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METEOROLOGICAL AND HYDROLOGICAL DETERMINATION OF WATER TEMPERATURE IN THE COASTAL AREA OF THE POMERANIAN BAY

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Abstract

The work presents the results of studies on meteorological and hydrological determination of water temperature in the coastal zone of the Pomeranian Bay. Different statistical methods used in the study revealed that coastal water temperature is under the influence of temperature of air masses and water temperature of inland input. The influence of water temperature of the Lower Odra River on sea temperature was stronger especially during the Odra flooding events and periods of air circulation coming from south-east to north-west directions. The influence of air temperature was increased when air circulation from north-east was noticed. As correlation coefficients received as a result of synchronous relating water temperature values at Międzyzdroje to water temperature values at Gozdowice and air temperature values at Świnoujście were highly statistically significant it was possible to describe water temperature at the coastal zone of the Pomeranian Bay using equations of simple and multiple regression.

Key words: water temperature, air temperature, circulation conditions, Pomeranian Bay, Lower Odra River

INTRODUCTION

The Pomeranian Bay is the estuarine region, where river and sea waters mix together. In the coastal zone water temperature is determined mostly by temperature of air masses and water temperature of inland input. It's also under the influence of other factors like wind conditions, water inflows from the North Sea, convection and advection processes in the area. The influence of each factor as well as interactions between them cause the great variability of water temperature in that region (Cyberska 1987, Majewski 1974, Piechura 1970).

Temperature of air masses is the most important factor shaping coastal water temperature in the Pomeranian Bay. It is generally lower than water temperature (because of great thermal capacity of water). Mean monthly differences reach as far as 2.0^{o}C in winter season (Majewski 1974).

Annual mean water temperature of the Lower Odra River is about 1.0°C higher than water temperature at the southern coasts of the Pomeranian Bay. In spring warmer water input from the Szczecin Lagoon causes heating of coastal waters of the bay. In autumn waters of the lagoon cool waters of the bay (Majewski 1980).

Polar-maritime and polar-continental air masses coming in over the Pomeranian Bay cause cooling or heating, depending on the season of the year, arctic masses - cooling and tropical ones - heating (Kwiecień 1987). Because of the reaction of a wind convection processes follow at the coasts of the bay. In summer, while winds coming from the land are blowing, the decrease of surface temperature can reach 0.5°C an hour (Cyberska 1984). From Urbański (1995) in the region of Kołobrzeg the decrease of temperature can reach even some degrees when winds from north-east are coming.

The work presents the results of studies on the influence of meteorological (air temperature and circulation of air masses) and hydrological (water temperature as well as water discharge of the Lower Odra River) conditions on water temperature at the southern coasts of the Pomeranian Bay. The aim of the study was:

1. To find the role of air temperature and water temperature of the Lower Odra River on coastal water temperature of the Pomeranian Bay,
2. To find the role of direction of air circulation on changes of sea temperature,
3. To describe water temperature at the coastal zone of the Pomeranian Bay using equations of simple and multiple regression for different meteorological and hydrological conditions.

DESCRIPTION OF THE STUDY

Daily water temperature values as measured at Międzyzdroje (the southern coast of the Pomeranian Bay) were analysed and compared with water temperature values at Gozdowice (the Lower Odra River) and air temperature values at Świnoujście using descriptive statistical methods. Next normalized values were used to cluster analysis. The cluster procedure was based on the Ward method and the probability function was calculated using the Canberra distance method (Kucharczyk 1982, Sneath and Sokal 1973). Finally cross-correlation, simple and multiple regression analyses were performed to find statistical relations between examined parameters (Dąbkowski 1992). Circulation conditions were taking into consideration in order to understand the physical processes occurring in the area.

The period 1971-1980 was taken into examination. In order to find the role of the amount of water discharge of the Lower Odra River on sea temperature the periods of high and low water in the years 1971-1980 from Buchholz (1991) were studied carefully. In order to find the prevailing direction of air circulation in the chosen periods, basing on the work by Barry and Perry (1973), circulation types from "Kalendarz typów cyrkulacji atmosferycznej (1951-1990)" were transformed into weighted coefficients of circulation indexes (Table 1). The observational material was obtained from published sources as well as from Institute of Meteorology and Water Management in Gdynia.

