Oxygen and thermohaline conditions in the Polish fishing zone in 1979–1983

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Baltic water temperature
Salinity
Water saturation
with oxygen

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Abstract

The article presents the thermohaline and oxygen conditions in the Polish fishing zone in the period 1979–1983. The discussion is based on the results of investigations carried out according to the I stage of the Baltic Monitoring Programme within the frame of the Helsinki·Convention. Long-term trends of water temperature, salinity and oxygen saturation fluctuations induced natural and anthropogenic factors are also presented.

1. Introduction

The thermohaline and oxygen conditions of the Polish fishing zone are well recognized after multidecade research carried out in this region (Majewski *et al.*, 1976). For quite a long time there had been observed considerable, unfavourable changes of the Baltic Sea environment and that was the reason for undertaking in 1979 systematic analysis of the open sea area within the frame of the international Baltic Monitoring Programme; the coastal zones were simultaneously examined according to national monitoring programmes, introduced succesively by the Baltic countries.

The article presents the results of water temperature, salinity and oxygen concentration measurements conducted by the Institute of Meteorology and Water Management, Maritime Branch in Gdynia during the

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period 1979–1983 (Trzosińska *et al.*, 1984), as well as trends of long-term variations of these parameters. The long-term trends were possible to calculate owing to a multiyear research set out in certain regions as early as the beginning of the present century.

2. Materials and methods

The presented analysis of the thermohaline and oxygen conditions of the Polish fishing zone is based on the results of systematic seasonal measurements carried out by the Institute of Meteorology and Water Management, Maritime Branch in Gdynia, in the years 1979–1983. The measurements were carried out within the frame of the international Baltic Monitoring Programme as one of the commitments of the Convention on the Protection of the Marine Environment of the Baltic Sea Area (Helsinki Convention). The 5 years period constituted the I stage of this Programme. To supplement the characteristics of the analysed parameters, the results of measurements conducted parallelly in the Polish coastal zone and in the bays have been included in the analysis.

The measurements of water temperature, salinity and oxygen concentration were carried out on board the r/v HYDROMET. Water temperature was recorded with reversed thermometers of the accuracy 0.02°C, installed on Nansen bathometers. Nansen bottles were also applied for water sampling for the salinity and oxygen determinations. Salinity was determined by conductivity measurements in a laboratory salinometer, standardized with 35‰ standard salinity water. Oxygen concentration was determined by routine Winkler method, while hydrogen sulphide spectrophotometrically.

The samples were collected at locations defined by the internationally unified system of stations and depths (Baltic Marine Environment, 1980). In the Polish fishing zone the station net was more dense and included, apart from the international Stations BY5 (the Bornholm Deep), BCS III 10 (the southern end of the Gotland Basin) and P1 (the Gdańsk Deep), also open sea stations located along the northern border of the Polish fishing zone, stations in the Pomeranian Bay and in the Gulf of Gdańsk, as well as coastal zone stations along the Polish coast from Rozewie to Dziwnów.

The results of measurements and analyses obtained in the period of study were averaged for the characteristic water layers, selected regions (open sea area, coastal zone, the Pomeranian Bay and the Gulf of Gdańsk), seasons and also for the entire 5 years period admitted as a statistical year. The seasons were adopted as follows: January to May – winter, April to June – spring, July to September – summer and October to December – autumn. The open sea region included: the Bornholm Deep, the Słupsk Furrow, northern part of the Gulf of Gdańsk and southern part of the Gotland Deep. Since the Gulf of Gdańsk is a hydrologically heterogeneous region, the data from this area were classified into 2 classes by dividing the gulf into an inner part – from the coast to the Hel Peninsula, and an outer part – from the Hel Peninsula to the line Rozewie – Taran Cape.

3. Temperature, salinity and oxygen concentration variations in the years 1979–1983

The Polish fishing zone is easily partitioned into the following regions: the deep water open sea region, shallow water coastal zone, as well as the Gulf of Gdańsk and the Pomeranian Bay together with the Vistula and Świna estuaries.

Water of the Polish fishing zone is characterized similarly to the entire Baltic by stratification. *i.e.* occurrence of water layers of significantly different hydrological properties: the top layer (surface) and the bottom one are separated by an intermediate water layer with considerable salinity gradients.

Waters of the coastal zone and the Pomeranian Bay, as well as those of the Gulf of Gdańsk and of the open sea zone down to 50–60 m depth form the surface water layer of the Southern Baltic. Water of the Gulf of Gdańsk and of the open sea region below 50–60 m depth is ranked to the deep or intermediate layers. Each layer is characterized by different, specific oxygen and thermohaline conditions. These conditions are subject to temporal changes depending on the water layer and the sea region.

3.1. Water temperature

The temperature of the top water layer is subjected to seasonal changes, and moreover, in the coastal zone, the changes are short-termed (a few or several degrees in a few hours) due to compensatory currents under the off-land winds.

Table 1: Extremal, seasonal and annual mean values of water temperature (°C) of the Polish fishing zone in 1979–1983

Region, water layer	Estimator	Winter	Spring	Summer	Autumn	Year
OPEN SEA						
0–20 m	$\tilde{T}$	1.63	8.13	15.87	9.34	8.69
	max	3.67	14.60	18.53	12.27	18.53
	min	–0.09	2.50	12.27	5.80	–0.09
	σ	0.81	2.24	1.05	2.51	4.46
isohaline layer	$\tilde{T}$	1.63	7.25	14.24	9.18	7.94
	σ	0.80	2.49	2.87	2.50	4.37
below isohaline layer	$\tilde{T}$	4.13	3.88	4.35	5.88	4.41
	σ	1.83	1.21	0.81	2.90	1.87
COASTAL ZONE						
central Polish coast						
0–20 m	$\tilde{T}$	0.72	7.32	15.40	7.63	8.78
	max	3.72	15.27	19.46	10.83	19.46
	min	0.10	2.89	6.69	5.14	0.40
	σ	0.86	3.52	1.79	1.42	5.40
POMERANIAN BAY						
surface to bottom	$\tilde{T}$	1.91	11.94	16.99	7.51	9.67
	max	3.72	15.27	19.91	9.12	19.91
	min	0.40	5.97	14.41	5.14	0.40
	σ	1.34	2.73	1.70	1.30	5.63
GULF OF GDAŃSK						
internal part						
0–20 m	$\tilde{T}$	1.84	10.69	16.21	8.87	10.29
	max	4.15	22.47	18.39	14.59	22.47
	min	0.14	1.97	12.93	3.94	0.14
	σ	1.16	5.10	1.22	2.28	5.52
isohaline layer	$\tilde{T}$	1.83	9.80	15.14	8.68	9.82
	σ	1.14	5.24	3.42	2.27	5.48
below isohaline layer	$\tilde{T}$	2.24	3.06	3.56	6.22	4.16
	σ	1.03	0.86	0.45	2.26	1.87
GULF OF GDAŃSK						
external part						
0–20 m	$\tilde{T}$	1.66	9.14	16.01	9.39	9.41
	max	3.45	16.72	17.92	12.26	17.92
	min	0.22	2.23	14.91	6.36	0.22
	σ	1.06	4.12	0.86	1.98	5.42
isohaline layer	$\tilde{T}$	1.64	7.93	14.99	9.34	8.80
	σ	1.04	4.53	2.36	1.98	5.37
below isohaline layer	$\tilde{T}$	4.22	4.29	4.06	5.00	4.37
	σ	1.90	1.42	1.03	1.54	1.51

