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COMPUTATION OF DAILY MEAN LEVELS OF THE BALTIC IN THE GULF OF GDAŃSK BY MEANS OF WEIGHTING FUNCTIONS

Contents:

1. INTRODUCTION

Computations of sea level variations on the basis of anemobaric (wind and air pressure) conditions are one of the basic problems in oceanography. The variations constitute a component phenomenon of a broader process which is generally referred to as sea-atmosphere interaction. In practical applications, the computations are closely related to the prediction of storm surges, which comprise the greatest threat to hydraulic engineering structures. Correct short-term prediction using an appropriate mathematical model is essential for inshore, as well as offshore maritime structures. The aim of this paper is to compute daily mean levels of the Baltic at Nowy Port and Hel on the basis of the response functions accounting for linear relationships between anemobaric conditions and the phenomenon considered in the frequency domain. The response functions are then transformed into weighting functions, which in turn permit computations in time steps to be conducted.

The computations were carried out for daily mean air pressures. These mean values were found from measurements at weather stations covering the air pressure situations of the south Baltic. Wind measurements at Hel were also conducted with the meridian wind component as the initial data of the model accepted. Table 1 lists the weather and tide gauge stations analyzed in this paper together with detailed data on the measurements applied. The geographical layout of the measuring stations is shown in Fig. 1. The horizontal components of the air pressure gradient were found by subtracting Hel pressures from those at the given stations. The air pressure values have been reduced to sea level.

