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Verification of a certain numerical model with the real storm surge of December 1976 in the Baltic sea*

Numerical model
Storm surge
Baltic Sea
North Sea

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Abstract

A numerical model of storm surges in the Baltic and the North Sea taking into account the water exchange between these two seas was verified with the real storm surge of 22nd to 28th December 1976. The results obtained from numerical calculations were compared with the observed water levels. Water volume balance during the considered storm surge in certain areas was calculated.

The conclusion of this paper is that water exchange between the North Sea and the Baltic Sea should be included in studies of storm surge in the Baltic.

1. Introduction

Kowalik and Chilicka works (1980, 1982) result in a theoretical description of storm surges phenomenon in the Baltic Sea including water exchange with the North Sea. These papers are based on the vertically integrated equations of motion and continuity which are numerically solved by using a finite difference method. The two-way nested grid model with fine resolutions in topographically interesting areas (*e.g.* the Danish Straits) was constructed. The area of the considered model was divided into fourteen subareas (Fig. 1) in which five different grid mesh sizes were used. The smallest grid size is $\Delta\lambda = 2'30''$, $\Delta\varphi = 1'15''$. The boundary conditions at the interface lines joining two meshes of different resolution were derived from the vertically integrated equation of motion solved using irregular-grid finite difference technique. The variable values of the horizontal eddy viscosity coefficient in each subarea were assumed, in view of the numerical stability. The non-linear terms were included in the model for the Danish Straits only.

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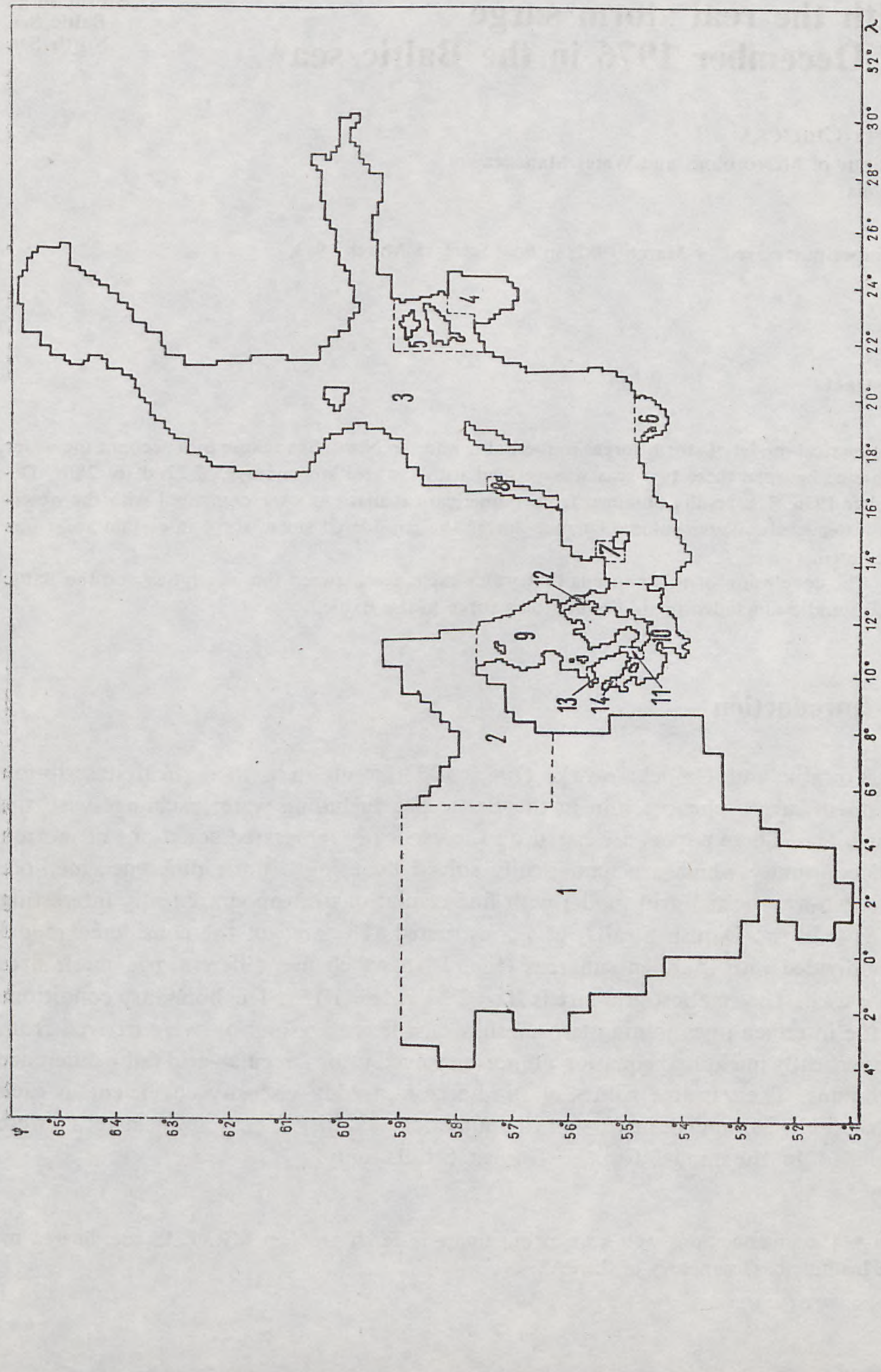


Fig. 1. Division of the basin into subareas

In comparison with the Chilicka and Kowalik paper (1982) certain modifications have been assumed in this paper. They are as follows:

– taking into account variability in time and space both of the wind stress and the atmospheric pressure gradient,

– assuming the sea level as a function of time and of the space – variables on the open boundary of the North Sea.

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

Number of the subarea	Grid size		Coefficient A CGS
	$\Delta\varphi$	$\Delta\lambda$	
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″	$4\cdot10^6$

The way of determining tangential components of the wind stress and components of the atmospheric pressure gradient is shown in chapter 2.2. Values of the sea level on the open boundary of the North Sea have been evaluated from the weather forecast data by using the hydrostatics equation.

The aim of this paper is to verify the numerical model presented above with the real surge from 22–28 December 1976.

The considered storm surge was physically quite complicated; in a short period of time (about 3 days) two or three (depending on areas) high or low water levels occurred.

The obtained model was studied in two situations: with and without filtering of the free sea surface. A five-point Shuman scheme (Shuman 1957) was used with half-amplitude damping of the shortes waves.

The water volume balance during the considered storm surge in chosen regions has been presented.

The conclusions of this work are similar to the results of the Chilicka and Kowalik paper (1982) who point out, that it is necessary to take into consideration water exchange with the North Sea, especially in the case of long-term surges, in order to obtain an adequate model of a storm surge in the Baltic Sea.

The model considered above uses (in comparison with others existing up to now) a lot of different factors. Each of them ought to have a significant influence on theoretical description of storm surge phenomenon. That is why a satisfactory agreement of the model constructed before with the real storm surge, quite physically complicated, seems to be an extremely important matter.