σ – standard deviation

The distribution of surface water layer (0–20 m) temperature in the Polish fishing zone during the period 1979–1983 is characterized by extremal values and seasonal means calculated for the following regions: coastal zone, central Polish coast, the Pomeranian Bay and the Gulf of Gdańsk, with a subdivision into the inner and outer part, and the open sea region (Tabl. 1).

The temperature of the surface water (0–20 m) ranged from –0.1 to 22.5°C, and the annual mean values from 8.7 to 10.3°C. The annual means were higher in regions exposed to the thermal influence of rivers and lower in the open sea region and the adjacent coastal zone. In the inner Gulf of Gdańsk the annual mean temperature of the surface water was 10.3°C. in the Pomeranian Bay 9.7°C, in the outer Gulf of Gdańsk 9.4°C and in the open sea zone along the central Polish coast 8.7°C. As regards the extremal values in the period of study the greatest amplitude of surface temperature was noticed in the inner Gulf of Gdańsk, *i.e.* 22.3°C, in the Pomeranian Bay 19.5°C while in the outer Gulf of Gdańsk and in the open sea region it did not exceed 18°C.

The seasonal mean values of the surface temperature ranged in winter from 0.7 to 1.9°C, and in summer from 15.4 to 17.0°C. In spring, during water temperature increase, the fluctuations of the seasonal mean were more significant (4.6°C) than during the cooling phase in autumn (1.8°C). In the phase of temperature rising, higher values were recorded in the inner Gulf of Gdańsk and Pomeranian Bay, lower – in the outer Gulf of Gdańsk and in the open sea region; the opposite distribution of the temperature was observed during the cooling phase (Tabl. 1). The described spatial temperature distribution in both phases resulted mainly from differences in heat capacity between the shallow and deep water zones, particularly intensified by warming (in spring) and cooling (in autumn) effect of the river run-off.

As regards the vertical temperature distribution in the surface water layer, the shallow coastal zone remained isothermic during the major part of the year, while in the deep water region a thermal stratification – thermocline – was observed, liable to seasonal alterations. The vertical distribution of temperature in particular seasons is shown in Figure 1, the examples being the Bornholm Deep and the Gdańsk Deep.

In winter the entire surface water layer became isothermal with the temperature range from 0 to 4°C. In spring, the gradual warming up of the upper layer produced the outset of thermocline, which remained in

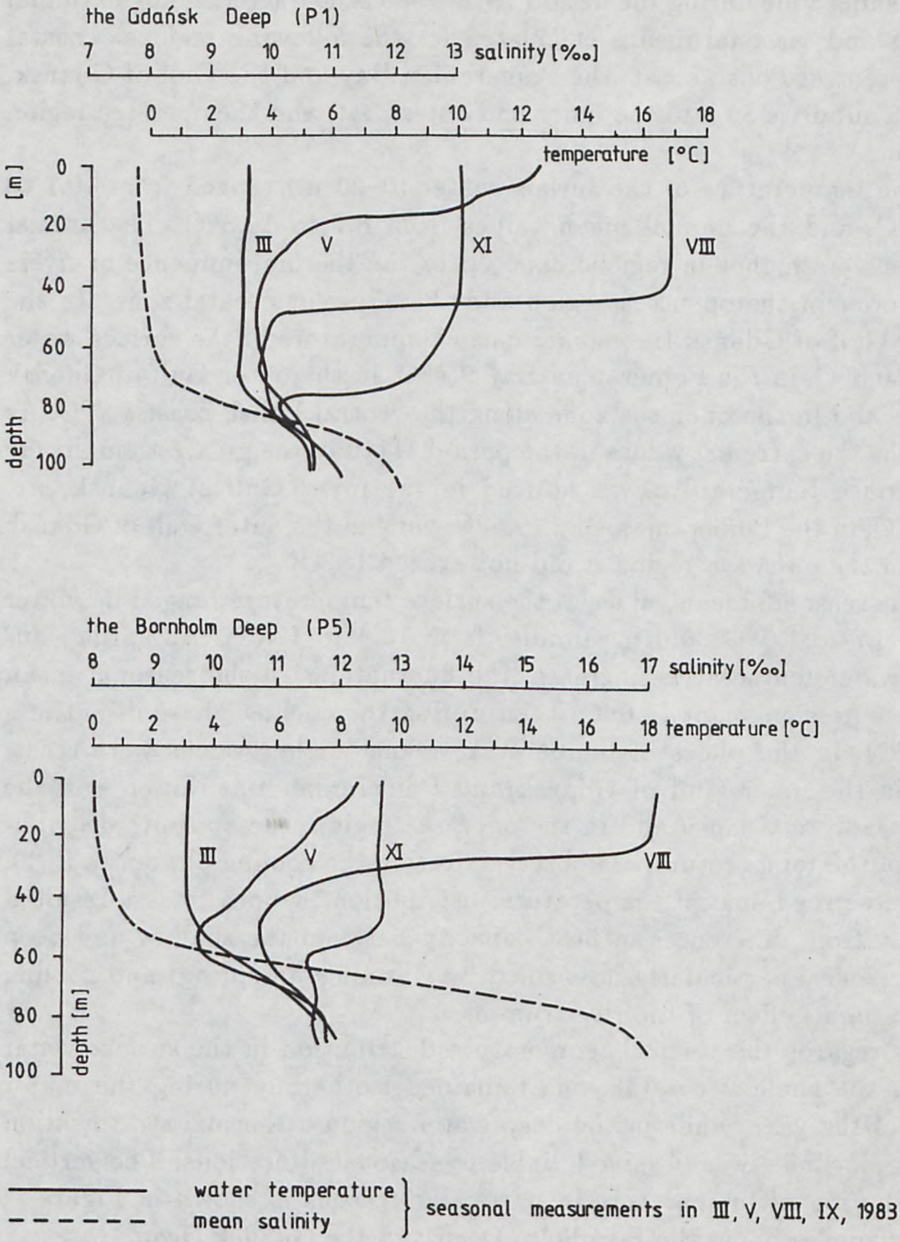

Figure 1: Vertical distribution of the water temperature and salinity in the Gdańsk Deep and in the Bornholm Deep in 1983