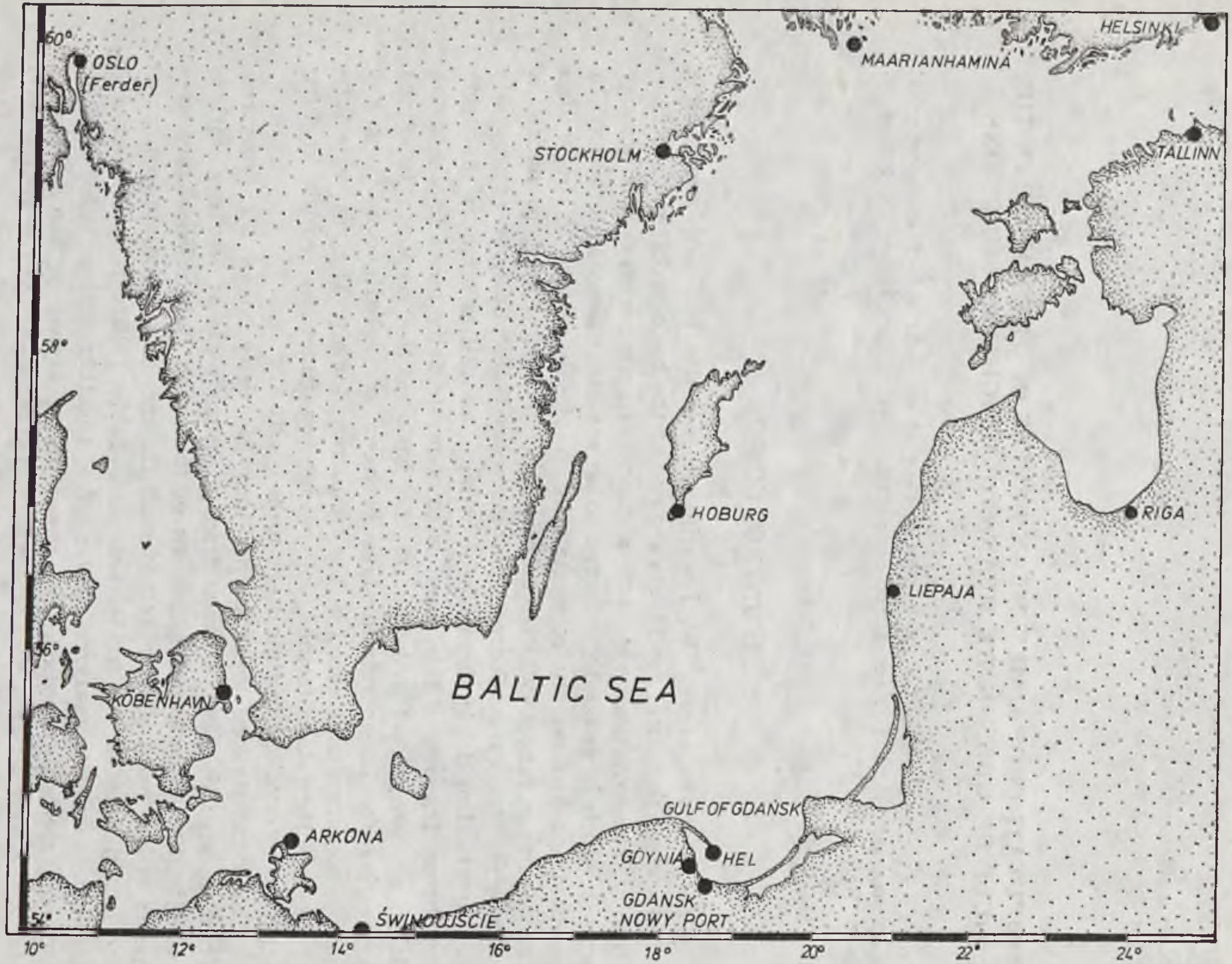

Fig. 1. Geographic layout of the weather and tide gauge stations analyzed in this paper
Ryc. 1. Położenie geograficzne stacji hydrometeorologicznych analizowanych w pracy

It can be seen from Table 1 that not all the data are homogeneous. The time increment of various observations differs. However, the application of the mean daily values permitted the assumption that the differences are not essential and do not obscure the relationships between particular processes. The results of the computations carried out have confirmed this assumption.

Table 1
Tabela 1

The air pressure and tide gauge measurements applied in the computations
Pomiary ciśnienia atmosferycznego i poziomów morza zastosowane w obliczeniach

Station	Phenomenon observed	Time increment	Data application	Measurement period	References
Stacje pomiarowe	Obserwowane zjawisko	Krok kwantowania	Zastosowanie danych	Okres pomiarów	Literatura
Arkona	air pressure	3 hours	daily mean	Jan. 1-Dec. 31 1968	[20*]
Ferder	air pressure	3 hours	daily mean	—„—	[20*]
Hel	air pressure	3 hours	daily mean	Jan. 1, 1968 — May 26, 1969	[18]
Hel	wind	4 hours	daily mean	—„—	[3]
Hel	sea levels	4 hours	daily mean	—„—	[19]
Helsinki	air pressure	3 hours	daily mean	Jan. 1-Dec. 31, 1968	[20*]
Hoburg	air pressure	3 hours	daily mean	—„—	[20*]
Liepaja	air pressure	3 hours	daily mean	—„—	[20*]
Maarianhamina	air pressure	3 hours	daily mean	—„—	[20*]
Nowy Port	sea levels	4 hours	daily mean and 4 hour data	Jan. 1, 1968— May 26, 1969	[19]
Oslo	air pressure	2 hours	daily mean	—„—	[14]
Świnoujście	air pressure	3 hours	daily mean	—„—	[18]

* The air pressures were determined from weather charts. The values given were sometimes interpolated. The data was employed to compute the general relationships illustrated in Fig. 2.
Ciśnienia atmosferyczne zostały wyznaczone z map synoptycznych. Dane były czasami interpolowane. Określone w ten sposób wartości ciśnienia atmosferycznego były podstawą obliczeń ogólnych zależności przedstawionych na ryc. 2.

2. THE METHOD OF COMPUTATION

It was assumed that sea levels are shaped by linear anemobaric effects in frequency space.

Superposition of three partial output processes of the system considered determines the output process.