Table 1

The weighted coefficients of circulation indexes

Air circulation	N	NE	E	SE	S	SW	W	NW	„O”
CS	0	-1	-2	-1	0	+1	+2	+1	0
CM	-2	-1	0	+1	+2	+1	0	-1	0

Explanations:
CS - the weighted coefficient of zonal air circulation
CM - the weighted coefficient of meridional air circulation

RESULTS AND DISCUSSION

Thermal conditions in the Odra Estuary region

In the years 1971-1980 annual average water temperature in the coastal area of the Pomeranian Bay at Międzyzdroje was lower about 0.83^{o}C than water temperature of the Lower Odra River at Gozdowice and higher about 0.93^{o}C than air temperature at Świnoujście. Monthly average water temperature at Międzyzdroje was lower than water temperature at Gozdowice from February to August and higher from September to January (Fig. 1).

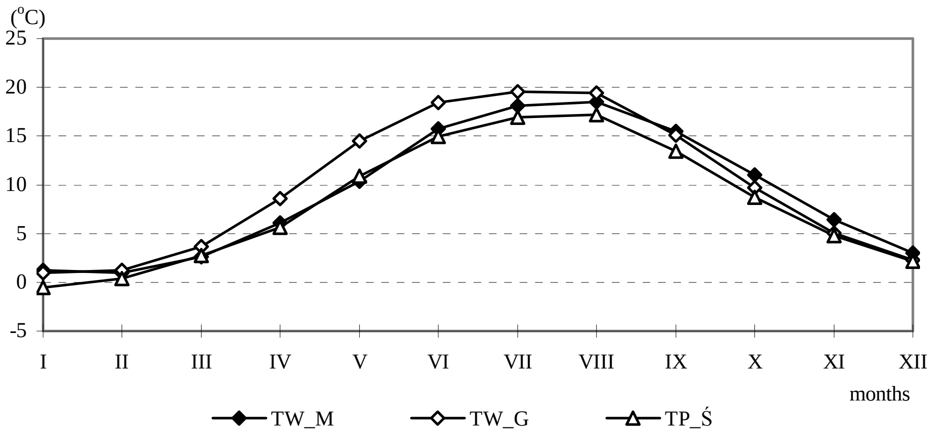

Fig. 1. The annual distributions of monthly mean water temperature as measured at Międzyzdroje and Gozdowice as well as air temperature at Świnoujście (1970-1980)
Explanations:
TW_M - coastal water temperature as measured at Gozdowice in ^{o}C
TW_G - water temperature of the River Odra as measured at Gozdowice in ^{o}C
TP_Ś - air temperature as measured at Świnoujście in ^{o}C

Mean coastal water temperature was higher than air temperature almost during all the year. As the Odra River drains into the Pomeranian Bay through a branched system of water flows and prior transformation of waters in the Szczecin Lagoon the minimum of water temperature at Międzyzdroje was observed in February while the minimum of temperature of the Odra River was recorded in January. The minimum of air temperature was observed in January as well. On the other hand water temperature at Międzyzdroje reached the maximum in August whereas the maximum of water temperature at Gozdowice was recorded in July. The results confirmed earlier studies by Majewski (1974, 1980).

Circulation conditions over the Odra Estuary

In the ten year period 1971-1980 the air circulation coming from the east sector was prevailing from February to July and coming from the west sector was prevailing from August to January (Fig. 2).