2. The storm surge from December 1976 in the Baltic Sea

2.1. Characteristics of the atmospheric circulation and the storm surge

From 22nd up to 28th December 1976 the Baltic Sea was influenced by several barometric depressions. Through most of considered period the North Sea was occupied by the ridge of barometric high pressure, with the centre in the North-West of British Islands.

The first depression with a shallow centre of low pressure area moved on 21st of December from the North Sea towards East and it got filled on 22nd December above the territory of Latvia (22nd December, 00h.). At that time the North Sea was the area of weak low pressure circulation from NE direction. At the beginning the Baltic Sea was found in a weak circulation from the South and after the centre of low pressure area had passed in a weak circulation from the North.

The second depression from 24th to 27th December was constituted by a very vast low pressure system from above North-Eastern Europe which moved step by step towards the Ural Mountains. It affected the Baltic Sea, at the beginning with a flow from NW and after passing of a cold front – with a flow of air mass from the North. In the meantime the North Sea was under the influence of a high pressure ridge in a weak northerly circulation.

The third depression which falled on the days between 25th and 26th December was formed by the centre of a low pressure area, which was getting more intensive and moved from the Norwegian Sea to the South over South Sweden and afterwards it turned across the Baltic Sea to the East where it got filled in the Moscow region.

At the beginning a weak flow from the North connected with a high pressure circulation predominated over the North Sea. This high pressure circulation has been changing into a low pressure circulation since 27th December. At the beginning the Baltic Sea was in SW circulation and since 26th December after a cold front had passed it was found in a very strong flow from the North. Since 27th December when the next low pressure area was passing by, a change of circulation into SW took place and then there occurred an increase of the flow intensity from NW in the western part of the Baltic Sea and from the SE direction in the central part of the Baltic Sea. The approximate tracks of four low pressure systems over the territory of Northern Europe are shown in Figure 2.

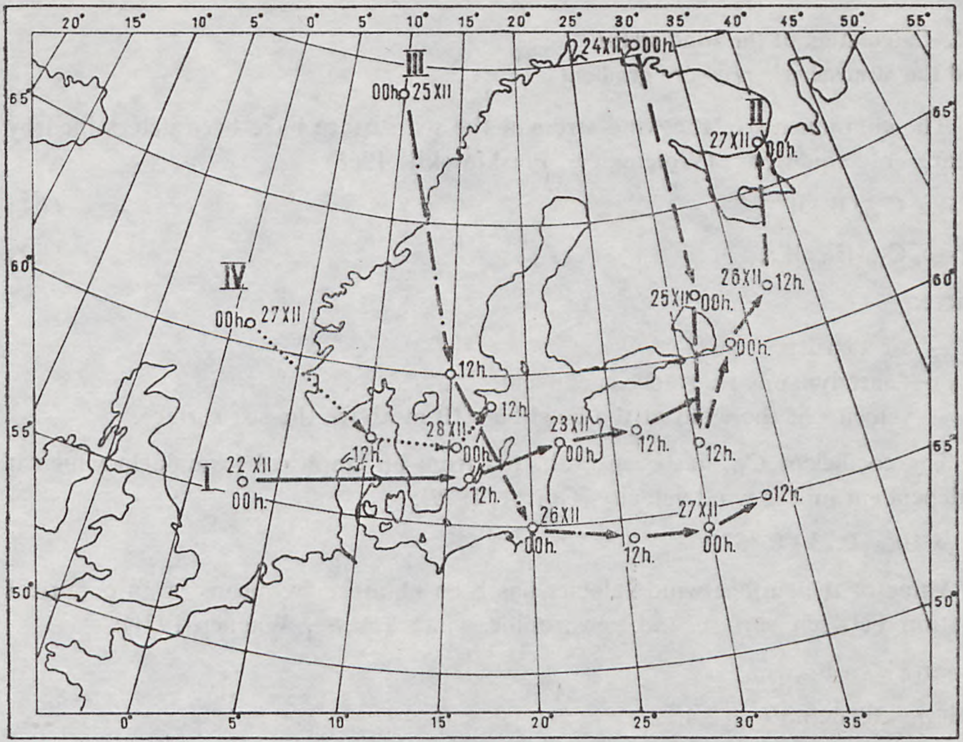


Fig. 2. Tracks of passing of low pressure systems during the period between 22nd and 28th December 1976

Water surface in the considered water regions was strongly affected by atmospheric processes. As a result of strong winds in certain centres of low pressure, some rapid movements of water surface of the whole water region were recorded.

A dynamic action of winds along the shores of the southern Baltic Sea, the Danish Straits and the Skagerrak caused two successive high water levels in a short period of time (about 3 days). The highest water levels occurred during the second surge. The amplitude of water level variations in the southern part of the Baltic Sea was considerably large: it equalled to 100 cm at Gdańsk-Nowy Port and to about 140 cm at Świnoujście. Still bigger amplitudes were noticed in the western part of the Baltic Sea and in the Belt Strait, *i.e.* 170 cm at Gedser, but much lower amplitude occurred in the Skagerrak and the Kattegat (about 40 cm).

In the period, when two successive high water levels occurred in the southern part of the Baltic Sea, two successive low water levels were noted in the Gulf of Bothnia but the second level was lower than the first one. The biggest depression of the sea surface was noted at Oulu – it reached about – 80 cm. Low levels of water were increasing gradually to the South direction.

But in the northern part of the central Baltic Sea and in the Gulf of Finland, three subsequent surges were noted in the considered period of time. The amplitude of these surges was increasing from the West to the East and it reached about 30 cm at Landsort and 100 cm at Hamina.

2.2. Calculation of the wind stress and the atmospheric pressure gradient

The components of the wind stress at the sea surface have been determined by means of equations (Wolcingier, Piaskowskij 1968)

$$T_\lambda^s = \rho_a C_{10}(W) W_\lambda , \tag{1.1}$$

$$T_\varphi^s = \rho_a C_{10}(W) \cdot W_\varphi , \tag{1.2}$$

where:

ρ_a – air density,
C_{10} – aerodynamic resistance coefficient,
W – velocity of the wind at the height $z = 10$ m above the sea surface.

The coefficient C_{10} has been evaluated from an empirical formula in which it is dependent on the wind velocity (Garratt 1979):

$$C_{10} \times 10^3 = 0.75 + 0.067W .$$

Value of the surface wind velocity has been obtained by means of an empirical relation between surface and geostrophic winds (Hasse, Wagner 1971):

$$W = a_1 \cdot W_G + b_1 ,$$

with $a_1 = 0.56$ and $b_1 = 2.4$.