Following the assumptions for correlated inputs given in monograph [1], one can determine the relationship between the response functions and weighting functions versus sea levels, which reads:

$$S_{ky}(f) = \sum_{j=1}^{3} \int_{-\infty}^{\infty} \left[\int_{-\infty}^{\infty} e^{-i2\pi f\zeta} h_j(\zeta) \right] e^{-i2\pi f(\tau-\zeta)} R_{kj}(\tau-\zeta)\, d\zeta\, d\tau \tag{1}$$

After transformations one obtains the following system of linear equations:

$$S_{1y}(f) = H_1(f) S_{11}(f) + H_2(f) S_{12}(f) + H_3(f) S_{13}(f) \tag{2}$$

$$S_{2y}(f) = H_1(f) S_{21}(f) + H_2(f) S_{22}(f) + H_3(f) S_{23}(f) \tag{3}$$

$$S_{3y}(f) = H_1(f) S_{31}(f) + H_2(f) S_{32}(f) + H_3(f) S_{33}(f) \tag{4}$$

Where:

$x_k(t)$ = input processes
$y(t)$ = output process
$h_j(\zeta)$ = weighting functions
$R_{kj}(\tau-\zeta)$ = correlation and autocorrelation functions
$S_{kj}(f)$ = spectral density and cross-spectral density functions
$H_j(f)$ = response functions

The relationship between the spectral density of the output process and the input processes, correlated for three inputs, is as follows:

$$S_y(f) = \sum_{k=1}^{3} \sum_{j=1}^{3} \int_{0}^{\infty} h_k(\zeta) e^{i2\pi f\zeta} d\zeta \int_{0}^{\infty} h_j(\eta) e^{-i2\pi f\eta} d\eta \int_{-\infty}^{\infty} R_{kj}(t) e^{-i2\pi ft} dt =$$

$$= \sum_{k=1}^{3} \sum_{j=1}^{3} H_k^*(f) H_j(f) S_{kj}(f) \tag{5}$$

Where:

$H_k^*(f)$ = conjugated value of the response function $H_k(f)$

$t = \zeta - \eta + \tau$, so that $dt = d\tau$

The superposition of the partial output processes in the time space is given by the equation:

$$y(t) = \sum_{j=1}^{3} \int_{0}^{\infty} h_j(\tau) x_j(t-\tau)\, d\tau \tag{6}$$

For uncorrelated inputs, the relationship between the response functions and the spectral densities of the processes computed is given by the simple formula:

$$S_{jy}(f) = H_j(f)\, S_{jj}(f) \tag{7}$$

The multiple coherence factor $\gamma^2_{y.x}(f)$ is presented by the formula:

$$\gamma^2_{y\cdot x}(f) = 1 - [S_{yy}(f)\, S^{yy}(f)]^{-1} \tag{8}$$

The quantity $S_{yy}(f)$ in formula (8) is found by the matrix form:

$$S_{yy}(f) = \mathbf{H}(f)\, \mathbf{S}_{xx}(f)\, \mathbf{H}^{*\prime}(f) \tag{9}$$

Where:

$\mathbf{S}_{xx}(f)$ — the quadratic matrix of the spectral densities of the input processes

$\mathbf{H}(f)$ = response function vector

$\mathbf{H}^{*\prime}(f)$ = conjugate transpose vector of the response function

$S^{yy}(f)$ = first diagonal element of the inverse matrix $\mathbf{S}^{-1}_{yxx}(f)$.

associated with $\mathbf{S}_{yxx}(f)$:

$$\mathbf{S}_{yxx}(f) = \begin{bmatrix} S_{yy}(f) & S_{yx_1}(f) & S_{yx_2}(f) & S_{yx_3}(f) \\ S_{x_1y}(f) & S_{x_1x_1}(f) & S_{x_1x_2}(f) & S_{x_1x_3}(f) \\ S_{x_2y}(f) & S_{x_2x_1}(f) & S_{x_2x_2}(f) & S_{x_2x_3}(f) \\ S_{x_3y}(f) & S_{x_3x_1}(f) & S_{x_3x_2}(f) & S_{x_3x_3}(f) \end{bmatrix} \tag{10}$$

All the spectral densities used in computations of the weighting functions were found by the Fast Fourier Transform [1, 17] with simultaneous cosine tapering of 10 per cent input data both at the beginning and at the end of a particular measurement series. The spectral densities used in evaluations of the coherence of anemobaric factors and water levels (Fig. 2) were found by the Blackman — Tuckey algorithm [2]. The Hamming filter was employed to smooth out these spectra. The confidence level of the coherence was determined for a probability of 95 per cent. The partial coherence functions were found by the partial spectral densities.

