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Water exchange
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Influence of water exchange between the Baltic Sea and the North Sea on storm surges in the Baltic*

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Abstract

The influence of water exchange between the Baltic Sea and the North Sea on the phenomenon of storm surges in the Baltic is studied in this paper. Calculations were carried out for the western wind with constant velocity of about 20 m/s in the time interval of 33 hours.

Two situations were considered: the first, treating the Baltic as a closed sea, and the second in which we considered the basin consisting of the Baltic Sea and the North Sea connected by the Danish Straits.

The principal result of the paper is the conclusion that the omission of the influence of water exchange in the central Baltic, the Gulf of Riga, the Gulf of Finland and the Gulf of Bothnia, in a time interval longer than 24 hours leads to considerable errors. In the Belt Straits and in the southern Baltic the influence of water exchange is considerable even during the first 12 hours of a storm.

1. Introduction

The aim of this paper is the analysis of the influence of water exchange between the Baltic Sea and the North Sea on the phenomenon of storm surges in various regions of the Baltic and in various time intervals, in an idealized meteorological situation when the western wind with constant velocity is considered.

In order to carry out such an analysis one should build a numerical model of the considered phenomenon and take into account the Baltic Sea as well as the Danish Straits.

It seems to be important to investigate the influence of water exchange because the majority of the hitherto existing numerical models describing storm surges in the Baltic Sea, have totally omitted this problem treating the Baltic as a closed sea.

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In connection with this there arose a problem in which regions of the Baltic and at what time interval the influence of water exchange with the North Sea through the Danish Straits is small enough to be practically omitted.

To solve the problem definitively it is necessary, above all, to choose an adequate numerical model of the storm surge phenomenon. Because of many reasons, the problem is complicated. The Danish Straits have a small cross-section, and both seas constitute two qualitatively different basins as far as their dimensions, topography of the bottom, configuration of shore line, etc. are considered. It leads to definite mathematical consequences. Above all it would be necessary to minimize computational grid size and to take under consideration advective terms together with the dependence of the depth on changes of the sea surface elevation in the numerical approximation of differential equations. Carrying out such a mathematical operation for the Baltic Sea, the Danish Straits and for the North Sea simultaneously at the present state of the development of computers would cause great technical difficulties. These difficulties were omitted by the use of a method of refining a grid in particularly interesting basins. In each of the considered regions, the eddy viscosity coefficient describing the horizontal exchange of momentum, was chosen experimentally. In this situation its role gains capital meaning due to the stability of the numerical scheme and an adequate reproduction of physical processes of momentum transfer in the horizontal plane. In the presented model we took into account advective terms and dependence of the depth on changes of the sea surface elevation in the Danish Straits only. Such an operation was inevitable in the Danish Straits because of their small depth and width.

Papers dealing with the numerical models of storm surges in the Baltic Sea, in their majority concern certain Baltic basins (*e.g.* Uusitalo's paper concerns the Gulf of Bothnia – 1962, 1971; Laska's – southern and central Baltic – 1966; Wolcingier's, Simuni's – 1963; Wolcingier's, Labzowski's, Piaskowski's – 1964; Krugliak's, Pomieranec's – 1976 – the Gulf of Finland; *etc.*). In this way the problem of the influence of water exchange did not appear in those papers at all. On the other hand a considerable number of authors treated the Baltic a priori as a closed sea (*e.g.* Henning 1962).

Koop in his paper (1974) presented a storm surges model in the Baltic Sea and took water exchange into consideration. However, Koop applied quite a large computational grid size in the Danish Straits (44.5 km) and limited the considered basin too close to the Baltic (an open boundary constituted a section that joined Skagen and Smögen).

A paper written by Kowalik and Staśkiewicz (1976) was the first to analyse the influence of water exchange on the Baltic surface elevation. The paper considered both seas as cuboidal basins having constant heights and connected by a channel immitating the Danish Straits. Consequently, it was not possible to say a lot about the influence of water exchange on the spatial distribution of sea level changes in the Baltic. Nevertheless, the conclusions of that paper are similar to those drawn in the present paper. Thanks to the more faithful reproduction of the bottom topography, shore configuration and more precise choice of physical parameters in our paper, we examined the influence of water exchange on the spatial distribution of sea level changes. It leads to a basic conclusion that when short-term surges are considered, the influence of water exchange may be omitted. Such omission would lead to considerable errors for long-term surges.

We must underline that in all the pre-cited papers the Cartesian coordinate system was used though a spherical coordinate system is more adequate for this kind of problems.

2. Mathematical model of storm surges phenomenon

The model is based on the vertically integrated, from the bottom at $z=-\bar{H}(\lambda, \varphi)$ to the surface at $z=\zeta(\lambda, \varphi; t)$, hydrodynamic equations of motion and continuity equation, for an incompressible fluid. The equation for the vertical component of velocity is simplified to the hydrostatic equation (Wolcingier, Piaskowskij 1968). Furthermore we assumed constant sea water density $\rho=1$ g/cm³. Resulting equations in a spherical coordinate system take the form:

$$\frac{\partial U}{\partial t}+\frac{1}{R\cos\varphi}\frac{\partial}{\partial\lambda}\frac{UU}{(\bar{H}+\zeta)}+\frac{1}{R}\frac{\partial}{\partial\varphi}\frac{UV}{(\bar{H}+\zeta)}-\frac{2UV\,\mathrm{tg}\,\varphi}{R\,(\bar{H}+\zeta)}-fV+\frac{g(\bar{H}+\zeta)}{R\cos\varphi}\frac{\partial\zeta}{\partial\lambda}+$$

$$-\frac{A}{R^2\cos^2\varphi}\frac{\partial^2 U}{\partial\lambda^2}-\frac{A}{R^2\cos\varphi}\frac{\partial}{\partial\varphi}\left(\cos\varphi\frac{\partial U}{\partial\varphi}\right)=-\frac{\bar{H}+\zeta}{R\cos\varphi}\frac{\partial p_a}{\partial\lambda}+T^s_\lambda-T^b_\lambda, \tag{1.1}$$