the layer 0–2 m with a gradient up to $0.5^{o}K \cdot 1\ m^{-1}$ under calm sea (Fig. 1, Station P1), while under strong mixing conditions due to the wind – induced waving – it ran slantwise through the surface layer with the gradient of about $0.1^{o}K \cdot 1\ m^{-1}$ (Fig. 1, Station P5). In summer, the thermocline gradually sank to 20–40 m depth, and the vertical temperature gradients increased to $1^{o}K \cdot 1\ m^{-1}$. Above the thermocline an isothermal water layer was formed with temperatures around the maximal values, and below the thermocline – a respective layer with temperatures around the minimal values. In autumn, the thermocline sank to the bottom of the surface water layer and the entire surface regained its isothermal character.

The highest annual mean temperature of the isohaline layer in the entire 20 m surface water layer of the Southern Baltic was recorded in the inner Gulf of Gdańsk – 9.8^{o}C – the value being clearly the effect of the Vistula river impact. In the outer Gulf of Gdańsk, where the influence of the Vistula was still noticeable, it reached 8.8^{o}C, while in the open sea zone – only 7.9^{o}C. The effect of the river water was well marked in spring – by increasing, and in autumn – by decreasing the temperature of the inner Gulf of Gdańsk. In spring the mean temperature of the isohaline layer in the inner Gulf of Gdańsk exceeded the respective values for the outer Gulf of Gdańsk by 1.9^{o}C and for open sea zone by about 2.6^{o}C, while in autumn it was lower by about 0.6^{o}C in comparison to the temperature of the deep water of the Polish fishing zone.

During the annual extremes periods, the differences between the mean surface temperature values of the particular regions diminished and ranged from 1.8 to 1.6^{o}C in winter and from 14.2 to 15.1^{o}C in summer (Tabl. 1).

The temperatures of the intermediate water layer depended on the seasonal changes observed in the upper layer and simultaneously on the temperature of water oozing into the intermediate layer from the Danish Straits region in the form of slow, yet almost continuous inflow resulting from the Baltic Sea and the North Sea levels arrangement.

In the deep water layer the temperature increment with depth was small. Temperature changes in this layer resulted from the temporal considerable inflows of warmer and more saline water from the North Sea.

Below the surface layer, the annual amplitude of water temperature for the period of study 1979–1983 was 9.6^{o}C, and the seasonal mean varied

Table 2: Long-term mean water temperature (°C) of the Gdańsk Deep

Water layers	Winter	Spring	Summer	Autumn	Year
	1950–1975				
	1979–1983				
0– bottom	3.86	4.61	7.88	7.07	5.83
	2.78	6.59	10.17	7.57	6.76
0–20 m	2.63	6.05	15.98	9.63	8.66
	1.49	9.58	15.81	9.46	9.07
0–50 m	2.66	4.44	11.34	8.77	6.82
	1.49	8.28	14.77	9.41	8.44
51 m – bottom	5.06	4.79	4.42	5.37	4.84
	4.45	4.39	4.22	5.05	4.54

from 5 to 8°C. The annual mean temperature of this layer reached 5.8°C in the Bornholm Deep, 4.5°C in the Gdańsk Deep and in the entire deep water layer of the Polish fishing zone – 4.4°C. This mean did not show significant seasonal variations; the differences between the seasonal mean values did not exceed 0.9°C in the outer Gulf of Gdańsk and 1.9°C in the open sea zone. Seasonal variability of temperature in the deep water layer was not clearly marked, however slightly higher temperatures were observed in autumn (Tabl. 1).

To compare the water temperature of the open sea region of the Southern Baltic in 1979–1983 with the long-term average, the seasonal and annual mean values have been presented in Table 2. The temperature concerning various water layers of the Gulf of Gdańsk were calculated for the period 1950–1975. In the period of study 1979–1983 water temperatures in the Gdańsk Deep were higher in the isohaline layer by 1.6°C and lower by 0.3°C in the deeep water layer in comparison to the long-term mean values. Water temperature of the Gdańsk Deep averaged from the surface to the bottom was almost 1°C higher in 1979–1983 than the long-term mean. This increment results from the fact that the spring and summer mean temperature values in 1979–1983 were significantly (by 3.4–3.8°C) higher than the respective long-term mean values. In autumn in the Gdańsk Deep the mean temperature of the isohaline water layer was only slightly higher (0.6°C) than the long-term mean, and in winter – lower by more than 1°C. In the deep water layer the mean temperatures were lower than the long-term mean in all the seasons of the 1979–1983 period.

3.2. Salinity

Water salinity of the Polish fishing zone, similarly to temperature, reveals different trends in the upper and deep water layers.

The upper water layer of the entire Polish fishing zone was an isohaline layer with the annual mean salinity (for the period 1979–1983) in the range from $7.4^{o}/_{oo}$, in the inner Gulf of Gdańsk, to $7.9^{o}/_{oo}$, in the open sea and along the central Polish coast. In the outer Gulf of Gdańsk and in the Pomeranian Bay the mean annual salinity reached $7.7^{o}/_{oo}$ (Tabl. 3).

