovo (Wladyslawowo) 54° 48' NL, 18° 25' EL. The stations were selected, firstly, due to the availability of sufficient duration of observations (at least 40 years), and, secondly, to the location of the stations. The stations of Gedser and Kobenhavn are located in the area of the Danish Straits, the station Smogen is located in the northern part of the Kattegat Strait, so the data of their observations can fairly reflect the variability of sea level in the region of close interaction between water masses of the Baltic and North Seas. The station Esbjerg is located on the western coast of Denmark and the data reflect the level fluctuations in the eastern part of the North Sea in direct adjacent to the strait. The station Vladislavovo reflects the level variability in the south-eastern part of the Baltic Sea. The station Kungholmsfort is located on the coast of Sweden near Eland island. Analysis of long-term data on the dynamics of sea-level leads to the following conclusion. The positions of Esbjerg and Gedser reveal a general trend towards a gradual geocratic movement over the entire period under review, the position of the station Smogen shows a trend to its reduction. The Kobenhavn station demonstrates slight level rising only at the beginning of 1970s. Apparently, this situation can be explained by effects of vertical crustal movements, expressed in a gradual lowering of Denmark and uplifting of Sweden. Sea level fluctuations recorded at the Vladislavovo station can not precisely prove any noticeable trend. The

Correlation coefficients between the average annual sea level fluctuations (ΔH) and the values of oxygen concentration and salinity in the Gotland and Gdansk Deeps of the Baltic Sea

Characteristics	Time shift relative to ΔH, years	ΔH at the stations, average year^{-1}			
		Smogen and Kobenhavn	Smogen and Gedser	Aarhus	Oslo and Kobenhavn
Oxygen concentration at the bottom of the Gotland Deep, 240 м.	0	0.54[a]	0.483[a]	0.22	0.56[a]
	1	0.55[a]	0.433[a]	0.38[b]	0.71[a]
	2	051[a]	0.431[a]	0.31[b]	0.64[a]
Oxygen concentration at the bottom of the Gdansk Deep, 100 м.	0	0.48[a]	0.45[a]	0.21	0.33[b]
	1	0.44[a]	0.42[a]	0.36[b]	0.24
	2	0.35[b]	0.33[b]	0.28	0.12
Salinity in the Gotland Deep, 240 м.	0	0.68[a]	0.57[a]	0.41[a]	0.51[a]
	1	0.57[a]	0.53[a]	0.37[b]	0.48[a]
	2	0.62[a]	0.51[a]	0.31[b]	0.36[b]
Salinity in the Gotland Deep, 100 м.	0	0.32[b]	0.28[b]	0.32[b]	0.41[a]
	1	0.28	0.27	0.25	0.32[b]
	2	0.18	0.16	0.18	0.28
Salinity in the Gdansk Deep, 100 м.	0	0.32[b]	0.31[b]	0.28	0.37[b]
	1	0.34[b]	0.33[b]	0.23	0.32[b]
	2	034[b]	0.32[b]	0.16	0.24

[a] Correlation coefficients correspond to 99 % of the confidence level. [b] Correlation coefficients correspond to 95 % of the confidence level.

significant raising of sea levels here were recorded in 1967, 1981 and 1989, while lowering levels were observed in 1960, 1969 and 1984. Two maximum and two minima levels can be marked within the course of seasonal level fluctuations for the most areas of the Baltic Sea. For the zone of the Danish Straits significant minimum within annual levels falls to the period from March to May and maximum occurs in August (in the western part of the Strait) or October (in the eastern part). The southern coast of the Baltic Sea is characterized by two peaks: primary in August and a secondary, less significant level rise, in December. The minima peaks respectively fall to March-April and September-October. Thus, owing to the high level in the North Sea, Skagerrak and Kattegat Straits during autumn, and the lowest level in the Baltic Sea during the same period, some favourable conditions for the increasing influx of saline the North Sea waters into the Baltic Sea appear. In this regard, while studying the mechanism of "pouring" the North Sea waters, particular attention should be payed to the magnitude of level differences during autumn.