$$\frac{\partial V}{\partial t}+\frac{1}{R\cos\varphi}\frac{\partial}{\partial\lambda}\frac{U\cdot V}{\bar{H}+\zeta}+\frac{1}{R}\frac{\partial}{\partial\varphi}\frac{V\cdot V}{\bar{H}+\zeta}+\frac{(U^2-V^2)\,\mathrm{tg}\,\varphi}{R\cdot(\bar{H}+\zeta)}+f\cdot U+\frac{g(\bar{H}+\zeta)}{R}\frac{\partial\zeta}{\partial\varphi}+$$

$$-\frac{A}{R^2\cos^2\varphi}\frac{\partial^2 V}{\partial\lambda^2}-\frac{A}{R^2\cos\varphi}\frac{\partial}{\partial\varphi}\left(\cos\varphi\frac{\partial V}{\partial\varphi}\right)=-\frac{\bar{H}+\zeta}{R}\frac{\partial p_a}{\partial\varphi}+T^s_\varphi-T^b_\varphi, \tag{1.2}$$

$$\frac{\partial\zeta}{\partial t}+\frac{1}{R\cos\varphi}\frac{\partial U}{\partial\lambda}+\frac{1}{R\cos\varphi}\frac{\partial}{\partial\varphi}(V\cdot\cos\varphi)=0, \tag{1.3}$$

where:

λ – longitude,
φ – latitude,
U, V – components of volume transport along the 0λ and 0φ axes of a coordinate system,
t – time,
ω – Earth's angular velocity,
f – Coriolis parameter, $f=2\omega\sin\varphi$,
p_a – atmospheric pressure,
A – eddy viscosity coefficient,

g – acceleration of the Earth's gravity,
H – sea depth,
ζ – elevation of the sea level from the mean,
T^s_λ, T^s_φ – components of wind stress at the sea surface,
T^b_φ, T^b_λ – components of bottom stress,
R – mean Earth radius.

Additionally, we assumed that the storm surge is generated being initially at the state of rest, *i.e.*:

$$U=V=\zeta=0 \quad \text{for } t=0.$$

We imposed the velocity vector vanishing condition at the closed shore line, which leads to:

$$U=V=0 \quad \text{for } t\geqslant 0.$$

On the open boundary of the North Sea we assumed the sea level as a constant function of time and position equal to zero

$$\zeta=\zeta_0(\lambda, \varphi; t)=0.$$

We calculated the bottom stress assuming its dependence proportional to the square of the volume transport, the proportionality factor depending on depth. Components of the bottom stress are described as follows:
along 0λ axis:

$$T^b_\lambda=\frac{r}{H^2}U\sqrt{U^2+V^2}, \tag{1.4}$$

similarly, along 0φ axis:

$$T^b_\varphi=\frac{r}{H^2}V\sqrt{U^2+V^2}, \tag{1.5}$$

where $r=3\cdot 10^{-3}$.
Calculations were carried out for the components of wind stress at the sea surface $T^s_\lambda=3.2$ CGS, $T^s_\varphi=0$, which corresponds to the wind velocity about 20 m/s. In the calculations we did not take into account the atmospheric pressure gradient.

For difference approximation of equations (1.1) - (1.3) we based on the implicit-explicit numerical scheme which, written on the grid shown in Figure 1, takes the form:

$$\frac{U^{n+1}_{k,l}-U^{n-1}_{k,l}}{2\tau}+\frac{1}{2R\cos\varphi\Delta\lambda}\left[\frac{(U^{n-1}_{k+1,l}+U^{n-1}_{k,l})^2}{H^n_{k+\frac{1}{2},l+\frac{1}{2}}+H^n_{k+\frac{1}{2},l-\frac{1}{2}}}-\frac{(U^{n-1}_{k,l}+U^{n-1}_{k-1,l})^2}{H^n_{k-\frac{1}{2},l+\frac{1}{2}}+H^n_{k-\frac{1}{2},l-\frac{1}{2}}}\right]+$$

$$+\frac{1}{2R\Delta\varphi}\left[\frac{(U^{n-1}_{k,l+1}+U^{n-1}_{k,l})(V^{n-1}_{k,l+1}+V^{n-1}_{k,l})}{H^n_{k+\frac{1}{2},l+\frac{1}{2}}+H^n_{k-\frac{1}{2},l+\frac{1}{2}}}-\frac{(U^{n-1}_{k,l}+U^{n-1}_{k,l-1})(V^{n-1}_{k,l}+V^{n-1}_{k,l-1})}{H^n_{k+\frac{1}{2},l-\frac{1}{2}}+H^n_{k-\frac{1}{2},l-\frac{1}{2}}}\right]+$$

$$-\frac{2U^{n-1}_{k,l}V^{n-1}_{k,l}\operatorname{tg}\varphi}{R\cdot H}-\frac{f}{2}(V^{n+1}_{k,l}+V^{n-1}_{k,l})+\frac{gH^n}{2R\cos\varphi\Delta\lambda}(\zeta^n_{k+\frac{1}{2},l+\frac{1}{2}}-\zeta^n_{k-\frac{1}{2},l+\frac{1}{2}}$$

$$+\zeta^n_{k+\frac{1}{2},l-\frac{1}{2}}-\zeta^n_{k-\frac{1}{2},l-\frac{1}{2}})-\frac{A}{R^2\cos^2\varphi(\Delta\lambda)^2}(U^{n-1}_{k+1,l}-2U^{n-1}_{k,l}+U^{n-1}_{k-1,l})+$$

$$-\frac{A}{R^2\cos\varphi(\Delta\varphi)^2}[\tfrac{1}{2}(\cos\varphi_{l+1}+\cos\varphi_l)(U^{n-1}_{k,l+1}-U^{n-1}_{k,l})-\tfrac{1}{2}(\cos\varphi_l+\cos\varphi_{l-1})\times$$