Seasonal fluctuations of salinity of the isohaline layer revealed variable intensity, depending on the region. The fluctuations included a decrease of salinity in spring and summer ensuing from the intensified in these seasons river run off, and an increase of salinity in autumn and winter due to the frequent storms inducing vehement waving, currents and deep mixing of water. The seasonal variability of salinity was clarly marked in the direct vicinity of river estuaries; the amplitude of changes of the seasonal mean salinity values in the Gdańsk Deep was about $1^{o}/_{oo}$ (Tabl. 3) and the amplitude of the extremal values was over $8^{o}/_{oo}$ (from 0.5 to 8.8 $^{o}/_{oo}$) in the entire period of study. In the Pomeranian Bay the seasonal amplitude was also $1^{o}/_{oo}$ while the absolute amplitude – $4.6^{o}/_{oo}$ (from 4.6 to $9.2^{o}/_{oo}$) in 1979–1983. The salinity fluctuations distinctly faded in the coastal zone beyond the estuarial regions: the absolute amplitude was quite high – $4.7^{o}/_{oo}$ (from 4.5 to $9.2^{o}/_{oo}$), but the seasonal amplitude did not exceed $0.4^{o}/_{oo}$ (Tabl. 3). The surface salinity of the open sea zone and of the Gulf of Gdańsk showed only weak variability: the seasonal amplitude did not exceed $0.2^{o}/_{oo}$, and the absolute amplitudes in the period of study were $2.4^{o}/_{oo}$ (6.9 to $9.3^{o}/_{oo}$) and $1.4^{o}/_{oo}$ (6.7 to $8.1^{o}/_{oo}$) in the open sea and the outer Gulf of Gdańsk, respectively.

Below the isohaline layer, a stepwise increase of in salinity with gradients up to $0.5^{o}/_{oo}$ per 1 depth occurred, forming an intermediate layer with respect to halocline. This intermediate water layer occurred at the depth of 50–80 m in the deep water region of the Polish fishing zone, in shallower regions it reached the bottom. In the intermediate water layer the salinity increased from the boundary with the surface layer to the boundary with the deep water layer from 9 to $15^{o}/_{oo}$ in the Bornholm Deep and from 9 to $11^{o}/_{oo}$ in the Gdańsk Deep (Figs. 2 and 3).

In the deep water layer the salinity increased gradually to reach the maximal values at the bottom. The fluctuations of salinity in this layer depended on the sporadic inflows of water from the North Sea. The re-

Table 3: Mean salinity ($^o/_{oo}$) of the Polish fishing zone in 1979–1983. In brackets – standard deviation values

Region, water layer	Winter	Spring	Summer	Autumn	1979–1983
OPEN SEA					
isohaline layer	**8.00**	**7.86**	**7.78**	**7.96**	**7.89**
	(0.19)	(0.17)	(0.17)	(0.29)	(0.22)
below isohaline layer	**10.81**	**11.00**	**11.51**	**11.68**	**11.21**
	(1.98)	(2.21)	(2.00)	(2.54)	(2.15)
COASTAL ZONE					
central Polish coast					
surface to bottom	**8.18**	**7.79**	**7.87**	**8.08**	**7.97**
	(0.42)	(0.75)	(0.40)	(0.76)	(0.61)
POMERANIAN BAY					
surface to bottom	**8.14**	**7.19**	**7.60**	**8.04**	**7.74**
	(0.78)	(0.99)	(0.62)	(0.95)	(0.91)
GULF OF GDAŃSK					
internal part					
isohaline layer	**7.48**	**6.84**	**7.43**	**7.56**	**7.36**
	(1.38)	(1.73)	(0.72)	(0.77)	(1.15)
below isohaline layer	**9.05**	**8.85**	**9.28**	**8.57**	**8.95**
	(1.05)	(0.56)	(0.83)	(0.89)	(0.87)
GULF OF GDAŃSK					
external part					
isohaline layer	**7.91**	**7.69**	**7.74**	**7.75**	**7.77**
	(0.20)	(0.30)	(0.08)	(0.08)	(0.20)
below isohaline layer	**10.28**	**10.40**	**10.28**	**10.15**	**10.28**
	(1.78)	(1.58)	(1.61)	(1.51)	(1.60)

corded salinity fluctuations in the Bornholm Deep and in the Gdańsk Deep (Figs. 2 and 3) indicated that larger inflows of oceanic water into the Baltic took place on the turn of 1979/80 and in the first halves of 1980 and 1983. These inflows resulted in an increase of the bottom salinity to almost 18$^o/_{oo}$ in the middle 1980 and 17.5$^o/_{oo}$ in the middle of 1983 in the Bornholm Deep, the respective values for the Gdańsk Deep being 13$^o/_{oo}$ and 12$^o/_{oo}$. During the stagnation periods, predecessing the inflows, the salinity of the bottom water layer in the Bornholm Deep had dropped to 14$^o/_{oo}$ in the summer of 1979 and to 14.5$^o/_{oo}$ in 1982. In the Gdańsk Deep, during the stagnation period, the near bottom salinity decreased to 10.5$^o/_{oo}$ in 1982.

Below the isohaline layer the salinity distribution varied according to the region (Tabl. 3). During the period 1979–1983 the salinity amplitude of the layer below halocline reached 5.2$^o/_{oo}$, while the difference between