Evaluation of long-term sea level data, averaged over three autumn months (September-November), reveals the following. During the autumn period, an average sea level at Vladislavovo station exceeds that of the Gedser station practically throughout the whole period of joint observation. Comparing the values of the sea levels of the stations Kobenhavn and Smogen the sea level in the northern part of Kattegat Strait shows a significant excess (from 100 to 250 mm) over the level of the south-western part of the Baltic during 1911–1938. Later, up to 1984 value of the differences in the sea levels were characterized by somewhat lower values relative to the previous period, which usually did not exceed 150 mm. During 1985–1993 the sea level in the northern part of Kattegat Strait exceeded the level at the Kobenhavn station by no more than 100 mm, in addition, in 1978, 1985, 1990 and 1991 the reverse situation was observed, when the sea level in south-western Baltic exceeded the level of the Smogen station. When comparing the averaged values for the autumn sea-level positions at the Smog and Gedser stations, the level at the Smogen

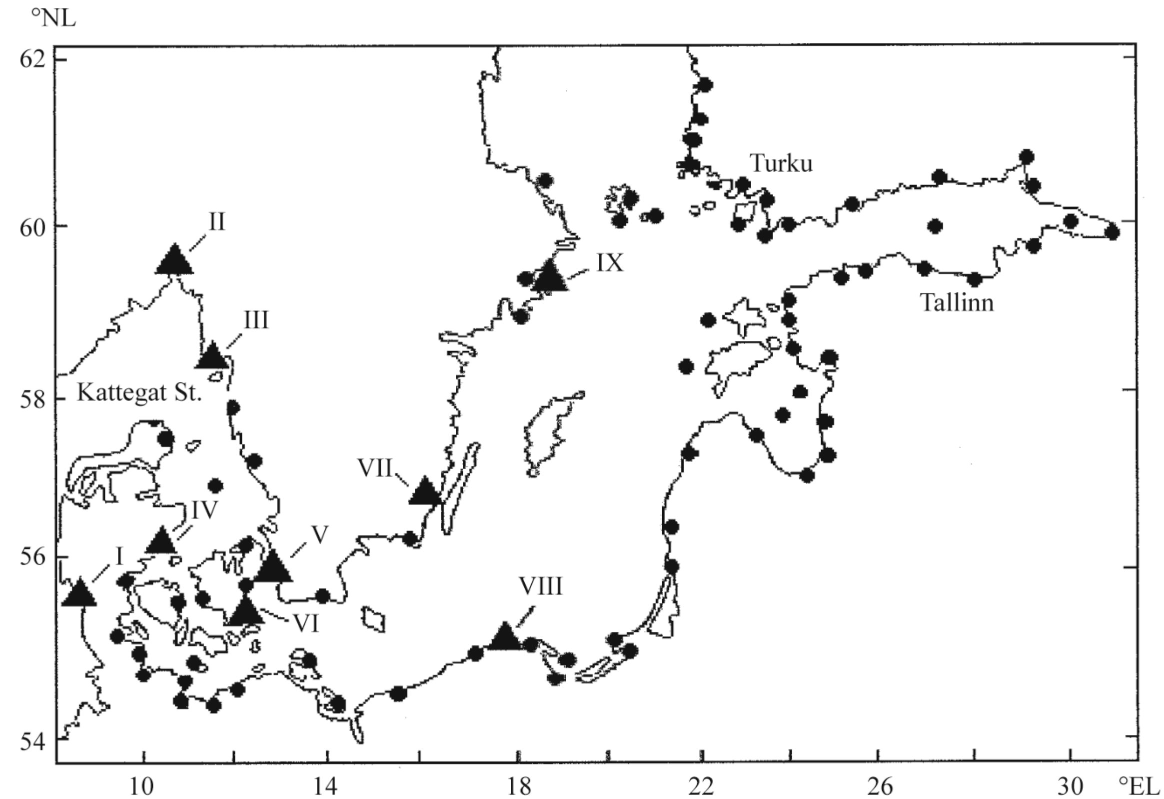

Fig. 7. Scheme of the mark level stations of the Baltic Sea. Conventional symbols and Roman numerals correspond to the positions of the level observations (▲) (I–IX) and to the positions of observations for the sea level (●). I is Esbjerg; II is Oslo; III is Smogen; IV is Aarhus; V is Gedser; VI is Kobenhavn; VII is Kungholmsfort; VIII is Vladislavovo; IX is Stockholm.

station was found to significantly exceed the level at the Gedser station in 1990.