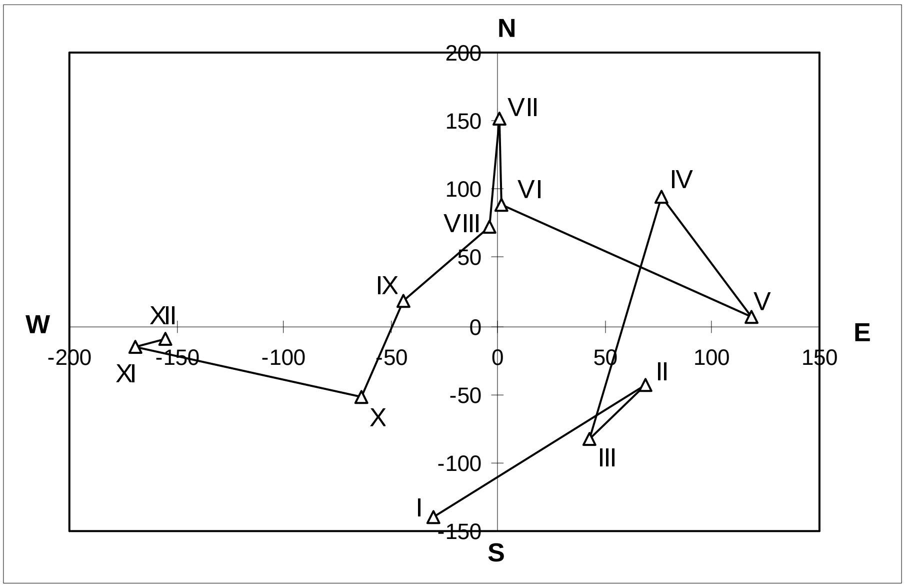

Fig. 2. The annual distribution of weighted coefficients of circulation indexes (1970-1980)

Water temperature in the coastal area of the Pomeranian Bay in relation to water temperature of the River Odra and air temperature

The results of former studies (Majewski 1980) revealed close statistical relations between water temperature of open waters of the Szczecin Lagoon and at its coasts. The calculated coefficient of correlation was 0.940-0.977. There were also found close relations between water temperature of the Szczecin Lagoon and air temperature over it. The computed coefficient of correlation was about 0.99 for positive values of air temperature and 0.63-0.81 for winter months.

Dendrograms received during cluster analysis showed close relations between water temperature in the coastal area of the Pomeranian Bay and water temperature of the Lower Odra River as well as air temperature during periods of low and high water of the River Odra - at the taxonomic distance *d* less than 0.2 (Fig. 3 and 4). Moreover the dendrograms indicate that circulation conditions had an influence on relations between examined parameters (the cluster at the taxonomic distance 0.3-0.4 for the same periods).

The cluster analysis performed for periods under different circulation conditions confirmed their effect on relations between inshore water temperature and water temperature of the Odra River as well as air temperature (Fig. 5-7). Generally it can be found that circulation conditions modify those relations. For example the relation between air temperature and coastal water temperature under air circulation coming from south-west was not so close than under air circulation coming from north-east.

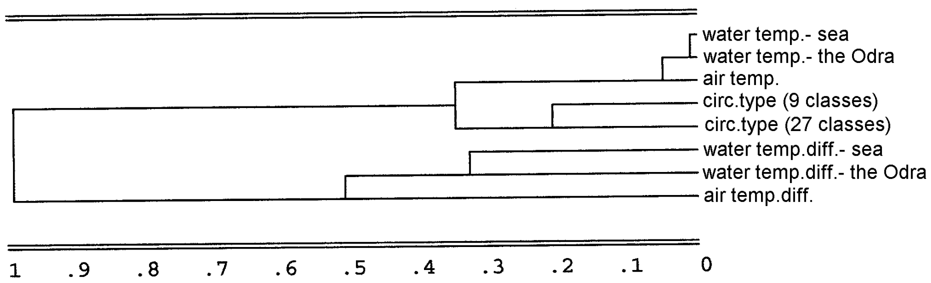

Fig. 3. The dendrogram for high water period in the summer 1977[1]

[1] Legend (Fig. 3-7):
water temp. - sea – water temperature at Międzyzdroje
water temp. - the Odra – water temperature at Gozdowice
air temp. – air temperature at Świnoujście
water temp. diff. - sea – 24-hour differences of water temperature at Międzyzdroje
water temp. diff. - the Odra – 24-hour differences of water temperature at Gozdowice
air temp. diff. – 24-hour differences of air temperature at Świnoujście
circulation type (A,C,O) – the type of air circulation (divided into anticyclonic (A), cyclonic (C) and lack of advection (O))
circ. type (9/27 classes) – the type of air circulation (divided into 9 classes or 27 classes)
.1 = the taxonomic distance *d* = 0.1