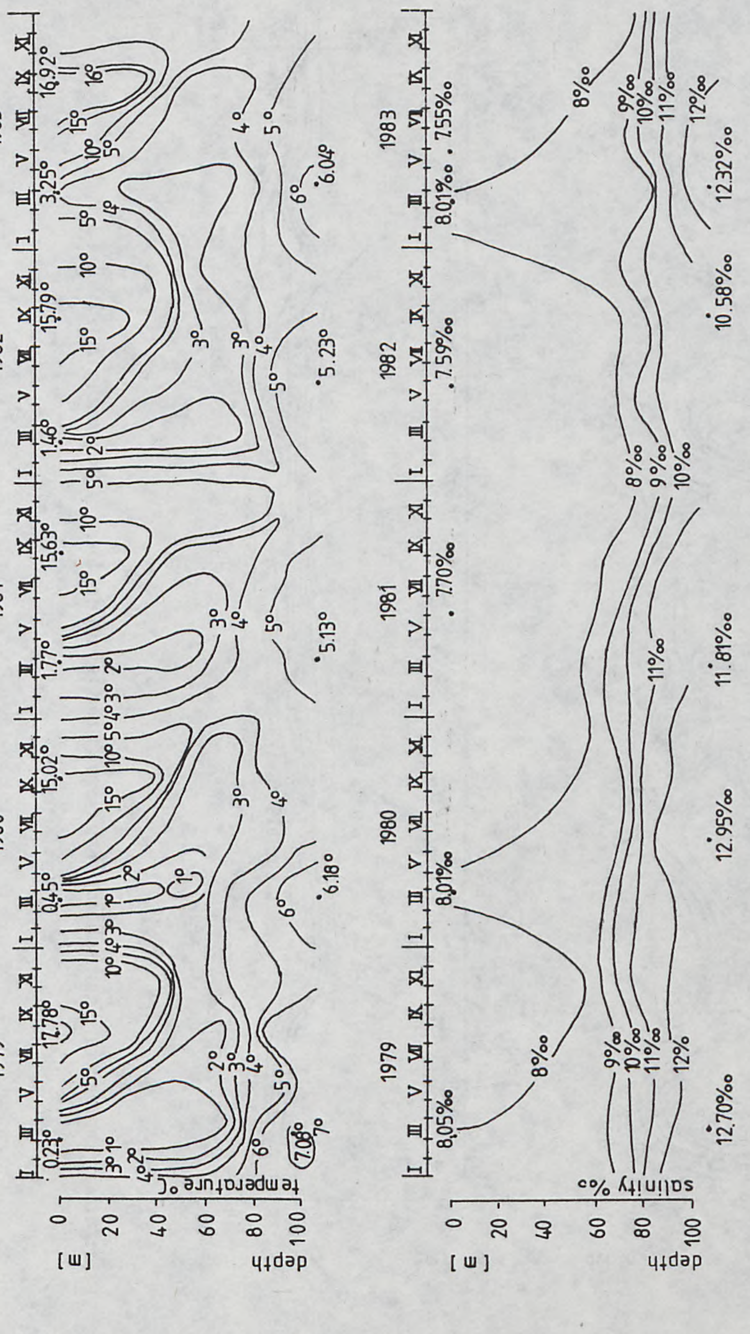

Figure 2: Temperature and salinity variations of the Gdańsk Deep (P1) water in 1979–1983

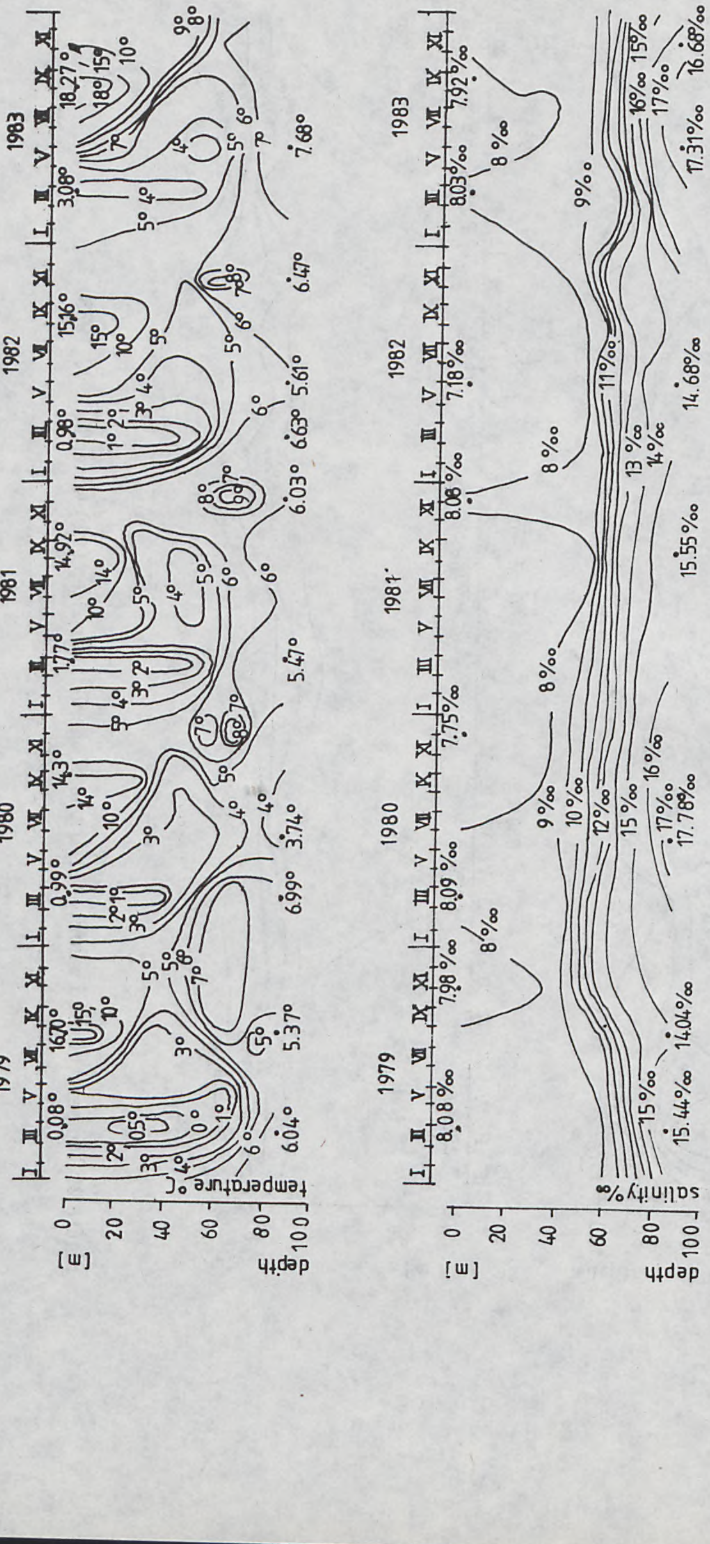

Figure 3: Temperature and salinity variations of the Bornholm Deep (BY5) water in 1979–1983

Table 4: Long-term mean salinity ($^o/_{oo}$) of the Gdańsk Deep water

Period	Water layers			
	0– bottom	0–20 m	0–50 m	51– bottom
1950–1975	9.109	7.528	7.602	10.616
1979–1983	8.957	7.781	7.802	10.475

Table 5: Long-term mean salinity ($^o/_{oo}$) of the Bornholm Deep water

Period	Water layers			
	0– bottom	0–20 m	0–50 m	51– bottom
1902–1960 after Soskin	10.584	7.410	7.555	14.828
1979–1983	10.200	7.935	7.974	14.275

the extremal values of the seasonal means was 0.2$^o/_{oo}$ in the outer Gulf of Gdańsk, the values being equal to 10.2 and 0.9$^o/_{oo}$, respectively, in the open sea zone. The annual mean salinity – 10.2$^o/_{oo}$ – of the outer Gulf of Gdańsk was lower by almost 1$^o/_{oo}$ than the mean salinity calculated for the entire open sea zone (Tabl. 3) and by 4$^o/_{oo}$ than the annual mean value for the Bornholm Deep.