3. SELECTION OF INPUT PROCESSES

The application of the response function in computations of changes in levels of a water body was discussed by Privalskii [16].

In the "two inputs — one output" system and for time increments of 6 hours, the storm surge at Kaliningrad during the period from February 11 to February 23, 1962 was simulated fairly accurately. The absolute value of the response function was used as an approximation of the weighting function, while the Blackman — Tuckey algorithm was em-

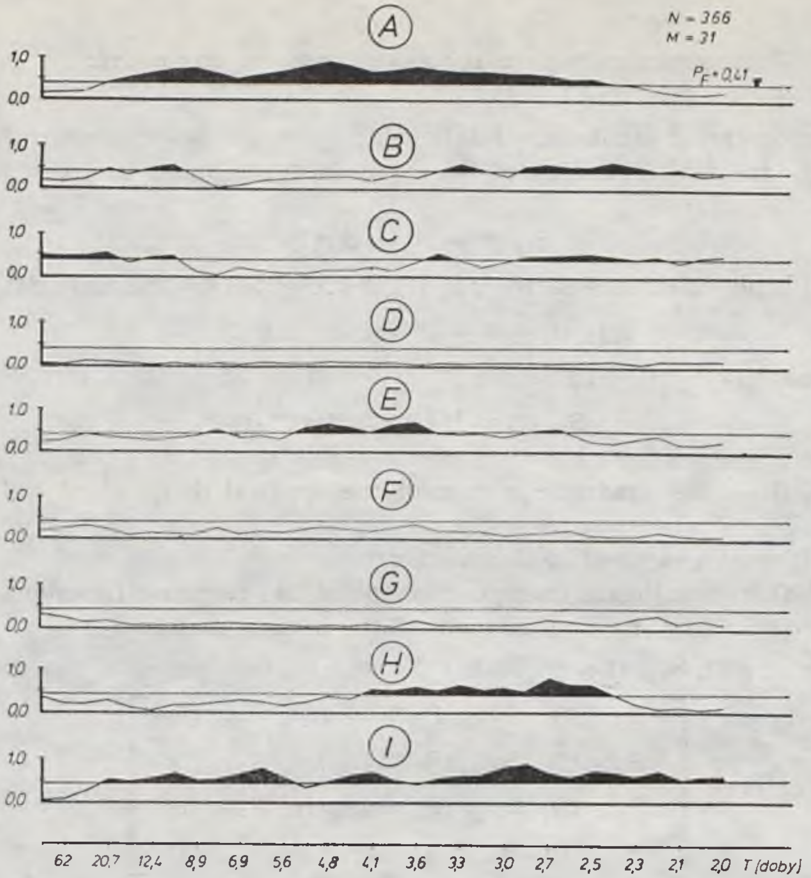

Fig. 2. Coherence of daily mean anemobaric parameters and daily mean sea levels in Nowy Port in 1968

A — horizontal component of air pressure gradient: Ferder — Hel
B — horizontal component of air pressure gradient: Arkona — Hel
C — horizontal component of air pressure gradient: Świnoujście — Hel
D — horizontal component of air pressure gradient: Hoburg — Hel
E — horizontal component of air pressure gradient: Maarianhamina — Hel
F — horizontal component of air pressure gradient: Helsinki — Hel
G — horizontal component of air pressure gradient: Liepaja — Hel
H — air pressure at Hel
I — meridian wind component at Hel

The shaded portions of the diagram indicate a coherence above the significance level

Ryc. 2. Koherencja średnich dobowych elementów anemobarycznych ze średnimi dobowymi poziomami morza w Nowym Porcie w 1968 r.