$$\times(U^{n-1}_{k,l}-U^{n-1}_{k,l-1})]+\frac{r}{2H^2}\sqrt{(U^{n-1}_{k,l})^2+(V^{n-1}_{k,l})^2}\,(U^{n+1}_{k,l}+U^{n-1}_{k,l})=(T^s_\lambda)^n \qquad (1.6)$$

$$\frac{V^{n+1}_{k,l}-V^{n-1}_{k,l}}{2\tau}+\frac{1}{2R\cos\varphi\Delta\lambda}\left[\frac{(U^{n-1}_{k+1,l}+U^{n-1}_{k,l})(V^{n-1}_{k+1,l}+V^{n-1}_{k,l})}{H^n_{k+\frac{1}{2},l+\frac{1}{2}}+H^n_{k+\frac{1}{2},l-\frac{1}{2}}}-\right.$$

$$\left.+\frac{(U^{n-1}_{k,l}+U^{n-1}_{k-1,l})(V^{n-1}_{k,l}+V^{n-1}_{k-1,l})}{H^n_{k-\frac{1}{2},l+\frac{1}{2}}+H^n_{k-\frac{1}{2},l-\frac{1}{2}}}\right]+\frac{1}{2R\Delta\varphi}\left[\frac{(V^{n-1}_{k,l+1}+V^{n-1}_{k,l})^2}{H^n_{k+\frac{1}{2},l+\frac{1}{2}}+H^n_{k-\frac{1}{2},l+\frac{1}{2}}}-\right.$$

$$\left.+\frac{(V^{n-1}_{k,l}+V^{n-1}_{k,l-1})^2}{H^n_{k+\frac{1}{2},l-\frac{1}{2}}+H^n_{k-\frac{1}{2},l-\frac{1}{2}}}\right]+\frac{(U^{n-1}_{k,l})^2-(V^{n-1}_{k,l})^2}{RH}\operatorname{tg}\varphi+\frac{f}{2}(U^{n+1}_{k,l}+U^{n-1}_{k,l})+$$

$$+\frac{gH^n}{2R\Delta\varphi}(\zeta^n_{k+\frac{1}{2},l+\frac{1}{2}}-\zeta^n_{k+\frac{1}{2},l-\frac{1}{2}}+\zeta^n_{k-\frac{1}{2},l+\frac{1}{2}}-\zeta^n_{k-\frac{1}{2},l-\frac{1}{2}})-$$

$$+\frac{A}{R^2\cos^2\varphi(\Delta\lambda)^2}(V^{n-1}_{k+1,l}-2V^{n-1}_{k,l}+V^{n-1}_{k-1,l})+ \qquad (1.7)$$

$$-\frac{A}{R^2\cos\varphi(\Delta\varphi)^2}[\tfrac{1}{2}(\cos\varphi_{l+1}+\cos\varphi_1)(V^{n-1}_{k,l+1}-V^{n-1}_{k,l})-$$

$$+\tfrac{1}{2}(\cos\varphi_l+\cos\varphi_{l-1})(V^{n-1}_{k,l}-V^{n-1}_{k,l-1})]+$$

$$+\frac{r}{2H^2}\sqrt{(U^{n-1}_{k,l})^2+(V^{n-1}_{k,l})^2}(V^{n+1}_{k,l}+V^{n-1}_{k,l})=(T^s_\varphi)^n,$$

$$\frac{\zeta^{n+2}_{k+\frac{1}{2},l+\frac{1}{2}}-\zeta^n_{k+\frac{1}{2},l+\frac{1}{2}}}{2\tau}=-\frac{1}{2R\cos\varphi\Delta\lambda}(U^{n+1}_{k+1,l+1}-U^{n+1}_{k,l+1}+U^{n+1}_{k+1,l}-U^{n+1}_{k,l})+$$

$$-\frac{1}{2R\cos\varphi\Delta\varphi}(\cos\varphi_{l+1}V^{n+1}_{k+1,l+1}-\cos\varphi_l V^{n+1}_{k+1,l}+$$

$$+\cos\varphi_{l+1}V^{n+1}_{k,l+1}-\cos\varphi_l V^{n+1}_{k,l}), \qquad (1.8)$$

where $H=\bar{H}+\zeta$.

We solved the system of equations (1.6) - (1.8) using the explicit procedure of solution.

In especially interesting basins we used the method of refining the grid. Figure 2 shows a selection of refined grids in the considered area. Table 1 gives the grid mesh sizes in the marked subareas.

In order to join grids with different mesh sizes one has to specify the way of imposing boundary conditions at the interface lines joining two meshes of different resolution. We chose a method based on calculation of boundary conditions from the vertically integrated equations of motion solved using irregular-grid finite difference technique. The accurate description of the way of investigating of the stability of the numerical solution is given by Chilicka *at al.* (1980).

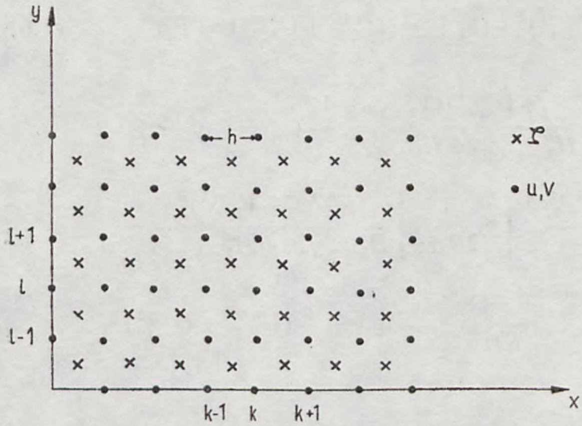

Fig. 1. Computational grid

Table 1. Grid mesh sizes and values of horizontal turbulent exchange coefficient in the subareas in figure 2

N umber of the subarea	Grid size $\Delta\varphi$	$\Delta\lambda$	Coefficient A CGS
1	20′	40′	10^9
2	10′	20′	10^9
3	5′	10′	10^8
4	5′	10′	10^8
5	2′30″	5′	10^8
6	2′30″	5′	10^8
7	2′30″	5′	10^8
8	2′30″	5′	$4\cdot10^6$
9	2′30″	5′	$4\cdot10^7$
10	2′30″	5′	$6\cdot10^6$
11	1′15″	2′30″	$4\cdot10^5$
12	1′15″	2′30″	$4\cdot10^4$
13	1′15″	2′30″	$4\cdot10^5$
14	1′15″	2′30″	$4\cdot10^6$

We took into account advective terms and depth dependence on changes of sea surface elevation $H=\bar{H}(\lambda, \varphi)+\zeta(\lambda, \varphi, t)$ in the Danish Straits (subareas 10 - 14). In other subareas we omitted advective terms and assumed the depth equal to the undisturbed depth: $H\approx\bar{H}(\lambda, \varphi)$.