To compare the salinity of the open sea zone of the Southern Baltic in the period of study (1979–1983) with the average long-term values, the mean salinity of the Gdańsk Deep (Tabl. 4) calculated for the period 1950–1975 and of the Bornholm Deep – calculated by Soskin (1968) for the period 1902–1960 (Tabl. 5) were used. The salinity of the isohaline layer was by 0.2$^o/_{oo}$ higher in the Gdańsk Deep and by 0.41$^o/_{oo}$ in the Bornholm Deep than the long-term mean value. In the deep water layer the salinity was lower than the long-term mean value by 0.15$^o/_{oo}$ in the Gdańsk Deep and by 0.55$^o/_{oo}$ in the Bornholm Deep.

3.3. Water saturation with oxygen

The upper water layer of the Polish fishing zone was well aerated because of the gas exchange with the atmosphere, photosynthesis process and factors promoting homogenization of water. Strong stratification of the Baltic water forms an effective obstacle for thermal convection and thus hinder vertical oxygen exchange, due to which the deeper water layers

Table 6: Mean oxygen concentration ($cm^3 \cdot dm^{-3}$) in the Polish fishing zone in 1979–1983. In brackets – standard deviation values

Region, water layer	Winter	Spring	Summer	Autumn	1979–1983
OPEN SEA					
isohaline layer	**9.19**	**9.17**	**6.66**	**7.53**	**8.18**
	(0.31)	(0.91)	(0.69)	(0.46)	(1.12)
below isohaline layer	**5.33**	**4.66**	**3.34**	**2.84**	**4.13**
	(2.39)	(2.43)	(1.92)	(2.43)	(2.39)
COASTAL ZONE					
central Polish coast					
surface to bottom	**8.71**	**8.84**	**6.56**	**7.52**	**7.71**
	(2.01)	(1.32)	(0.71)	(0.92)	(1.53)
POMERANIAN BAY					
surface to bottom	**9.31**	**7.67**	**6.09**	**7.98**	**7.64**
	(0.37)	(1.77)	(1.85)	(0.25)	(1.75)
GULF OF GDAŃSK					
internal part					
isohaline layer	**9.11**	**8.30**	**6.30**	**7.36**	**7.51**
	(0.55)	(1.42)	(1.00)	(0.72)	(1.40)
below isohaline layer	**6.55**	**5.67**	**4.33**	**5.58**	**5.36**
	(2.84)	(2.24)	(1.74)	(2.48)	(2.35)
GULF OF GDAŃSK					
external part					
isohaline layer	**9.24**	**9.14**	**6.43**	**7.35**	**7.97**
	(0.57)	(0.84)	(0.60)	(0.86)	(1.38)
below isohaline layer	**3.90**	**3.60**	**3.46**	**2.85**	**3.45**
	(3.61)	(3.29)	(2.71)	(2.64)	(3.06)

are not so well aerated. Water inflows from the North Sea constitute the main source of oxygen in this layer.

The mean oxygen concentration in the isohaline layer of the Southern Baltic reached ca 8.0 $cm^3 \cdot dm^{-3}$ (100.8% of saturation) in the period 1979–1983. Higher concentrations were noticed in the open sea zone, lower in the Pomeranian Bay, in the inner part of the Gulf of Gdańsk and in the coastal zone (Tabl. 6). These values corresponded to the average aeration of the isohaline layer – slightly over the saturation level as regards the open sea zone of the Southern Baltic and the Pomeranian Bay and slightly below the saturation level as regards the central Polish coast and the Gulf of Gdańsk (Tabl. 7). The largest amplitude of oxygen content fluctuations was observed in regions of direct competition between the land and marine factors with the variation coefficient – about 0.2 – almost two fold higher than that for the open sea zone.

Table 7: Mean values of water saturation with oxygen (%) in the Polish fishing zone in 1979–1983. In brackets – standard deviation values

Region, water layer	Winter	Spring	Summer	Autumn	1979–1983
OPEN SEA					
isohaline layer	**99.4**	**114.2**	**97.7**	**98.4**	**102.5**
	(4.5)	(12.0)	(5.4)	(7.1)	(9.0)
below isohaline layer	**60.9**	**52.3**	**39.1**	**34.7**	**47.9**
	(25.7)	(23.9)	(18.1)	(29.4)	(25.1)
COASTAL ZONE					
central Polish coast					
0–30 m	**91.9**	**109.0**	**97.1**	**94.6**	**97.9**
	(21.3)	(16.2)	(11.7)	(11.2)	(16.0)
POMERANIAN BAY					
surface to bottom	**101.4**	**106.8**	**99.8**	**100.3**	**101.2**
	(4.0)	(25.7)	(11.1)	(3.5)	(14.0)
GULF OF GDAŃSK					
internal part					
isohaline layer	**98.7**	**109.9**	**93.8**	**94.6**	**98.2**
	(5.9)	(25.6)	(12.0)	(7.4)	(12.6)
below isohaline layer	**73.6**	**63.8**	**49.5**	**69.0**	**62.4**
	(30.7)	(24.7)	(19.7)	(32.1)	(27.5)
GULF OF GDAŃSK					
external part					
isohaline layer	**99.9**	**115.8**	**95.6**	**96.1**	**101.6**
	(6.1)	(15.6)	(10.7)	(10.1)	(13.7)
below isohaline layer	**43.8**	**40.9**	**39.5**	**34.4**	**39.6**
	(38.7)	(36.1)	(30.6)	(32.8)	(34.6)

The mean oxygen concentrations in the euphotic zone (0–30 m) were higher than in the isohaline layer as a whole. The greatest differences, up to 5% of the saturation level, were recorded in spring and summer in connection with the thermocline building up; however, throughout the year these differences were on the order of 1–2% of the saturation level.

Dissolved oxygen content in the Baltic Sea varies seasonally. The maximum saturation (Tabl. 7) appeared in all the regions in spring due to intensive primary production. The autumn phytoplankton blooms produced only a slight increase of the average saturation compared to summer when oxygen concentrations dropped to the minimum level (Tabls. 6 and 7). Cooling of water and homogenization of the isohaline layer in winter facilitated oxygen dissolution in water, and thus increased the absolute concentrations. The five-years (1979–1983) mean oxygen concentration reached 9.2 $cm^3 \cdot dm^{-3}$ in the isohaline layer in winter and in

Table 8: Appearance of hydrogen sulphide ($\mu mol \cdot dm^{-3}$) in the deep part of the Southern Baltic in 1979–1983

Region	Estimator	Winter	Spring	Summer	Autumn	Year
GDAŃSK DEEP	n	–	2	8	3	13
	$\bar{x}$	–	1.63	16.45	6.34	11.84
	σ	–	–	3.59	–	9.80
	max	–	2.03	23.03	11.25	26.03
	min	–	1.23	3.59	1.68	1.23
BORNHOLM DEEP	n	–	2	8	8	18
	$\bar{x}$	–	0.89	3.72	8.48	5.52
	σ	–	–	2.55	7.61	5.90
	max	–	1.77	6.88	18.14	18.14
	min	–	0.01	0.08	0.02	0.01

n – number of observations
$\bar{x}$ – mean value
σ – standard deviation

summer it dropped to 6.7 $cm^3 \cdot dm^{-3}$ (Tabl. 6). Water saturation with oxygen remained around 100% in winter isohaline waters of all the regions except for the coastal zone where the considerable oxygen demand for organic matter utilization manifested itself in a significant decrease of the average oxygen concentrations (Tabls. 6 and 7).