In general, based on a comparative analysis of the dynamics of sea levels, an extreme increase of the level at the beginning of 1990s in the southwestern Baltic Sea can be stated, which blocks the penetration of a significant amount of salty water with high content of dissolved oxygen from the North Sea. The long-term dynamics of salinity and concentration of oxygen in the bottom layer of the Gotland Deep in the central part of the Baltic Sea is characterized by the strong connection with the difference in the sea levels between the Smogen-Kobenhavn and the Smogen-Gedser and Oslo -Kobenhavn stations (Table).

Fig. 8 shows a comparison of the level difference between the stations with the inflow component and salinity in the bottom layer of the Gotland Deep (layer 240 m). Thus, the ratio of the values of the sea level in south-western Baltic Sea and the Kattegat Strait is one of the most important factors determining the possibility and the inflow water rate from the North Sea into the Baltic Sea. Conversely, the equalized surface, obviously, depends on a large-scale atmospheric circulation and water balance components including the significant role played by the runoff.

INFLUENCE OF A LARGE-SCALE ATMOSPHERIC CIRCULATION AND RUNOFF OF RIVER ON THE EQUALIZED REGIME

Weather and climate of the North Atlantic and adjacent regions of North America and Eurasia depend to a large extent on the atmospheric circulation over the North Atlantic, which is represented by a system of Iceland minimum and Azores maximum pressure. These systems are called centers of action of the atmosphere. There is a constant transfer of the air masses from west to east in the middle latitudes over the North Atlantic, due to this. The intensity of the transfer is subjected to significant fluctuations over time due to their parameters of the centers of action vary. The difference in atmospheric pressure at the stations located near the climatic