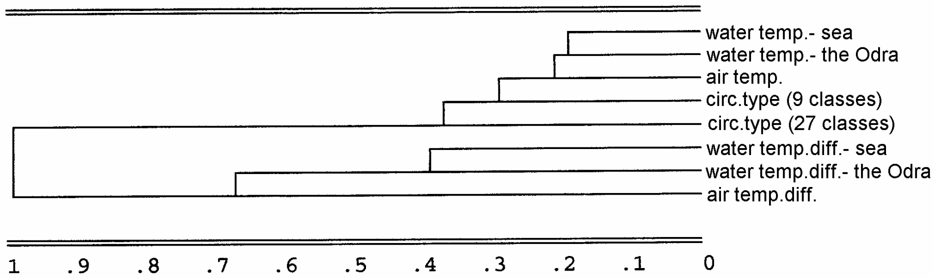

Fig. 4. The dendrogram for high water period in the spring 1979

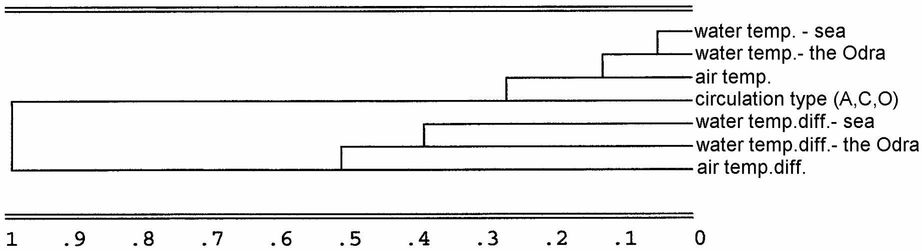

Fig. 5. The dendrogram for north-east circulation

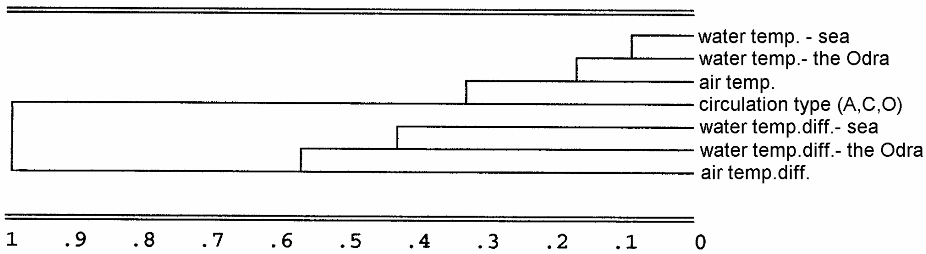

Fig. 6. The dendrogram for south-west circulation

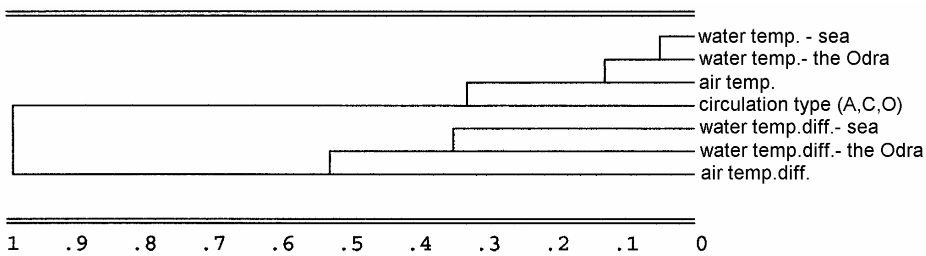

Fig. 7. The dendrogram for north-west circulation

The results received during cluster analysis indicated existence of significant statistical relations between water temperature at Międzyzdroje and Gozdowice as well as air temperature at Świnoujście. So cross-correlation, simple and multiple analyses were performed.

The cross-correlation analysis showed that the change of water temperature at Międzyzdroje under the influence of the change of water temperature of the Lower Odra River or air temperature follows fast. When air temperature was a forcing factor the reaction of coastal water temperature was quicker – on average after 1-2 days. When temperature of the River Odra forced sea temperature, the change of inshore water temperature followed on average after 6-7 days (Fig. 8). When the influence of both factors had ceased the process of getting over as a result of changes spread in time. It was longer when water temperature at Gozdowice was a forcing factor, shorter – air temperature at Świnoujście (up to 3 months).