Directly below the isohaline layer the oxygen concentrations rapidly decreased. The largest oxygen concentration gradients were encountered in the halocline. In 1979–1983 the lowest mean aeration of water below the isohaline layer (Tabls. 6 and 7) was noticed in the deep part of the Gulf of Gdańsk whereas in the open sea zone it was slightly higher. Seasonal variations in oxygen concentration were also noticeable below the halocline (Tabls. 6 and 7). The highest oxygen concentration and the greatest saturation occurred in winter, while from spring to autumn these good oxygenation conditions succesively deteriorated. This seasonal rhythm of oxygen fluctuations was occasionally affected by irregular inflows of oceanic water.

During the stagnation periods the dissolved oxygen was completely utilized below the halocline of the Bornholm Deep and the Gdańsk Deep and hydrogen sulphide appeared (Tabl. 8), usually in summer and autumn. Particularly unfavourable conditions occurred in 1982, when small amounts of hydrogen sulphide appeared already in spring. In the period of study hydrogen sulphide appeared temporarily in the layer of about

20 m above the bottom of the both Deeps in concentrations from trace to 26 $\mu mol \cdot dm^{-3}$.

4. Long-term variations

Water temperature, salinity and oxygen contents, besides the temporal, seasonal and random fluctuations, reveal also long-term variations (Tabl. 9). Since the beginning of the present century an increase of temperature and salinity is being observed, accompanied by a depletion of oxygen content in the near bottom water; since the 50's also an increase of the surface layer aeration is being noticed. The intensity of the observed oscillations varied during the century, depending on the periodicity and trends of factors influencing the analysed parameters. Long-term variations of water temperature and salinity are generally related to climate changes, particularly to changes of water exchange between land and sea, as well as to water exchange with the ocean; in the case of oxygen content an additional factor exerting an influence was eutrophication of water.

Long-term behaviour of surface water temperature of the Baltic, though considerably variable from year to year, showed a general weak tendency to increase, hard to calculate in the authors' opinion (Melvasalo *et al.*, 1981). Taking into account the considerable increase of the air temperature observed in the northern hemisphere for several decades it was assumed that the temperature of the surface Baltic water increased by over $1\,^{0}$C in comparison to the values measured in the second half of the XIX century and at the beginning of the present century (Baltic Marine Environment, 1987). Calculations performed for the Gulf of Gdańsk area point out that the average annual temperature increased by $0.0085\,^{0}$C in the coastal zone (the Hel Peninsula) in the 1951–1975 (Majewski, 1979) and even more – $0.012\,^{0}$C in the surface layer of the Gdańsk Deep during 1974–1983 (Tabl. 9).

Similarly to temperature, the salinity shows an increasing trend of various intensity depending on the region and period (Tabl. 9). In the years 1900–1974 the mean annual increase of salinity observed in the Bornholm Deep and in the Gotland Deep (1977–1984) was around $0.007^{o}/_{oo}$ and it was more intensive – $0.009^{o}/_{oo}$ in the Gdańsk Deep. This increasing trend was weak in the years 1952–1974, and since 1977 a decrease of salinity by about $0.015^{o}/_{oo}$ per year in the Gotland Deep (1977–1984) and by about $0.009^{o}/_{oo}$ in the Gdańsk Deep (1974–1983) is being noticed. In the

Table 9: Mean annual fluctuations of water temperature, salinity and oxygen concentration in the Southern Baltic

Region	Period	Depth [m]	Temperature $[^oC \cdot y^{-1}]$	Salinity $[^o/_{oo} \cdot y^{-1}]$	Oxygen $[cm^3 \cdot dm^{-3} \cdot y^{-1}]$	Source
BORNHOLM DEEP	1900–1975	0		0.00680		Matthäus, 1979
	1952–1974	0		0.00400		Matthäus, 1979
	1900–1975	80	0.0356	–0.00050*	–0.0311	Matthäus, 1979
	1952–1974	80	0.0169	–0.01770*	–0.0340	Matthäus, 1979
GOTLAND DEEP	1900–1975	0		0.00670		Matthäus, 1979
	1952–1974	0		0.00130		Matthäus, 1979
	1977–1984	0		0.01500		Matthäus, 1985**
	1900–1975	200	0.0196	0.01310	–0.0359	Matthäus, 1979
	1952–1974	200	–0.0147	–0.04240	–0.0653	Matthäus, 1979
	1977–1984	200	–0.1700	–0.07000	–0.4700	Matthäus, 1985**
GDAŃSK DEEP	1900–1975	0		0.00910		Matthäus, 1979
	1952–1974	0		–0.00180*		Matthäus, 1979
	1956–1976	0		0.00600		Majewski, 1979
	1951–1983	0		0.01000		Cyberska and Trzosińska, 1984
	1960–1983	0			0.0190	Cyberska and Trzosińska, 1984
	1974–1983	0	0.0120*	–0.00900*	0.0490	Cyberska and Trzosińska, 1984
	1900–1975	100	0.0164	0.01090	–0.0269	Matthäus, 1979
	1952–1974	100	0.0073*	0.00112*	–0.0537	Matthäus, 1979
	1956–1975	100–bottom		0.05000		Majewski, 1979
	1956–1983	100	0.0340	0.01600		Cyberska and Trzosińska, 1984
	1960–1983	100			–0.0480	Cyberska and Trzosińska, 1984
	1974–1983	100	–0.1550	–0.10200	–0.0740	Cyberska and Trzosińska, 1984

* statistically insignificant according to Student's t-test

** quoted after Baltic Marine Environment, 1987 coastal zone of the Gulf of Gdańsk (the Hel Peninsula) this increase of salinity was slower than in the deeper parts of the Gulf – 0.003‰ per year in the period 1951–1975 (Majewski *et al.*, 1979).