Taking into consideration an angle of backing between the directions of a surface wind and a geostrophic wind, equal to $\delta = 18°$ following formulae for components of the surface wind velocity have been obtained:

$$W_\lambda = \frac{a_1 |W_G| + b_1}{|W_G|} (W_{G\lambda} \cos\delta - W_{G\varphi} \sin\delta) , \tag{1 3}$$

$$W_\varphi = \frac{a_1 |W_G| + b_1}{|W_G|} (W_{G\varphi} \cos\delta + W_{G\lambda} \sin\delta) . \tag{1.4}$$

To determine the tangential wind stress at the sea surface and the gradient of the atmospheric pressure a computational grid has been covered with an additional grid of size $\Delta\lambda = 2°$ and $\Delta\varphi = 1°$ (Fig. 3). Values of the atmospheric pressure taken from synoptic weather charts, carried out every three hours, have been written down in this grid. The difference of sizes of both grids has caused a necessity of choice of an approximation of the atmospheric pressure gradient. The following procedure has been used: constant values of the atmospheric pressure gradient have been assumed in points of the computational grid. These values have been determined in accordance with the following formulae (Fig. 4):

$$\frac{\partial p_a(i)}{\partial \lambda} = \frac{p_2(i) + p_4(i) - p_1(i) - p_3(i)}{2\Delta\lambda} ,$$

$$\frac{\partial p_a(i)}{\partial \varphi} = \frac{p_1(i) + p_2(i) - p_3(i) - p_4(i)}{2\Delta\varphi} .$$

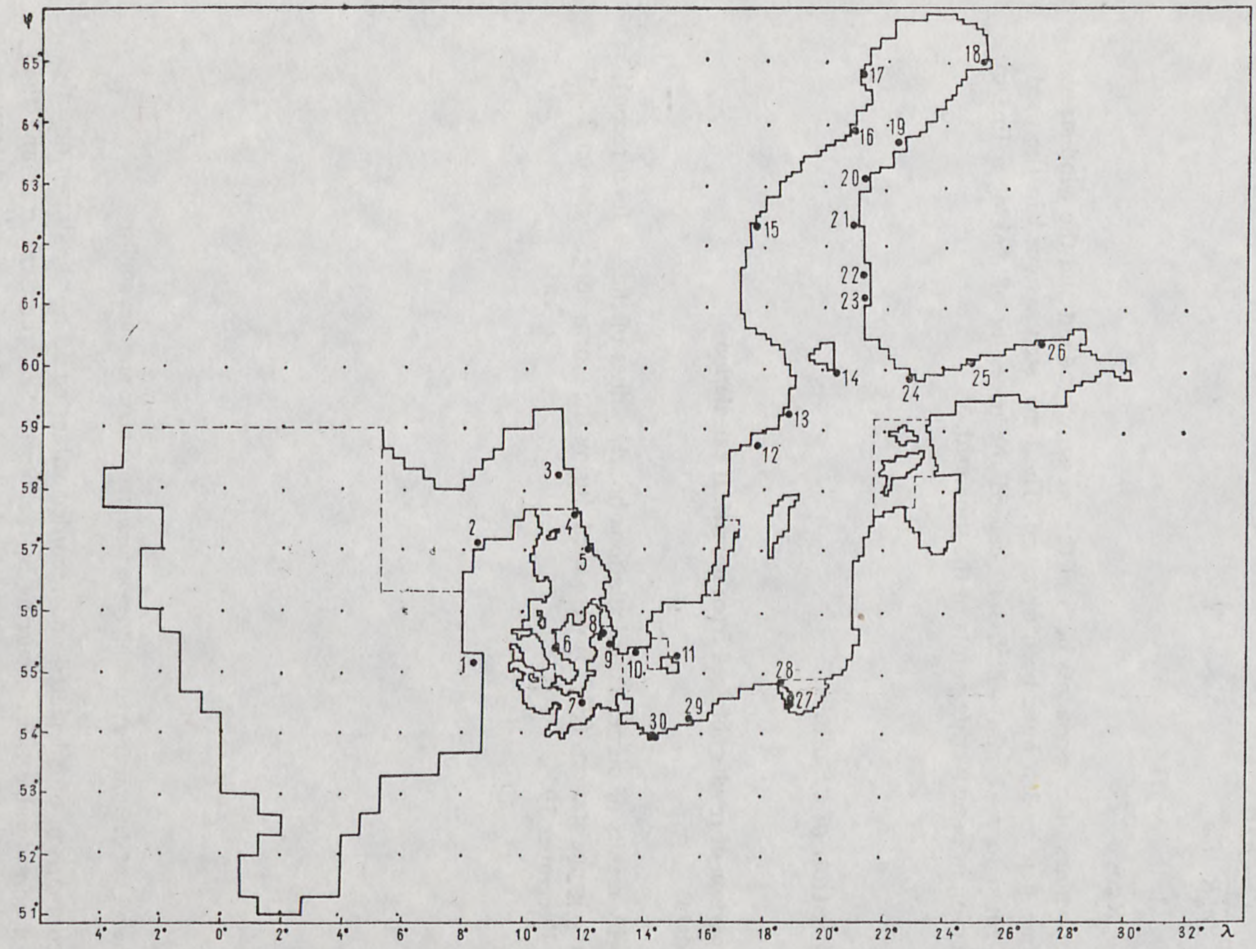


Fig. 3. Refined grids with a meteorologic grid and with marked gauge stations
1 – Esbjerg, 2 – Hanstholm, 3 – Smögen, 4 – Göteborg, 5 – Varberg, 6 – Korsör, 7 – Gedser, 8 – Copenhagen, 9 – Klagshamn, 10 – Ystad, 11 – Christiansö, 12 – Landsort, 13 – Stockholm, 14 – Degerby, 15 – Spikarna, 16 – Ratan, 17 – Furuögrund, 18 – Oulu, 19 – Pietarsaari, 20 – Vaasa, 21 – Kaskinen, 22 – Mantyluoto, 23 – Rauma, 24 – Hanko, 25 – Helsinki, 26 – Hamina, 27 – Gdańsk-Nowy Port, 28 – Władysławowo, 29 – Kołobrzeg, 30 – Świnoujście

To determine components of the tangential wind stress at the sea surface the formulae (1.1)–(1.2) have been used, where components of the geostrophic wind velocity have been calculated from formulae:

$$W_{G\lambda}(i) = -\frac{1}{f\rho_a R}\,\frac{\partial p_a(i)}{\partial \varphi},$$

$$W_{G\varphi}(i) = \frac{1}{f\rho_a R\cos\varphi}\,\frac{\partial p_a(i)}{\partial \lambda}.$$

In this way values of components both of the pressure gradient and the wind stress for the time step $\tau = 3$ h have been obtained. The time step assumed in the used model is equal to $\tau = 1$ min which has caused the necessity of making a linear approximation in noncovering points of the time grid.

3. Verification of results

3.1. Comparison of results obtained from numerical calculations with real data

To verify results of numerical calculations hourly values of the sea level records from 30 the gauge stations (Fig. 3) were used during the storm surge between 22nd and 28th December 1976.

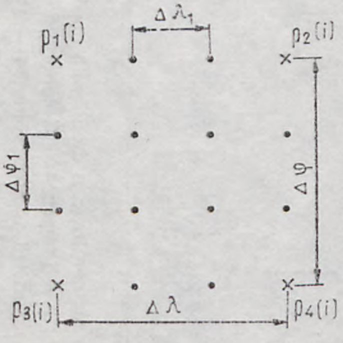


Fig. 4. The way of determining the wind stress and atmospheric pressure gradient

The comparison of calculated and recorded values could not be drawn directly because of considerable tides occurring in the North Sea, the Skagerrak and the Danish Straits. That is why a harmonic analysis of data coming from tide gauges situated in this region has been done. Values of the sea level caused by anemobaric factors have been obtained by subtracting the value of tide from the total variations of the sea level.