A — składowa pozioma gradientu ciśnienia atmosferycznego: Ferder — Hel
B — składowa pozioma gradientu ciśnienia atmosferycznego: Arkona — Hel
C — składowa pozioma gradientu ciśnienia atmosferycznego: Świnoujście — Hel
D — składowa pozioma gradientu ciśnienia atmosferycznego: Hoburg — Hel
E — składowa pozioma gradientu ciśnienia atmosferycznego: Maarianhamina — Hel
F — składowa pozioma gradientu ciśnienia atmosferycznego: Helsinki — Hel
G — składowa pozioma gradientu ciśnienia atmosferycznego: Liepaja — Hel
H — Ciśnienie atmosferyczne dla Helu
I — składowa południkowa wiatru dla Helu

Zaczernione części wykresu oznaczają przekroczenie przez koherencję poziomu znaczącego ployed to depict spectral densities. The meridian wind component and the air pressure in Kaliningrad were assumed as the input processes. The method proved successful because of specific hydrometeorological conditions at Kaliningrad. However, the conditions of water level variations in the south Baltic, and thus in the Gulf of Gdańsk are shaped not only by local anemobaric conditions which appear to be a single component of general air pressure field. It was decided to conduct the computations for daily mean water levels, which permitted periods of from 48 hours to about 1 month to be considered. Many bibliographical sources provide the analysis of semi-daily mean and daily mean sea levels against the background of anemobaric conditions and thus give the first approximation for the prediction of the effect of these on water levels [7, 9, 15].

The water levels determined for 4 hour time increments do not differ from the respective mean diurnal values by more than a few centimetres, on average, for the Hel and Nowy Port tide gauges.

It is known from the general weather situation of the south Baltic that the effect of anemobaric variations on water levels changes in both time and space [4, 9, 11]. In order to study this effect by stochastic methods the coherence was computed for the daily mean water levels at Nowy Port and the daily mean horizontal components of the air pressure gradients between various measuring stations and Hel. The daily mean values of the meridian wind component and air pressure at Hel were also considered as a local factor. The year 1968 was taken for the computations, which means that $N = 366$. The maximum correlation lag was $M = 31$. The results of the coherence computations are presented in Fig. 2.

The computations confirm the previously known effect of the horizontal component at the Świnoujście — Hel pressure gradient on the water levels in the Gulf of Gdańsk [10]. The meridian wind component also shows a high coherence level. The highest coherence values appeared for the Ferder — Hel gradient, which can be explained by the fact that this gradient is associated with the wide air pressure field which affects large water areas of the south Baltic and controls the water exchange through the Danish Straits. The remaining coherence relationships are weaker than the above. In the system of computations accepted, the horizontal air pressure gradients Oslo — Hel (instead of Ferder — Hel), and Świnoujście — Hel together with the Hel air pressure and the Hel meridian wind component were taken as the input processes. The shapes of spectral densities of the daily mean sea levels in Nowy Port and Hel, shown in Fig. 3, were also taken into account in the selection of the input processes.