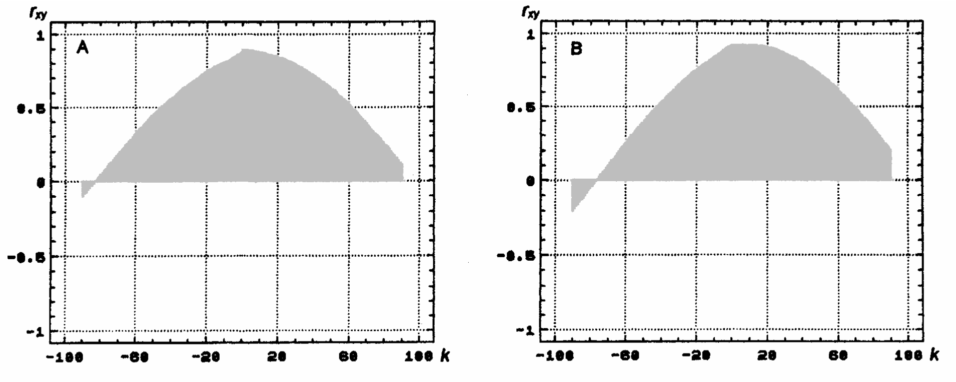

Fig. 8. The coefficients of cross-correlation (r_{xy}) between inshore water temperature at Międzyzdroje and air temperature at Świnoujście (A) and between water temperature as measured at Międzyzdroje and Gozdowice (B)

Correlation coefficients obtained as a result of synchronous relating of water temperature values at Międzyzdroje to water temperature values at Gozdowice and air temperature values at Świnoujście were highly statistically significant. Hence it was possible to describe water temperature in the coastal zone of the Pomeranian Bay using equations of simple and multiple regression:

1. X_1 = TP_Ś, Y = TW_M, $r = 0.915$, $r^2 = 0.838$, $p_\alpha < 0.001$, N = 3288
   TW_M = 0.869 TP_Ś + 2.093
2. X_2 = TW_G, Y = TW_M, $r = 0.949$, $r^2 = 0.902$, $p_\alpha < 0.001$, N = 3288
   TW_M = 0.867 TW_G + 0.572
3. X_1= TP_Ś, X_2 = TW_G, Y = TW_M, R-SQ(ADJ) = 0.913, $p_\alpha < 0.01$, N = 3288
   TW_M = 0.738 + 0.254 TP_Ś + 0.642 TW_G

The results indicate the significant role of water temperature of the Lower Odra River as well as air temperature in shaping water temperature in the coastal area of the Pomeranian Bay.

Highly statistically significant coefficients of correlation between water temperature values at Międzyzdroje and water temperature values at Gozdowice and air temperature values at Świnoujście were also obtained for two 6-month periods of prevailing east or west circulation. So it was possible to describe water temperature in the coastal zone of the Pomeranian Bay using the following equations:

1. For the period under prevailing east circulation (II – VII):

   a. X_1 = TP_Ś, Y = TW_M, $r = 0.922$, $p_\alpha < 0.001$, N = 1688
      TW_M = 0.898 TP_Ś + 1.247
   b. X_2 = TW_G, Y = TW_M, $r = 0.954$, $p_\alpha < 0.001$, N = 1688
      TW_M = 0.862 TW_G – 0.460
   c. X_1= TP_Ś, X_2 = TW_G, Y = TW_M, R-SQ(ADJ) = 0.921, $p_\alpha < 0.01$, N = 1688
      TW_M = –0.241 + 0.273 TP_Ś + 0.628 TW_G

2. For the period under prevailing west circulation (VIII – I):

   a. X_1 = TP_Ś, Y = TW_M, $r = 0.917$, $p_\alpha < 0.001$, N = 1809
      TW_M = 0.854 TP_Ś + 2.761
   b. X_2 = TW_G, Y = TW_M, $r = 0.977$, $p_\alpha < 0.001$, N = 1809
      TW_M = 0.914 TW_G + 1.293
   c. X_1= TP_Ś, X_2 = TW_G, Y = TW_M, R-SQ(ADJ) = 0.957, $p_\alpha < 0.01$, N = 1809
      TW_M = 1.341 + 0.097 TP_Ś + 0.824 TW_G

The results indicate the increased influence of air temperature on coastal water temperature in the 6-month period under prevailing east circulation, and the increased influence of water temperature of the River Odra during the 6-month period under prevailing west circulation.