Figures 5–16 present a variation in time of the calculated and observed values of the sea level during the considered period of time and at the chosen stations, using the procedure presented before. Two curves have been drawn for the points placed nearest to the stations: a continuous one and a dotted one. The continuous line illustrates variation in time of the computed sea level values without filtering of the sea surface elevation. The dotted line is an analogon of the continuous line in case of calculations with filtering. The dashed line corresponds to real values of the sea level records.

From the presented figures we can conclude, that theoretical curves obtained from numerical calculations and real curves drawn on the basis of recorded values show quite great agreement of shape. The lack of better correlation between calculated and real results can be explained by following reasons:

1. the real curve illustrates a record of a coastal tide gauge (where the sea depth does not generally exceed 10 m) often placed in bays, ports and shallow waters; the theoretical curve gives the value in the centre of the assumed grid mesh. This

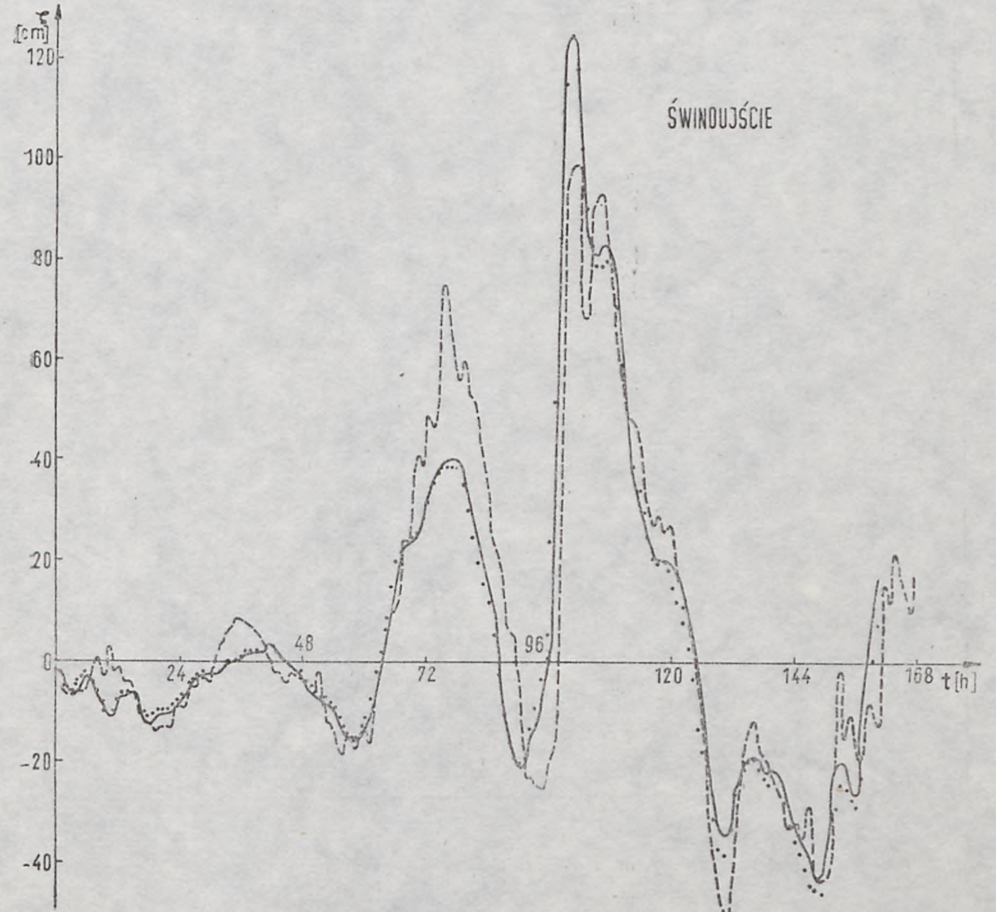
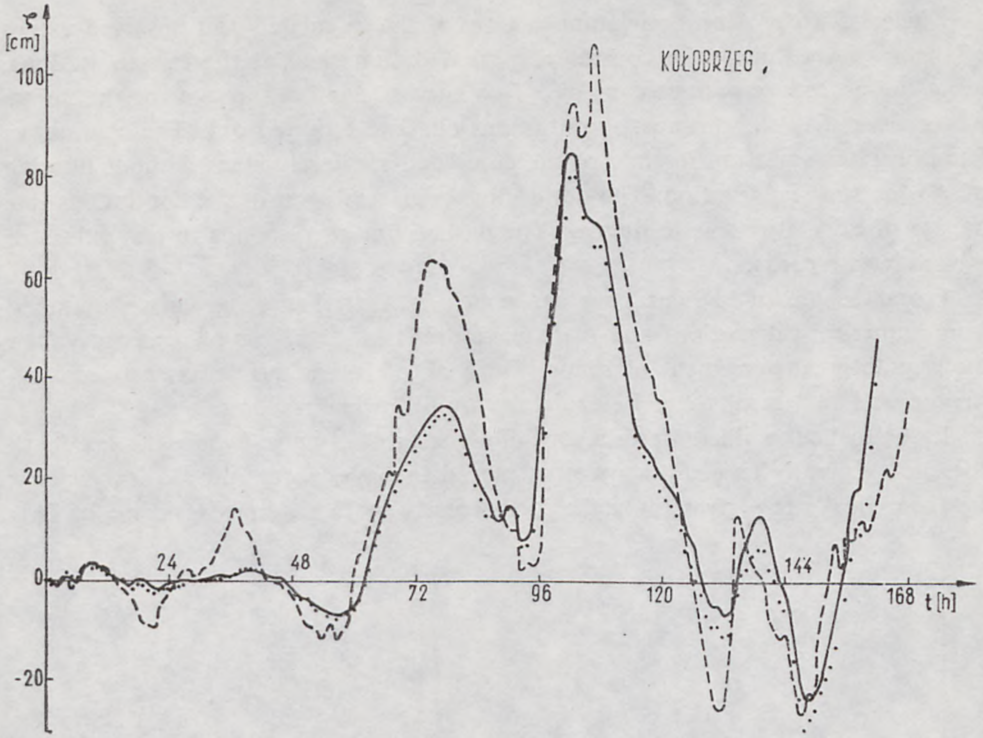