The proper choice of the eddy viscosity coefficient which characterizes horizontal momentum exchange is very important in the construction of numerical models of hydrodynamic phenomena. In oceanographic processes this coefficient is of physical nature and usually for its evaluation one uses the so-called "four-thirds power law" (Richardson 1926), *i.e.*:

$$A = k \cdot l^{\frac{4}{3}},$$

where: k – dimensional constant depending on the rate of transfer of turbulent energy by turbulent eddies from big to small scales (Monin, Ozmidow 1978), l – length scale of turbulence.

In real hydrodynamic processes there is a phenomenon of turbulent cascade of energy from the large scale motion into motion on the smaller scales. At the smallest scale the energy is dissipated into heat. This natural process is distorted when described numerically by the imposed grid system because the processes of energy transfer and dissipation are not taken into account in a scale smaller than a computational mesh size. This leads to numerical instability. A common procedure for removing this effect is the introduction of a differential coefficient A and its proper choice in relation to the computational grid step in order to achieve a stable numerical scheme. To find the appropriate value of coefficient A we carried out several numerical experiments for each of the considered subareas, assuming the values of A to range from 10^4 to 10^9 CGS, considering also stability and certain physical factors. The values of the coefficient of the horizontal turbulent momentum exchange in depicted subareas are shown in Table 1.

3. Influence of water exchange on the Baltic surface elevation and adjacent basins

In order to realize the principal aim of the paper we tested sea level changes in the Baltic Sea in two alternative cases: in the first we took under consideration water exchange and in the second we treated the Baltic as a closed sea. All the experiments were made for the western wind with the constant velocity of about 20 m/s.

Changes of the mean sea level in the Baltic Sea and in the southern part of the Danish Straits (subareas 3 - 8 and 10; Fig. 2) were calculated for the time interval of 33 hours for both cases. The following procedure was used in order to determine time changes of mean sea level: for each of the interesting subareas the mean sea level was calculated from the formula:

$$\bar{\zeta} = \frac{\bar{V}}{S},$$

where $\bar{V}$ states volume changes that are expressed as follows:

$$\bar{V} = \sum_{l=0}^{L_{max}-1} \sum_{k=0}^{K_{max}-1} R^2 \Delta\lambda \Delta\varphi \cos \varphi_{l+\frac{1}{2}} \zeta_{k+\frac{1}{2}, l+\frac{1}{2}},$$