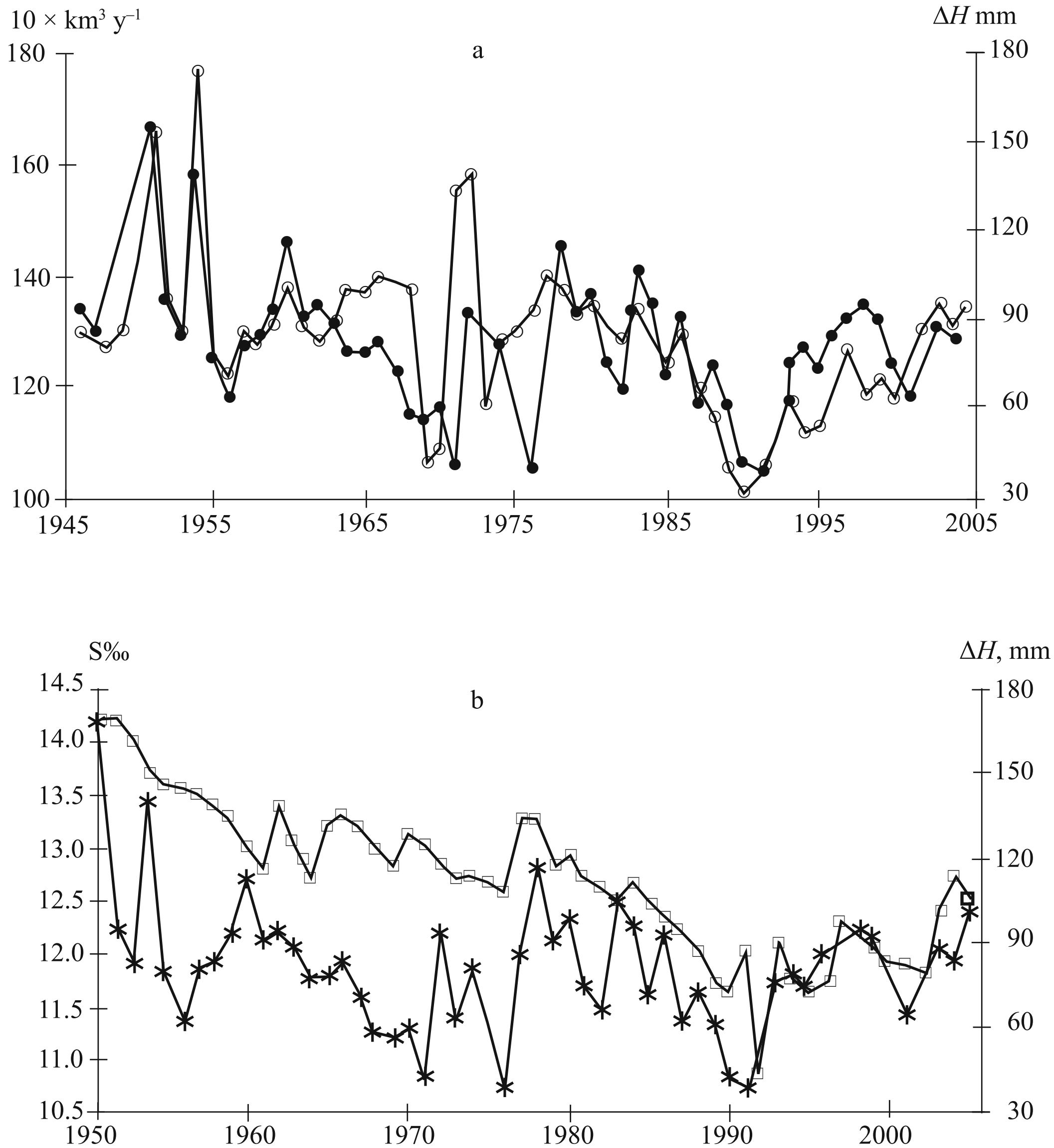

Fig. 8. Effect of the inflow on the annual average values of the sea level differences (ΔH, mm) at the Smogen and Kobenhavn stations in the North and Baltic Seas (a). Dots and hollow dots correspond to inflow and to the level difference, respectively. Effect of the the salinity (S) (□) on the annual average values of the sea level differences (∗) in the bottom layer of the Gotland Deep (b).

centers is taken as a measure of the intensity of western transfer [11]. This pressure difference, defined as a rule, during the winter months, is called the North Atlantic Oscillation (NAO). NAO index of atmospheric circulation is widely used in international practice in research of climatic variations and their reasons.

It was established that the increase in the intensity of atmospheric circulation over the North Atlantic is accompanied by the growth of heat and moisture transfer rate from the ocean towards the North and North-Eastern Europe. The development of cyclonic activity also leads to increase in liquid and solid atmospheric precipitations over the territory of Norway, Central and Northern Sweden and Finland. Increase in the intensity of precipitation leads to a significant increase in the river discharge of western and northern parts of the catchment area into the Baltic Sea. The presence of a positive nature of the relationship between some rivers of the Baltic states and the North Atlantic Oscillation may be explained by assuming some change in the trajectory of some cyclones to the south-east as they move over the continent [3]. The circulation of surface waters in the Baltic Sea, as well as in most other seas of the northern hemisphere on the whole is cyclonic in nature, i.e. in a counterclockwise direction. In this regard, the river waters entering the sea from the territory of Sweden are supposed to circulate mainly to the south and southwest, due to their relatively low density. Intensification of the western transfer will promote the development of this tendency. It will result in a certain rising of sea level in the south-eastern part of the Baltic Sea, especially in shallow and narrow straits of Sund (the level station Kobenhavn) and the Little Belt (the level station Gedser), which in turn leads to slowing of the entry of water masses from the North Sea. The positive and relevant at 99% reliability correlation coefficients between the values of average annual river runoff from the Scandinavian peninsula into the Baltic Sea and the annual sea level data at the stations of Gedser (Denmark) (r = 0.43) and Kobenhavn (r = 0.46) confirm the above mentioned data.

During the periods of lower intensity of atmospheric circulation over the North Atlantic water content of rivers, which collecting areas are located in Germany and Poland, increases, while the runoff within the Scandinavian Peninsula reduces. A similar situation could also lead to some increase in the sea level in south-western part of the Baltic Sea and to the corresponding limit of inflow of North Sea waters. However, the positive correlation coefficients between the NAO_{gent} index values and salinity as well as dissolved oxygen concentration should be obtained in this case. Yet, the calculation results indicate the opposite. The increase of the generalized index NAO_{gen} is accompanied by a decrease in salinity and dissolved oxygen concentration in the bottom layer of the Gotland Deep (r =– 0.445 at P = 99%).