The surface water of the Gdańsk Deep shows also an increase of oxygen concentration since the 50's. The average annual increase of the oxygen concentration equaled 0.019 $cm^3 \cdot dm^{-3}$ in the years 1960–1983. The more intensive rising trend appeared from 1974 (Tabl. 9); this trend is observed throughout the entire year with a particular intensity in spring (0.034 $cm^3 \cdot dm^{-3} \cdot year^{-1}$) and autumn (0.032 $cm^3 \cdot dm^{-3} \cdot year^{-1}$), (Cyberska and Trzosińska, 1984). The described increase of oxygen concentration results most probably from the copious growth of phytoplankton intensified by the enhanced fertility of the surface water layer in the Gulf.

This increasing trend of water temperature and salinity observed since the beginning of XX century is more intensive in the near bottom layer than at the surface. In the years 1979–1983 the average annual increase of temperature, although its intensity varied, reached 0.036°C at the bottom of the Bornholm Deep (200 m) and 0.016°C in the Gdańsk Deep (100 m). The mean annual salinity increase reached 0.013‰ in the Gotland Deep and about 0.011‰ in the Gdańsk Deep in the period of study. The noticed increase of temperature and salinity is explained by intensive inflows of water from the North Sea that took place in this period.

In recent years, the salinity and temperature of the near bottom water layer revealed a decreasing trend. In the Gotland Basin the decrease of temperature and salinity was noticed since 1950's (Hupfer, 1975; Matthäus, 1983) and particularly marked in 1977–1984 (Tabl. 9). In the Gdańsk Deep this negative tendency was observed only since 1977. In the years 1974–1983 the mean annual coefficient of the temperature trend was about –0.15°C and the salinity one –0.11‰. This decreasing tendency is due to the appearance of a stagnation period following an immense inflow at the turn of 1975/1976; this stagnation period, begun in 1977 and lasting till now, is the longest recorded in this century (Baltic Marine Environment, 1987).

Since the beginning of the XX century a progressive deterioration of the oxygen conditions is observed in the deep water layer of the Baltic. In the years 1900–1974 the mean annual decrease of the oxygen concentration was 0.03% (Tabl. 9) at the depth of 100 m in the Gdańsk Deep and at the depth of 200 m in the Gotland Deep. It has been statistically proved that the intensity of the overall decrease of the oxygen content varied temporarily during the present century (Matthäus, 1979): at the beginning of 1950's the process was quite advanced, but it reached particular intensity in 1977–1983 (Tabl. 9) during the severe stagnation. Deterioration of oxygen conditions in the deep layers of the Baltic could be due to the following natural processes undergoing in the sea since the beginning of this century:

- heating of the deep water masses and an increase of salinity that caused the decrease of oxygen solubility in this water layer and accelerated oxidation processes of the degradation products,
- intensification of the bottom saline current stabilizing water stratification and thus hindering the exchange of oxygen between the water layers,
- progressing nutrient run off from land,
- water eutrophication,
- enhanced biochemical oxygen demand (Fonselius, 1972, 1974).

5. Conclusions

1. The temperature of the top water layer (to the depth of 60–70 m) of the Southern Baltic altered gradually during the year from the isothermicity in winter, with temperatures around the minimal values, to the autumnal isothermicity, with temperatures close to the annual mean value.
2. Seasonal fluctuations of the temperature in the surface water layer of the Polish zone of the Baltic Sea in 1979–1983 scoped the range from 0 to 22.5 ^{o}C with the annual mean about 9 ^{o}C. In the deep water layer the temperature amplitude did not exceed 30 and the annual mean – 4.5 ^{o}C.
3. Water layer of considerable vertical temperature gradients, from 0.5 to $1\,^{o}K \cdot m^{-1}$ (thermic stratification), became mixed from the surface – in spring, down to the border with the deep layer – in autumn.
4. The salinity changes of the isohaline upper water layer of the Southern Baltic as well as the thickness of this layer were directly related

to the seasonal changes of the volume of fresh water entering the Baltic on one hand and on the other on the regular inflows of oceanic water. In the period 1979–1983 the salinity of isohaline water layer of the Polish zone of the Baltic Sea ranged from 7 to $9^o/_{oo}$, with the mean value of about $7.5^o/_{oo}$.

5. The salinity changes in the deep water layer of the Southern Baltic were related directly to the oceanic inflows from the region of the Danish Straits. The inflows recorded in 1979–1983 increased the salinity of the bottom water of the Baltic Deeps to $18^o/_{oo}$ (the maximum value) in the Bornholm region and to $13^o/_{oo}$ in the Gdańsk Basin. In the stagnation periods, alternating with the inflows, the salinity in these Deeps decreased to the minimum values of 14 and $10.5^o/_{oo}$, respectively.

6. The long-term fluctuations of temperature and salinity of the Baltic water showed an increasing trend in the present century of $0.01\,^oC$ and $0.01^o/_{oo}$ per year in the surface water and slightly greater (with the maximum of 0.036^oC and $0.013^o/_{oo}$) in the bottom layer. Recently, this incrasing trend was still noticeable in the surface layer, while the temperature of the bottom water layer and salinity of the entire water column showed the decreasing tendency, *e.g.* $-0.15\,^oC$ and $-0.11^o/_{oo}$ per year in the Gdańsk Deep.

7. Oxygen concentration in the isohaline water layer of the Polish zone of the Baltic Sea, with the average 8 $cm^3 \cdot dm^{-3}$ and 100% saturation in 1979–1983, demonstrated seasonal fluctuations related to the respective changes of temperature and biological activity. The maximum aeration, significantly over 100%, appeared with the greatest intensity of the primary production in spring, and the maximum concentrations of oxygen, over 9 $dm^3 \cdot dm^{-3}$, were recorded in winter, when the low temperature facilitated the solubilization of oxygen in sea water.

8. In the deep water layer oxygen concentration, 4 $cm^3 \cdot dm^{-3}$ on average in 1979–1983, depended on the inflows of the well oxygenated oceanic water. During stagnation periods, between the inflows, oxygen became totally utilized in the processes of organic matter degradation and hydrogen sulphide appeared in the bottom water layer, its concentrations ranging from trace to 26 $\mu mol \cdot dm^{-3}$.

9. The long-term fluctuations of oxygen concentration in the deep water layer of the Southern Baltic presented a decrasing tendency of about 0.03% per year. This tendency intensified considerably in recent years due to the significant biochemical oxygen demand ensuing from the increased inflow of organic matter from land sources as well as from the increased eutrophication of the sea water.

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