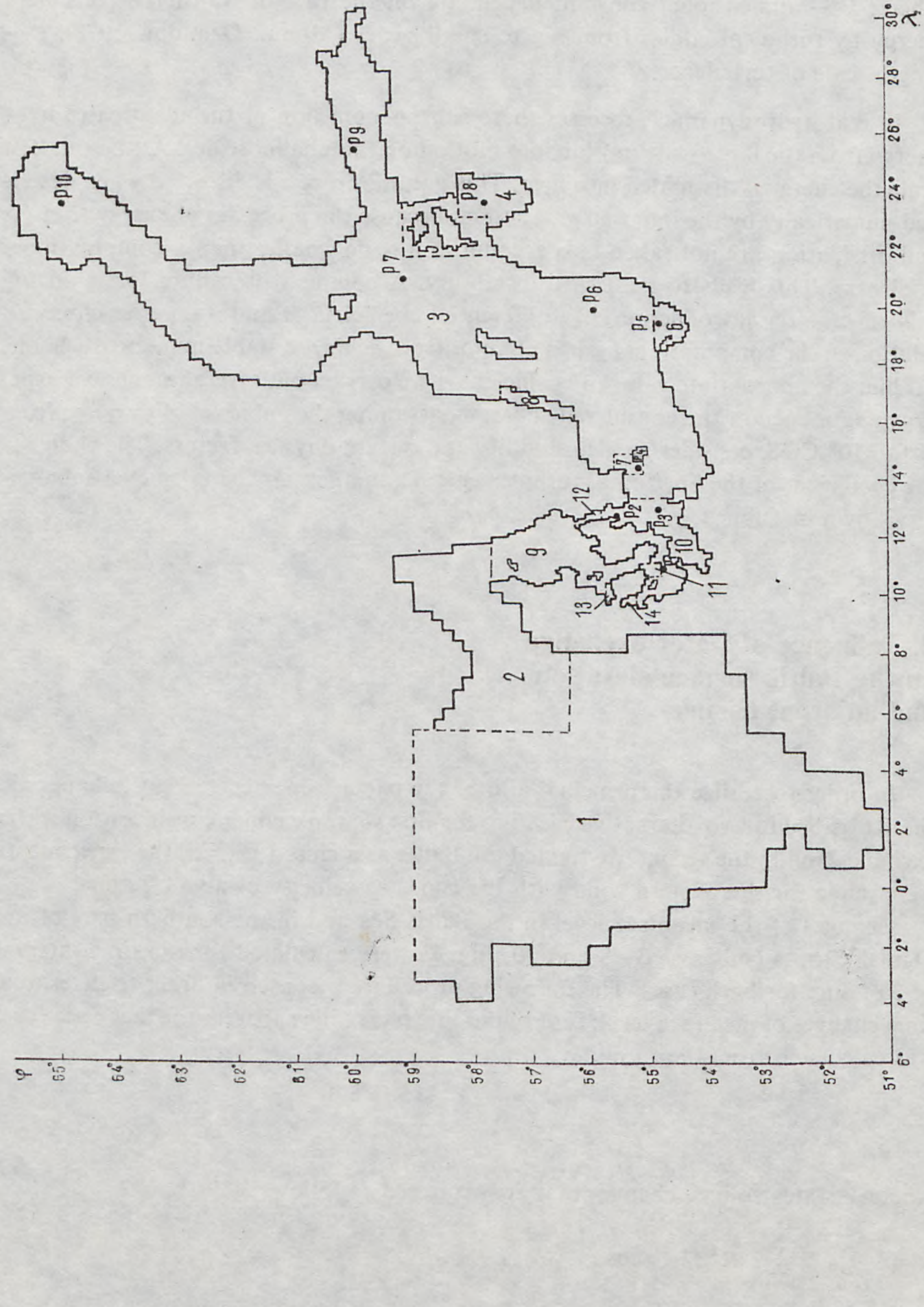

Fig. 2. Division of the basin into subareas

S is the area calculated from the formula:

$$S = (K_{max} - 1) \sum_{l=0}^{Lmax-1} R^2 \Delta\lambda \Delta\varphi \cos \varphi_{l+\frac{1}{2}}.$$

Moreover, we examined sea level changes in chosen points (see Fig. 2).

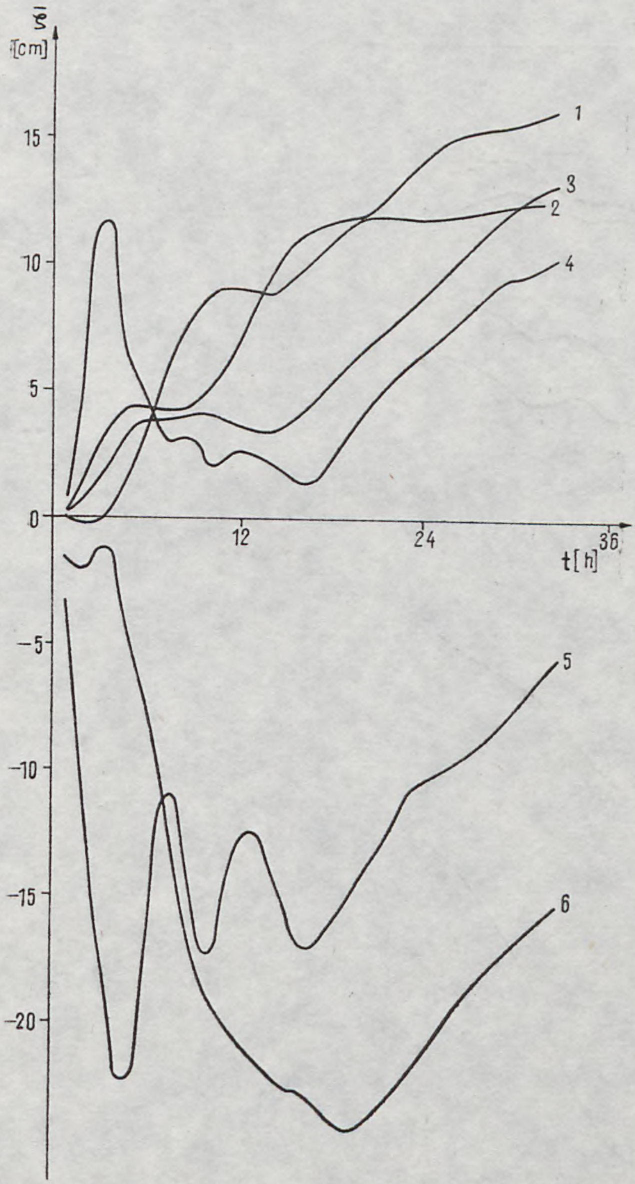

Fig. 3. Changes of the mean sea level
1 – in the Skagerrak (subarea 2; fig. 2), 2 – in the North Sea (subarea 1; fig. 2), 3 – in the Kattegat (subarea 9; fig. 2), 4 – in the Öresund (subarea 12; fig. 2), 5 – in the northern part of the Little Belt (subarea 13; fig. 2), 6 – in the Great Belt (subarea 11; fig. 2)

The results we received are presented in Table 2 and 3, and graphically in Figures 3 - 10. Figure 11 presents time changes of the water volume in the North Sea (subarea 1), in the Skagerrak (subarea 2), in the Kattegat (subarea 9) and in the Baltic Sea (subareas 3 - 8, 10 - 12 and 14).

Fig. 4. Changes of the mean sea level
——— the Baltic as a closed sea, – – – water exchange considered. 1 — near Oland (subarea 8; fig. 2), 2 — near Bornholm (subarea 7; fig. 2), 3 — in the southern part of the Danish Straits (subarea 10; fig. 2)