Fig. 5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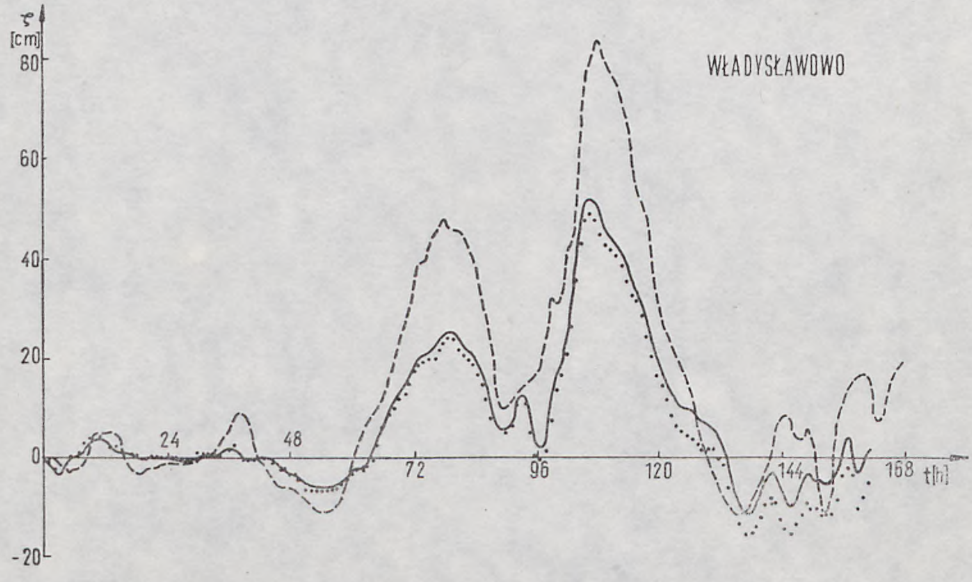
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Fig. 7

fact causes an error the greater, the greater is the grid size and the greater is the influence of local conditions on fluctuations of the sea level at the gauge stations;

2. the geostrophic wind is only a simplified representation of the real wind at the sea surface. According to observations the reduction factor describing the dependence between the real wind and the geostrophic one seems to be dependent on space coordinates. In the paper it is assumed to be constant. Moreover, the

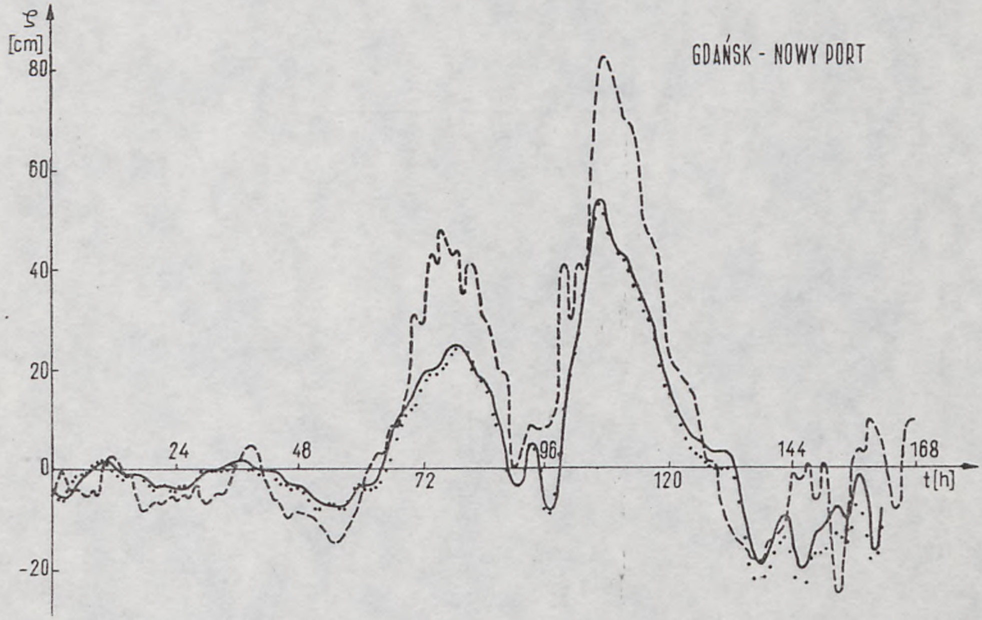
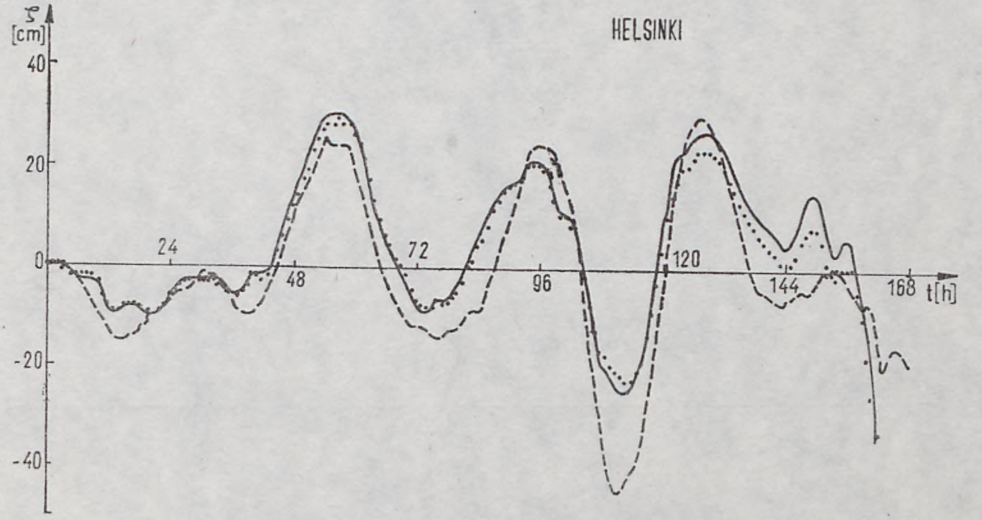


Fig. 8



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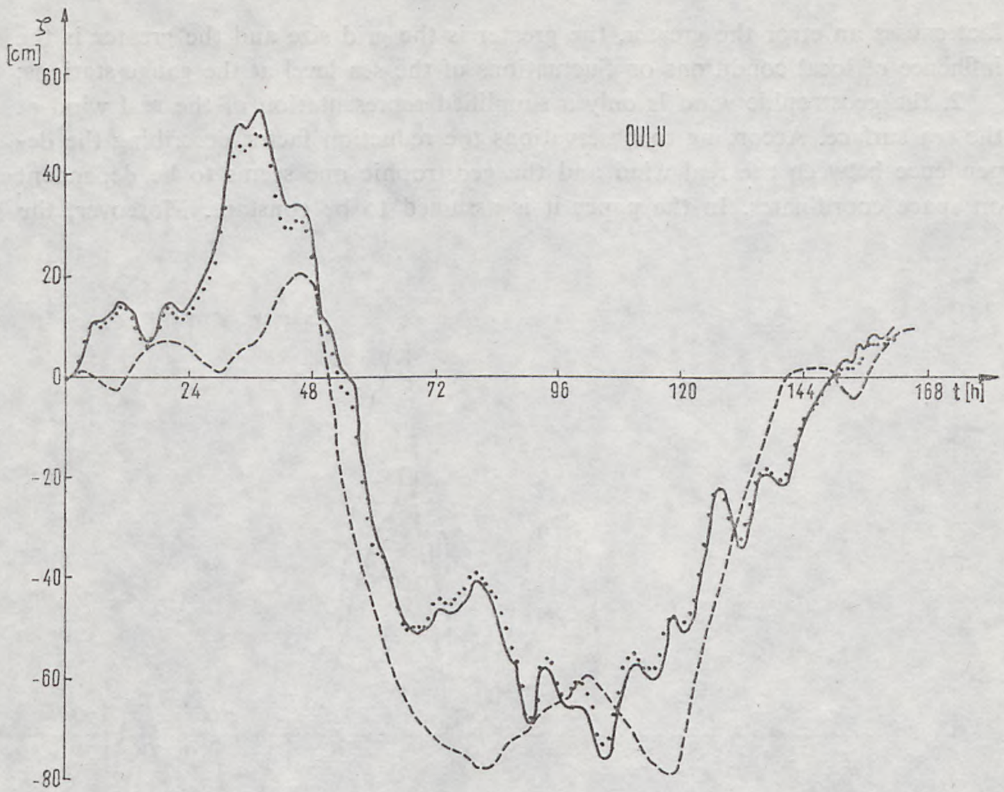
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Fig. 10