Next simple and multiple regression analyses were performed in order to examine carefully shaping coastal water temperature under different types of air circulation. As highly statistically significant coefficients of correlation between examined parameters were obtained the equations of simple and multiple regression were written for each type of air circulation (Table 2). The multiple regression equations revealed that the influence of water temperature of the River Odra on coastal water temperature was increased, especially during the periods under air circulation from south-west to north-west directions. The effect of air temperature was increased during the periods under air circulation coming from north to east directions, especially when north-east circulation was recorded. In such cases the effect of water temperature of the Odra was decreased.

Highly statistically significant coefficients of correlation were also received for chosen periods of high and low water of the River Odra. Multiple regression equations showed that during the Odra flooding events the influence of water temperature of the Lower Odra was increased and the influence of air temperature was decreased. In case of the Odra flooding event in the late summer 1977, the equation of multiple regression explained almost 95 % of all the cases (Fig. 9).

Table 2

Statistical relations between coastal water temperature at Międzyzdroje and air temperature at Świnoujście as well as water temperature at Gozdowice

Period	TW_M= f (TP_Ś, TW_G)	
	R-SQ(ADJ)	Multiple regression
N	0.943	TW_M = 0.939 + 0.330TP_Ś + 0.604TW_G
NE	0.920	TW_M = 2.023 + **0.728TP_Ś** + 0.199TW_G
E	0.906	TW_M = 1.404 + 0.383TP_Ś + 0.452TW_G
SE	0.877	TW_M = 0.897 + 0.135TP_Ś + 0.644TW_G
S	0.881	TW_M = 0.963 + 0.146TP_Ś + 0.691TW_G
SW	0.917	TW_M = 0.320 + 0.176TP_Ś + **0.734TW_G**
W	0.923	TW_M = 0.486 + 0.249TP_Ś + 0.678TW_G
NW	0.940	TW_M = 0.676 + 0.227TP_Ś + **0.724TW_G**
NZ73	0.936	TW_M = 3.748 + 0.283TP_Ś + 0.545TW_G
WZ74	0.649	TW_M = 1.567 - 0.021TP_Ś + 0.918TW_G
NZ76	0.867	TW_M = 4.244 + 0.305TP_Ś + 0.470TW_G
WZ77	0.947	TW_M = 4.392 + 0.022TP_Ś + 0.681TW_G
WZ79	0.907	TW_M = 0.160 + 0.158TP_Ś + 0.437TW_G

Explanations:
R-SQ(ADJ) - correlation coefficient squared
NZ73 - the period of low water of the Odra (27.6.-22.12.73);
NZ76 - the period of low water of the Odra (26.6.-19.10.76);
WZ74 - the period of high water in the winter 1974/75 (19.10.74-8.3.75);
WZ77 - the period of high water in the late summer 1977 (4.8.-25.10.77);
WZ79 - the period of high water in the spring 1979 (27.02.-5.6.79).

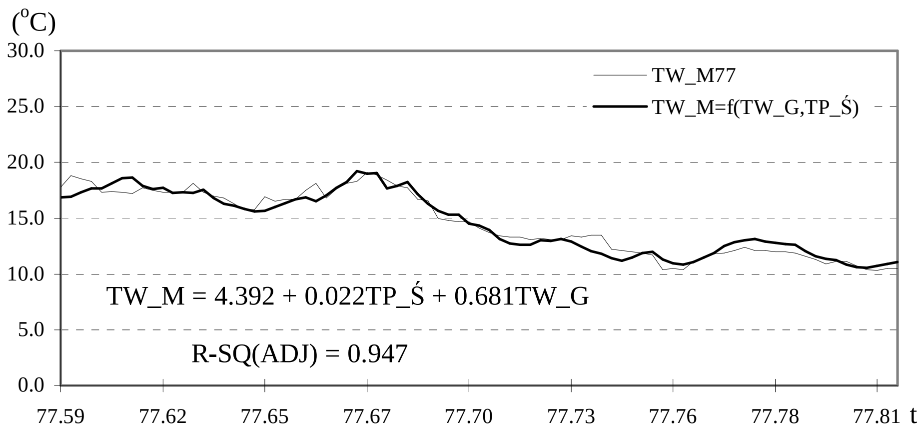

Fig. 9. Water temperature at Międzyzdroje (TW_M) as measured *in situ* at Międzyzdroje and obtained from multiple regression function taking into calculations water temperature values as measured at Gozdowice (TW_G) and air temperature at Świnoujście (TP_Ś) during the period of high water of the Odra in the summer 1977