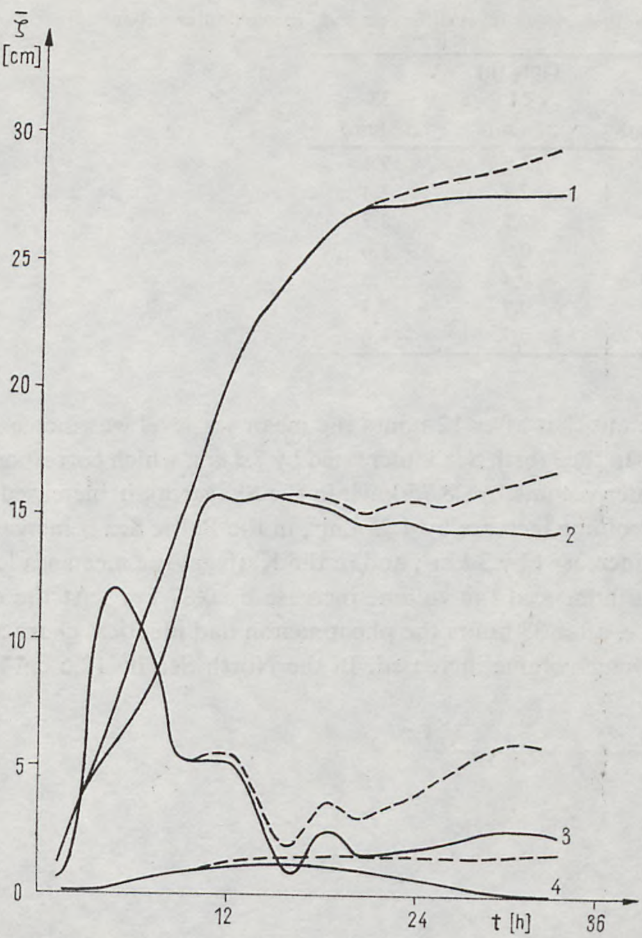

Fig. 5. Changes of the mean sea level
——— the Baltic as a closed sea – – – water exchange considered. 1 – in the Gulf of Riga (subarea 4; fig. 2), 2 – near Sarema and Muru Islands (subarea 5; fig. 2), 3 – in the Gdańsk Bay (subarea 6; fig. 2), 4 – in the Baltic Sea (subarea 3; fig. 2)

Table 2. Changes in time of values of sea level differences in particular points

Points	Time (h) 12 $\Delta\zeta$ (cm)	24 $\Delta\zeta$ (cm)	33 $\Delta\zeta$ (cm)	Maximum difference $\Delta\zeta$ (cm)
P1	17,0	22,0	15,0	26,0
P2	3,0	4,0	3,0	4,0
P3	3,0	5,0	3,0	5,0
P4	1,0	2,0	3,0	3,0
P5	0,0	3,0	4,0	4,0
P6	0,0	2,0	3,0	3,0
P7	0,0	1,0	3,0	3,0
P8	0,0	1,1	1,0	1,0
P9	0,0	1,0	2,0	2,0
P10	0,0	0,0	1,0	1,0

Numbers of points correspond with Figure 2

Table 3. Changes in time of values of sea level differences $\Delta\zeta$ in particular subareas

Subareas	Time (h) 12 $\Delta\zeta$ (cm)	24 $\Delta\zeta$ (cm)	33 $\Delta\zeta$ (cm)
10	9,3	12,9	9,1
7	0,9	2,4	2,4
6	0,3	2,2	3,5
3	0,1	0,9	1,6
4	0,0	0,4	1,5
5	0,0	0,9	2,3
8	0,0	0,7	1,6

Figures 3 and 11 point out that after 12 hours the mean sea level was increasing in all four pre-cited basins. In the North Sea it increased by 7.3 cm, which corresponds with the increase of the water volume by 28.75 km^3; in the Skagerrak it increased by 9.0 cm which leads to the volume increase by 4.25 km^3; in the Baltic Sea it increased by 0.9 cm and the volume increased by 3 km^3, and in the Kattegat the mean sea level increased by 3.6 cm which influenced the volume increase by 0.87 km^3. At the end of the considered period, *i.e.* after 33 hours the phenomenon had identical character: both mean sea level and water volume increased. In the North Sea by 12.5 cm and

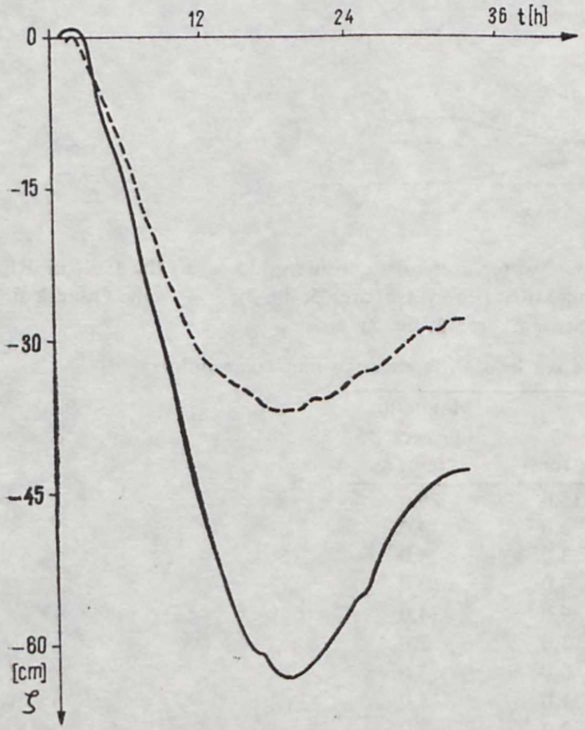

Fig. 6. Sea level changes in point P1 presented in fig. 2
——— the Baltic as a closed sea, – – – water exchange considered

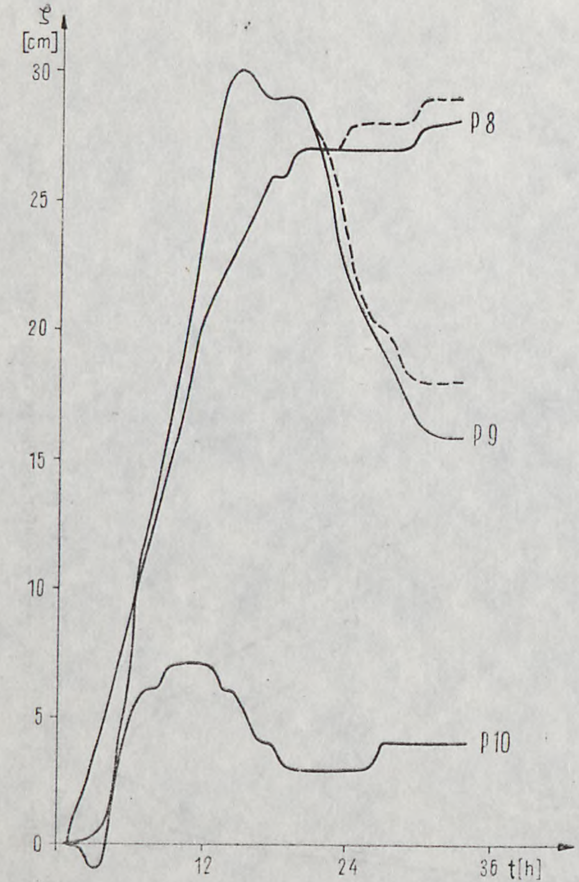

Fig. 7. Sea level changes in points P8, P9 and P10 presented in fig. 2
——— the Baltic as a closed sea, – – – water exchange considered