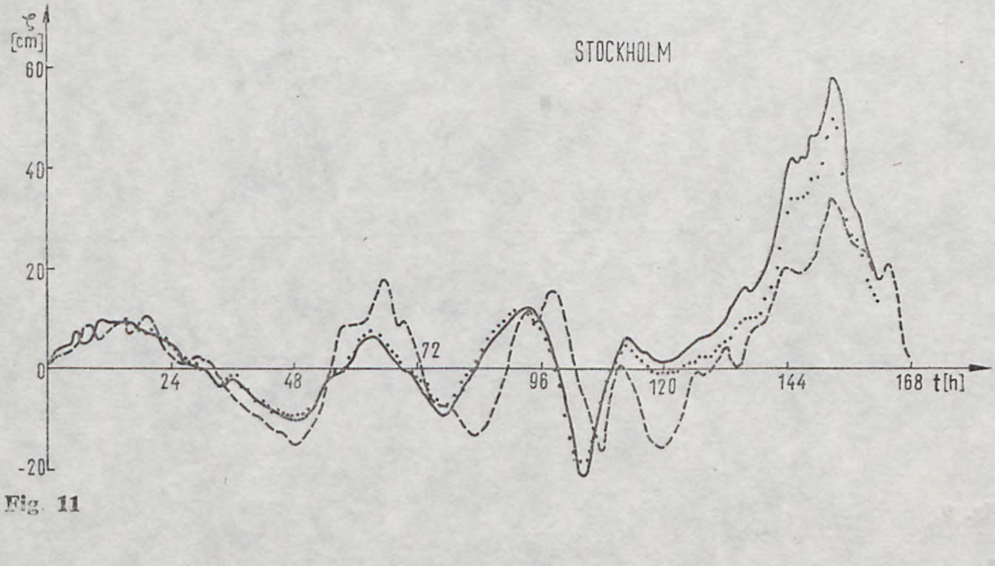
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Fig. 11

linear interpolation in time of the pressure distribution within three-hour weather charts is a rough approximation;

3. the damping effect of the ice cover which has been neglected in calculations leads to a discrepancy between real and theoretical curves at stations of the Gulf of Bothnia;

4. the theoretical curve describing oscillations of the sea surface elevation does not include all interactions between the existing forces influencing the position of the sea surface elevation. The phenomenon of tides is a characteristic example of this situation. In the theoretical model tides have been filtered off, that is the reason why their real influence on the storm surge phenomenon has not been taken into account. But the shape of the real curve is connected with the interaction of the tide and the wind surge;

5. the way of using of differential equations in a description of real phenomena of dynamic character implies usefulness of comparison of theoretical and real results after a passage of certain time from given initial conditions, because the influence of initial conditions decays as time elapses.

The results of application of the smoothing operator of the sea surface elevation prove, that its influence is considerable only in the case of smoothing small-scale disturbances in some regions (near to the open boundary of the North Sea and in the Skagerrak and the Öresund).