CONCLUSIONS

The study revealed that:

1. Temperature of air masses and water temperature of the Lower Odra River shape water temperature in the coastal area of the Pomeranian Bay. Highly statistically significant coefficients of correlation between water temperature values at Międzyzdroje and water temperature values at Gozdowice and air temperature values at Świnoujście made possible to describe water temperature in the coastal zone of the Pomeranian Bay using equations of simple and multiple regression.
2. Circulation conditions modify relations between examined parameters. The increased influence of air temperature on coastal water temperature was found in the 6-month period under prevailing east circulation (II–VII). The increased influence of water temperature of the River Odra was found in the 6-month period under prevailing west circulation (VIII-I). Moreover the increased influence of air temperature was found when air circulation from north to east directions was coming. The increased influence of water temperature of the Odra River was found in periods of air circulation from south-west and north-west directions.
3. The water discharge of the River Odra has an effect on relations found during the studies. During the periods of high water of the Odra the influence of water temperature of the Odra was increased and the influence of air temperature was decreased on coastal water temperature in the Pomeranian Bay.

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METEOROLOGICZNE I HYDROLOGICZNE UWARUNKOWANIA TEMPERATURY WODY W STREFIE BRZEGOWEJ ZATOKI POMORSKIEJ

Streszczenie

U wybrzeży Zatoki Pomorskiej rozkład przestrzenny temperatury wód powierzchniowych oznacza się typowo sezonowym charakterem, uwarunkowanym rocznym rytmem temperatury powietrza oraz temperatury wód śródlądowych wypływających

z Zalewu Szczecińskiego. Praca przedstawia wyniki badań nad meteorologicznymi i hydrologicznymi uwarunkowaniami temperatury wody w strefie brzegowej Zatoki Pomorskiej.

Wyniki przeprowadzonych analiz statystycznych wskazują, że zmiana temperatury wód przybrzeżnych Zatoki Pomorskiej pod wpływem zmiany temperatury wody Odry lub powietrza pojawia się dość szybko. Gdy czynnikiem wymuszającym jest temperatura powietrza zmiana temperatury wód przybrzeżnych występuje średnio po dwóch dniach. Zmiana temperatury wody w Międzyzdrojach pod wpływem zmiany temperatury wody Odry w Gozdowicach występuje średnio po 6-7 dniach.

W pracy wykazano, że warunki cyrkulacyjne odgrywają ważną rolę w kształtowaniu temperatury wód przybrzeżnych Zatoki Pomorskiej. Rola temperatury Odry w kształtowaniu termiki wód strefy przybrzeżnej Zatoki Pomorskiej uwidacznia się szczególnie w półroczu o przewadze cyrkulacji zachodniej (od sierpnia do stycznia). Wpływ temperatury powietrza na temperaturę wód przybrzeżnych wzrasta natomiast w półroczu o przewadze cyrkulacji wschodniej (od lutego do lipca). W czasie przeważania cyrkulacji z sektora zachodniego i południowego (zwłaszcza przy cyrkulacji NW i SW) wzrasta wpływ temperatury wód Odry na temperaturę wód przybrzeżnych zatoki. Natomiast przy napływie mas powietrza z sektora wschodniego i północnego (zwłaszcza przy cyrkulacji NE) wzrasta wpływ temperatury powietrza.

Wielkość przepływu wody w dolnym biegu Odry odgrywa pewną rolę w kształtowaniu temperatury wód przybrzeżnych zatoki. W czasie wezbrań Odry wzrasta rola temperatury wód rzecznych, natomiast w czasie niżówek wzrasta rola temperatury powietrza.

Zastosowane w pracy metody statystyczne pozwoliły na oszacowanie wpływu czynników meteorologicznych i hydrologicznych w kształtowaniu temperatury wód przybrzeżnych Zatoki Pomorskiej oraz umożliwiły ich wyrażenie w oparciu o analizy regresji prostej i wielorakiej.