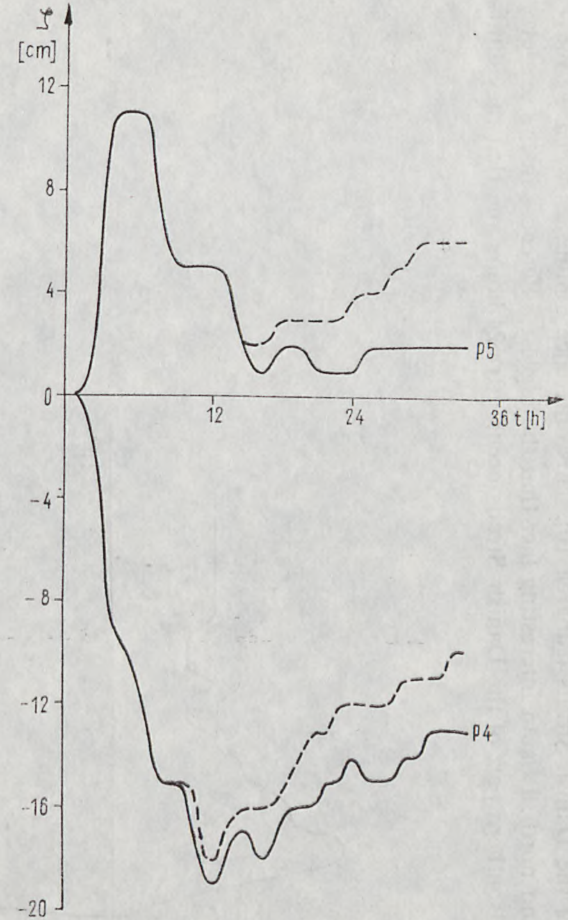

Fig. 8. Sea level changes in points P4 and P5 presented in fig. 2
——— the Baltic as a closed sea, – – – water exchange considered

39.75 km^3 respectively, in the Skagerrak by 16.1 cm and by 9.75 km^3, in the Baltic Sea by 1.81 cm and 6.5 km^3, and in the Kattegat by 13.3 cm and 3 km^3.

In Figure 12 we marked sea level isolines after 33 hours in two situations: assuming water exchange with the North Sea and treating the Baltic as a closed sea. According to our expectations the biggest difference between sea levels occurs in the southern part of the Danish Straits (subarea 10). This difference diminishes when we move east and north. It is an interesting fact that the biggest differences in the sea level in the southern part of the Danish Straits occur after 24 hours and that they dimi-

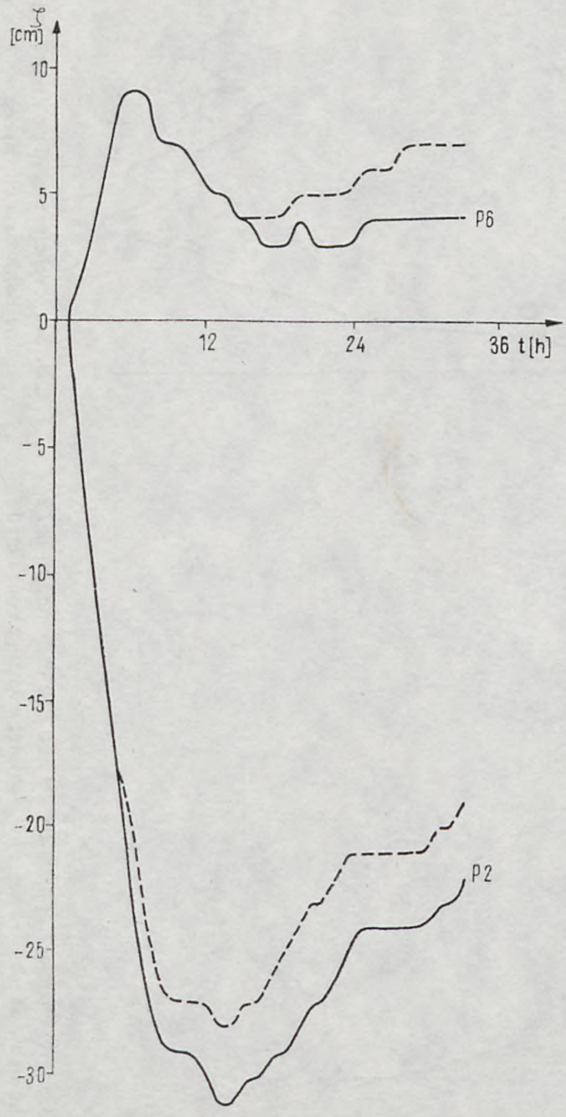

Fig. 9. Sea level changes in points P2 and P6 presented in fig. 2
——— the Baltic as a closed sea, – – – water exchange considered

nish later. It seems to be caused by the Danish Straits morphometry as well as by the adjacent regions and by the assumed direction of the wind.

The analysis of results in chosen points leads to a conclusion that very considerable level differences appear near to the Great Belt and it may be explained by the predominant water flow through the strait.