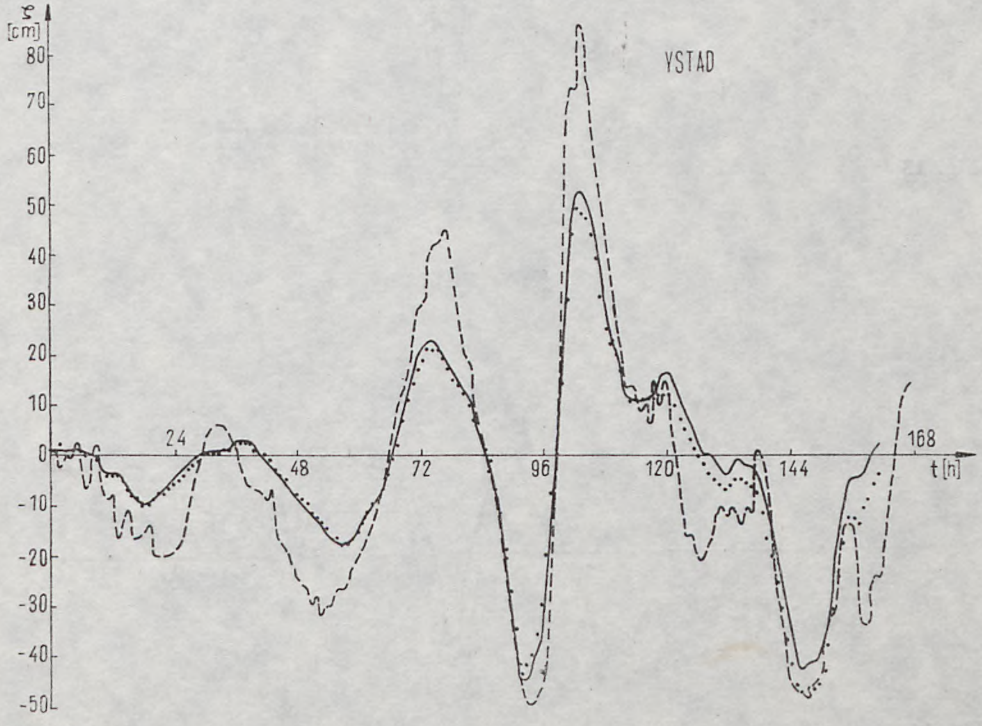

Fig. 12

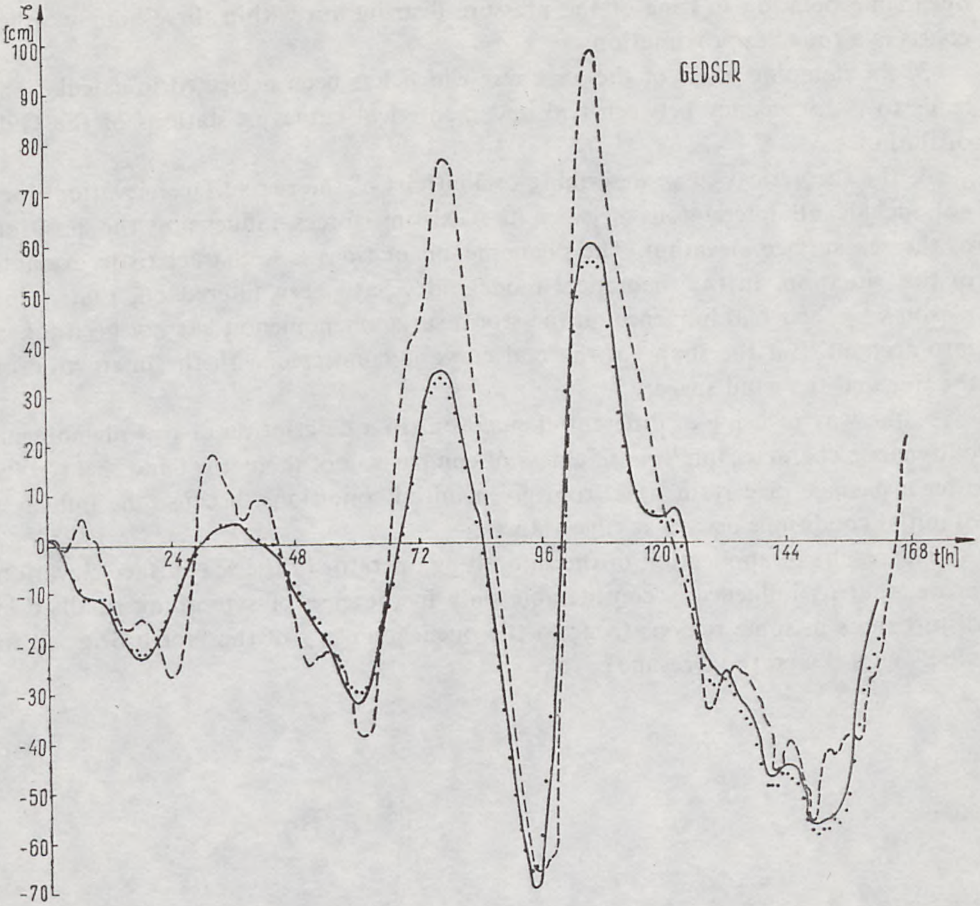
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Fig. 13

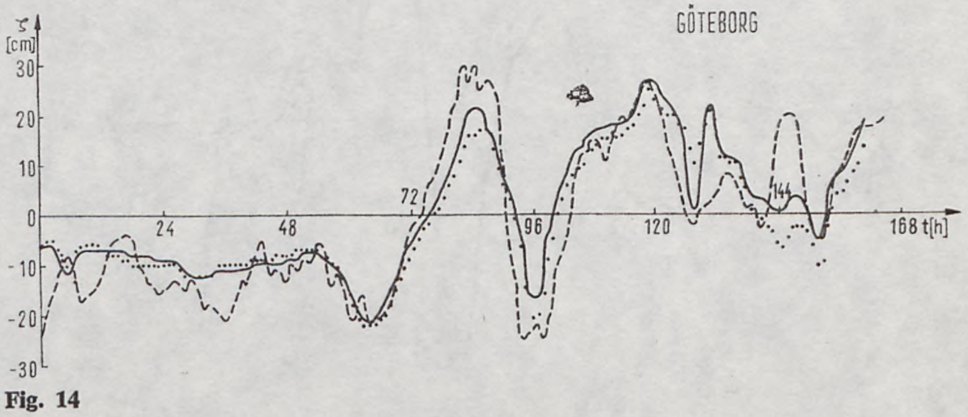
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Fig. 14

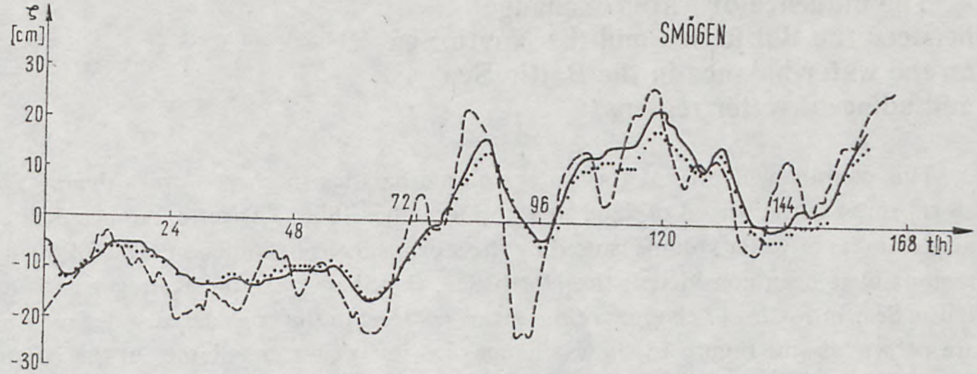

Fig. 15

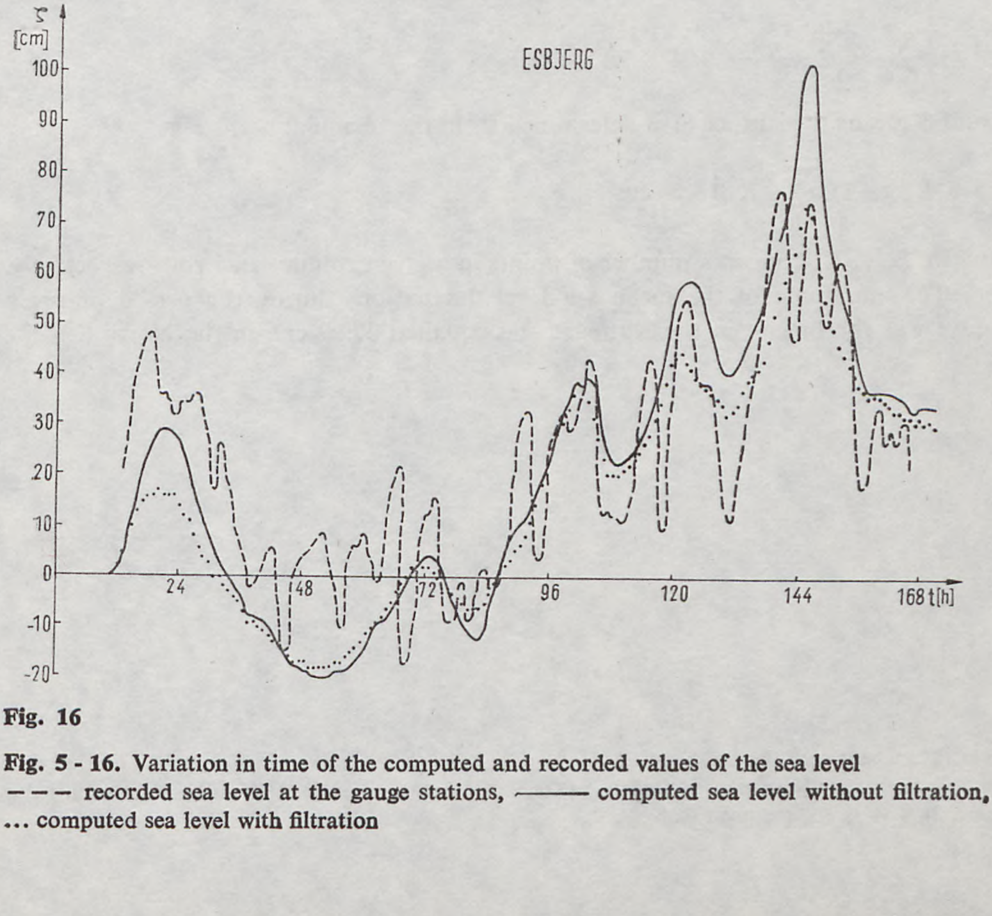

Fig. 16

Fig. 5 - 16. Variation in time of the computed and recorded values of the sea level
– – – recorded sea level at the gauge stations, ——— computed sea level without filtration, ... computed sea level with filtration

4. The influence of water exchange between the Baltic Sea and the North Sea on the water balance in the Baltic Sea and adjacent water regions

This chapter will present the water volume balance in chosen areas during the storm surge in the period of 22nd to 28th December 1976. The term balance defines here changes of water volume caused by the storm surge phenomenon. The following regions have been considered: the North Sea, the Skagerrak, the Kattegat and the Baltic Sea. In Figure 17 changes of the mean sea level in the considered water regions are presented and Figure 18 shows changes in time of water volumes in the North Sea (subarea 1), the Skagerrak (subarea 2), the Kattegat (subarea 9) and the Baltic Sea (subarea 3–8, 10–12, 14).