Thus, the sea level in south-western part of the Baltic Sea and southern Danish Straits depends mainly on the river waters inflow from the northern and north-western areas of the basin. However, this does not mean that low values of the intensity of atmospheric circulation over the North Atlantic and, consequently, reduced runoff in Sweden is favorable for penetration of water masses from the North Sea into the Baltic Sea. It should be taken into account that at low intensity of cyclonic processes a significant increase in the level of the North Sea can not be expected, and, consequently, the corresponding lift in the Kattegat Strait that along with the increasing spring-time flush of southern regions make it impossible for a considerable amount of Atlantic water masses penetrate into the Baltic Sea. Optimal conditions for the penetration of North Sea waters into the Baltic Sea can be expected at the values of the indices NAO, close to the average.

Generally, the growth in the intensity of atmospheric circulation over the North Atlantic region leads to a slight (r = 0.302 at P = 95%) rise in the sea level off the coast of western Denmark at the Esbjerg station. In the north-eastern part of the Kattegat Strait at the Smogen station the links with NAO are even weaker. In this regard, significant inflow of the water masses from the North Sea into the Baltic Sea and the rise of the sea level in the Baltic Sea due to horizontal advection can not be expected. However, the sea level at the Kobenhavn and Kungholmsfort stations, located off the coast of southern Sweden, shows sufficiently high dependence on the North Atlantic Oscillation. Relationship between dynamics of the intensity of atmospheric circulation and the sea level difference between the northern part of the Kateggat Strait and south-western regions of the Baltic Sea having a negative character is a point of interest. This fact confirms the above mentioned concerning the periods of NAO rising not providing any conditions for the formation of a strong inflow.

CONCLUSION

Summarizing the peculiarities of long-term dynamics of the meteorological parameters, it can be concluded that over the past 50–100 years, the most extreme values were observed in the period from late 1980 until early 1990. It was the period when the intensity of atmospheric circulation over the North Atlantic over the past 100 years reached its extremely high values, that led to an increase in the average annual air temperatures in the western and eastern coasts of the Baltic Sea up to some of the highest values as well as significant rise of water temperature in the intermediate and deep layers of the deep-sea trenches. At the same time the sea level in south-western Baltic Sea at the Kobenhavn, Gedser and Kungholmsfort stations reached the highest value during the last 100 years of regular observations. During the period from 1990 to 1992 the value of salinity in the deep and bottom layers of the deep-sea trenches abruptly decreased, while in the bottom layer of the Gotland Deep extremely low value of salinity for the entire period of instrumental observations was marked in 1992. Reduced salinity and oxygen concentration in the deep and bottom layers of the largest cavities of the Baltic Sea along with the atmospheric circulation over the North Atlantic suggests the formation of a certain barriers for penetration of the North Sea waters into the Baltic Sea during the period. The only reason can be the rise of the sea level in the southern and especially in the south-western sea areas located directly in front of the Danish straits.

So, according to above mentioned, a strong and long-term inflow of the North Sea waters into the Baltic which can lead to significant changes of hydrochemical and hydrobiological regime of the southern and central regions is possible only when the values of the intensity of atmospheric circulation over the North Atlantic are close to the average or slightly below normal. This entirely fits the analysis of field data. For example, a very powerful inflow of 1951, developed against the NAO_{gen} values, equal to 0.1, with the average value — 0.022 was observed for the period from 1895 to 2005. Less powerful inflows of 1970, 1978, 2004 occurred at NAO_{gen} values, being respectively, –0.8, –1.1 and –0.79. Extremely low-powered inflows are formed at NAO values, far exceeding the standard. For example, the extremely low inflow of North Sea waters in 1989 and 1990 was against NAO_{gen} values, respectively, +3.9 and +3.1. This consistent pattern should be reasonably used in the future to develop the methods of prediction the parameters of water exchange between the North and Baltic Seas.

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