The data presented in Table 2 and 3 and in the figures testify of quite considerable differences during the course of the phenomenon while taking and not taking into account the water exchange between the Baltic Sea and the North Sea. They

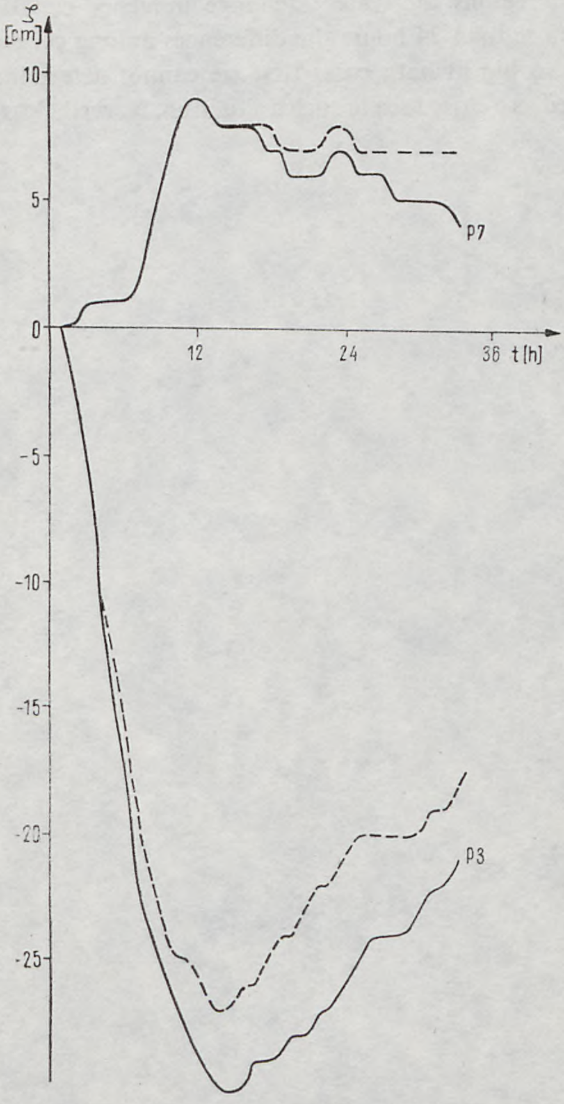

Fig. 10. Sea level changes in points P3 and P7 presented in fig. 2
——— the Baltic as a closed sea, – – – water exchange considered

also testify that as we go east and north from the Danish Straits, the water exchange influence is smaller and smaller and it appears after a long period of time.

The data analysis shows that in the storm surges calculations the Danish Straits and the southern part of the Baltic may be regarded as a closed basin only for 12 hours' period; the Central Baltic, the Gulf of Riga, the Gulf of Finland and the southern part of the Gulf of Bothnia – for about 24 hours' period. In the northern part of the Gulf of Bothnia the water exchange influence is noticeable at the end of the considered period, *i.e.* after about 32 hours.

This analysis pointed out that in the case of considering storm surges in time intervals of 12–24 hours in certain regions the water exchange influence can be neglected. In storm surges lasting more than 24 hours the differences among curves presenting mean level changes are so big in both cases that we cannot determine definitively if the Baltic may be treated as a closed sea in such a situation. Nevertheless,

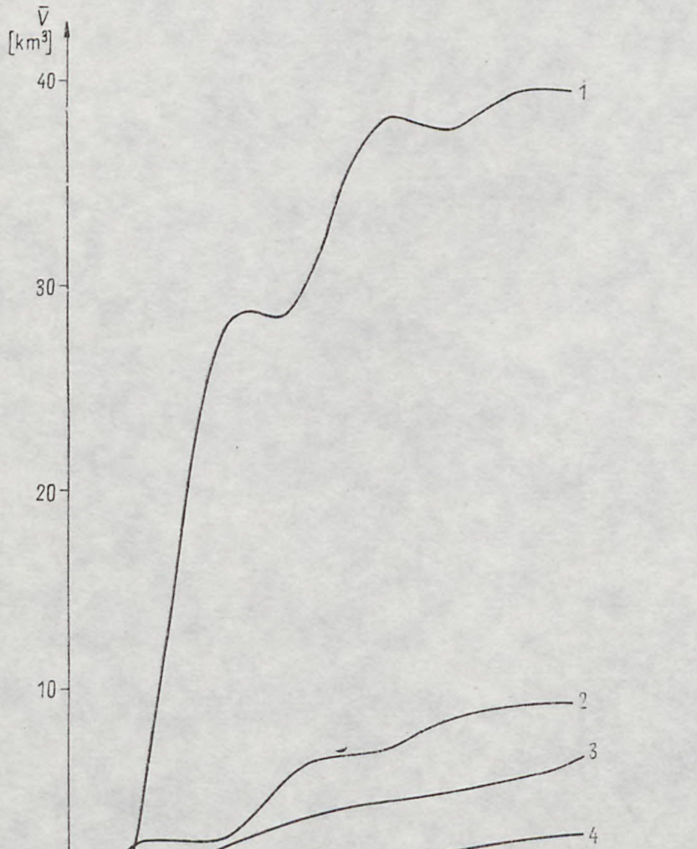

Fig. 11. Water volume changes
1 – in the North Sea (subarea 1), 2 – in the Skagerrak (subarea 2), 3 – in the Baltic Sea (subareas 3 - 8, 10 - 12, 14), 4 – in the Kattegat (subarea 9)

Fig. 12. Sea level isolines after 33 hours. ——— water exchange considered, – – – the Baltic as a closed sea

it seems obvious that the curve corresponding to the situation in which we take into account water exchange is closer to a real curve. The physical analysis of the considered phenomenon proves it.

4. Conclusions

The analysis of the influence of water exchange between the Baltic Sea and the North Sea on the sea surface elevation give fragmentary results because we took under consideration only wind with constant velocity and constant determined direction, and we did not investigate the situation for other wind directions and velocities. Nevertheless, it seems that certain conclusions resulting from this paper are of deeper and more universal character.

The principal conclusion that results from this paper is that it is necessary to take into account the water exchange influence in situations of long-term storm surges and the basins of the Baltic Sea adjacent to the Danish Straits. However, the time scale and sizes of the basins in which this influence can be neglected should stay in the direct correlation with a concrete considered surge. If a storm surge has features similar to a surge examined in this paper, then in the central, eastern, and northern regions of the Baltic Sea the influence of water exchange between the Baltic Sea and the North Sea on the course of a storm surge can be omitted up to 24 hours. The omission of this influence in western and southern regions of the Baltic, even in periods to 12 hours leads to considerable errors.

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