To determine changes in time of the mean sea level a following procedure has been used: for each of interesting regions the mean sea level — $\bar{\zeta}$ has been calculated from the formula:

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

where $\bar{V}$ means water volumes changes, which can be expressed by

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

and S means the surface area determined from the formula:

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

where $L_{\max}$, $K_{\max}$ mean a number of points in a given column and row respectively.

The amplitude of the mean sea level fluctuations during the period of seven days was the biggest in the Kattegat and equalled 37.99 cm; in the North Sea the

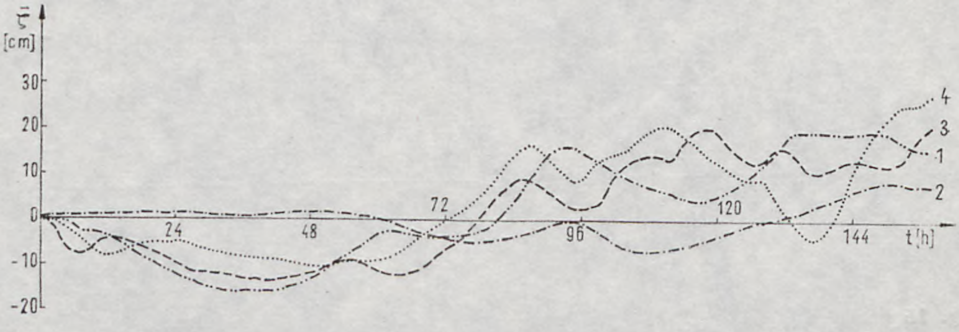

Fig. 17. Changes of the mean sea level
1 — in the North Sea (subarea 1), 2 — in the Baltic Sea (subarea 3), 3 — in the Skagerrak (subarea 2), 4 — in the Kattegat (subarea 9)

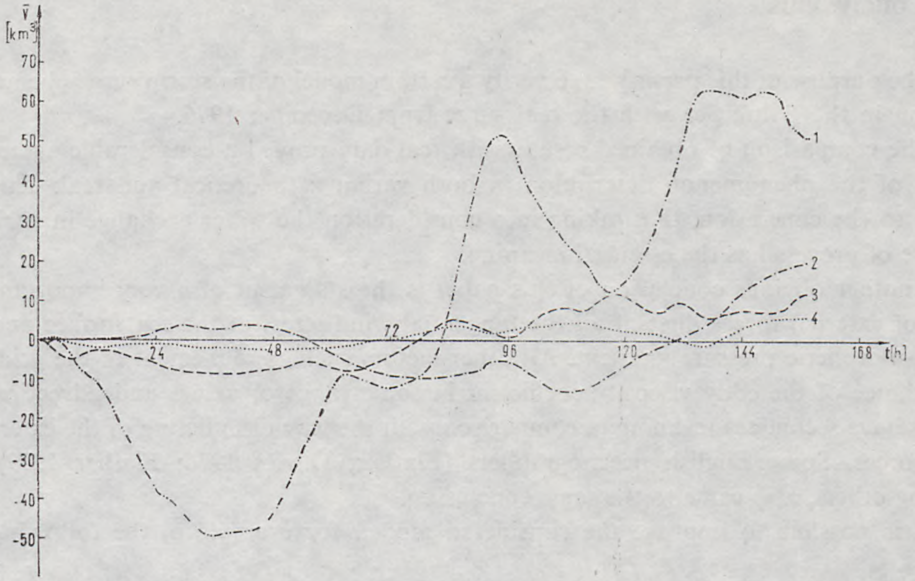

Fig. 18. Changes of the water volume
1 – in the North Sea (subarea 1), 2 – in the Baltic Sea (subareas 3 - 8, 10 - 12, 14), 3 – in the Skagerrak (subarea 2), 4 – in the Kattegat (subarea 9)

amplitude was equal to 35.28 cm; in the Skagerrak it was a little smaller as it worked out 34.90 cm; whereas it was equal to 15.33 cm in the Baltic Sea (considering subarea 3 only). It appears from Figure 18 that during the first 24 h of the process the water exchange between the North Sea and the Baltic had no essential influence on the water balance in the Baltic Sea. Such a conclusion is probably the result of the assumption of the beginning of the storm surge at the moment, when the Baltic Sea was relatively quiet, whereas the North Sea was already stormy. Taking into consideration about one week time of duration of the storm surge the influence of water exchange on the water balance in the Baltic Sea becomes visible and is bigger than in the Skagerrak and the Kattegat.

In the end we will show volume changes in the considered regions after 1, 4 and 7 × 24 h.

Table 2. Changes in time of water volumes in the considered subareas

Subareas	Time (1 × 24 h)			The amplitude of water volume variations during 7 days (km³)
	1 $\bar{V}$ (km³)	4 $\bar{V}$ (km³)	7 $\bar{V}$ (km³)	
The North Sea	−35.24	51.92	50.77	112.64
The Skagerrak	−5.43	1.46	12.83	21.11
The Kattegat	−1.22	1.97	6.31	8.60
The Baltic Sea	1.41	−4.87	20.11	32.98

5. Conclusions

The purpose of this paper was to verify a certain model of the storm surge phenomenon in the Baltic Sea with the real surge from December 1976.

The comparison of obtained results with real data proved a considerable agreement of the phenomenon description in both variants: theoretical and real. This leads to the conclusion, that taking into consideration the water exchange in such a type of process has the essential meaning.

Another obvious conclusion of this paper is the statement of a very important role of external forces, first of all the tangential wind stress at the sea surface and the atmospheric pressure gradient. All other factors such as refinement of the grid, the choice of the eddy viscosity coefficient in some range of values and advection terms have secondary meaning in comparison with the way of inflicting of the external forces. Some English oceanographers (Flather, Davies 1976; Flather 1979), among others, also came to the same conclusion.

It is possible to improve the considered model, for example in the following way:

a) by using of local models with a finer grid in these regions where the configuration of the coast-line or the depth distribution require it,

b) by the construction of a three-dimensional numerical model of a storm surge,

c) by the assumption of less idealized initial conditions,

d) by making the eddy viscosity coefficient characterizing the exchange of momentum in the horizontal direction dependent on motion characteristics,

e) by the application of a combined model, considering the atmosphere and the sea as a physical unity and taking sufficiently into account the transfer of energy through the interface between water and air.

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