The optimum choice of the three input processes from the above four

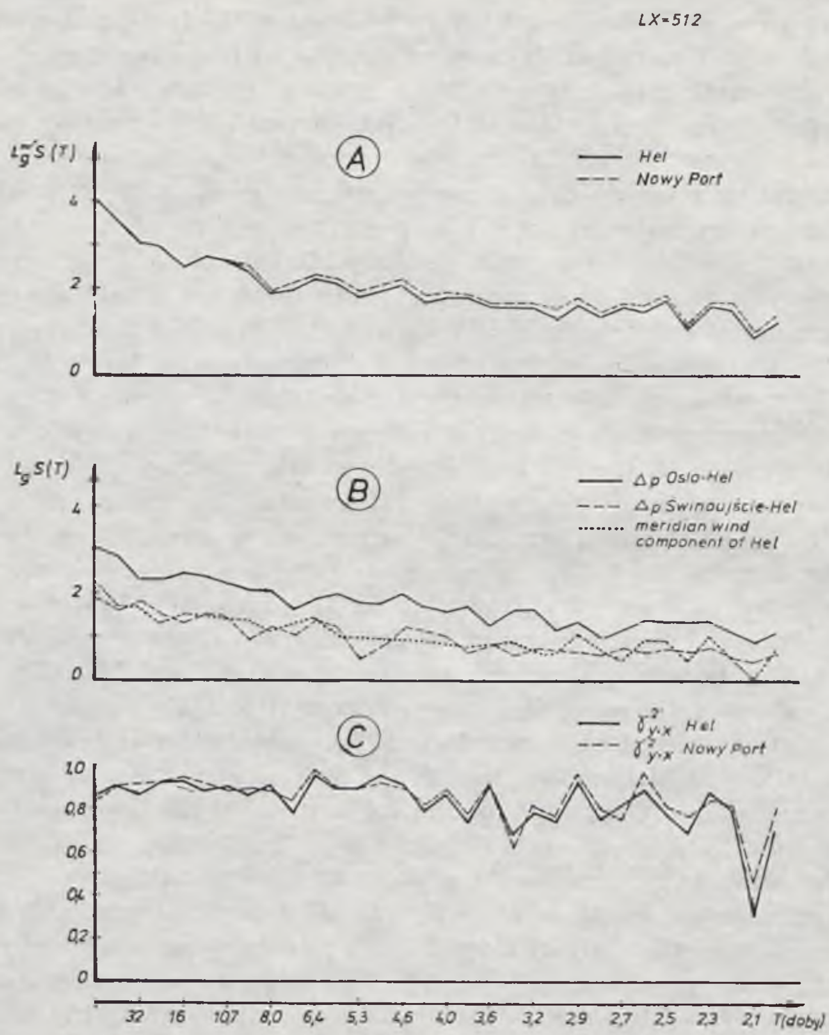

Fig. 3. A — Spectral densities of daily mean sea levels in Nowy Port and Hel
B — Spectral densities of input processes
C — multiple coherence coefficient for input processes and sea water levels in Nowy Port and Hel

Ryc. 3. A — widmowe gęstości średnich dobowych poziomów morza w Nowym Porcie i Helu
B — widmowe gęstości procesów wejściowych
C — współczynnik wielokrotnej koherencji procesów wejściowych z poziomami morza w Nowym Porcie i Helu

was accomplished by taking as a criterion, the mean error* of the computed levels with respect to the data measured.

The stochastic model of the linear interaction of the anemobaric factors accepted herein is no doubt an approximation to the real effect of the air pressure and wind on water level. This model is equivalent to one with constant system parameters and a stationary random function. The lack of stationarity in our case has little effect on the results of the computations, and the assumption of linearity is confirmed by the partial coherence calculations showing only linear relationships between the processes analyzed.

The conformity with the measurement data, which is a decisive factor in prediction, was taken as the conclusive criterion.

4. THE RESULTS OF COMPUTATIONS

The weighting functions of the input processes were computed for the period January 1, 1968 to May 26, 1969. The number of data in the series measured was then $LX = 512$. The maximum time lag $\tau = 31$. The spectral densities of the daily mean sea levels in Nowy Port and Hel, presented in Fig. 3, show that no clear periodicity can be singled out for the oscillations determined. The differences between Nowy Port and Hel are insignificant. The slightly higher spectral density of Nowy Port in the band of average periods can be attributed to higher amplitudes of oscillations at the shallow-water tide gauge in Nowy Port, as compared with the Hel tide gauge, where the effect of nearshore flats is much smaller. The increase of spectral densities at the axis of ordinates is mainly due to annual and semi-annual periods. Similar characteristics are displayed by the spectral densities of the input processes shown in the same drawing. The coefficient of multiple coherence for Nowy Port and Hel, which depicts the joint effect of the input processes on water levels, is also shown in Fig. 3. The multiple coherence illustrates that the dependence of the spectral density of the output process on the spectral density of the input processes is at a coherence level which permits prediction application.

The computations were carried out, assuming the Oslo — Hel and Świnoujście — Hel air pressure gradients as input data. The mean error of water level variations computed from the measurements and simulated for the Hel pressures as the third input process was $\pm$ 8 cm in Nowy Port for correlated inputs. The computation was repeated with the Hel meridian wind component as the input process indicated that the mean error was $\pm$ 7 cm.

* rms error

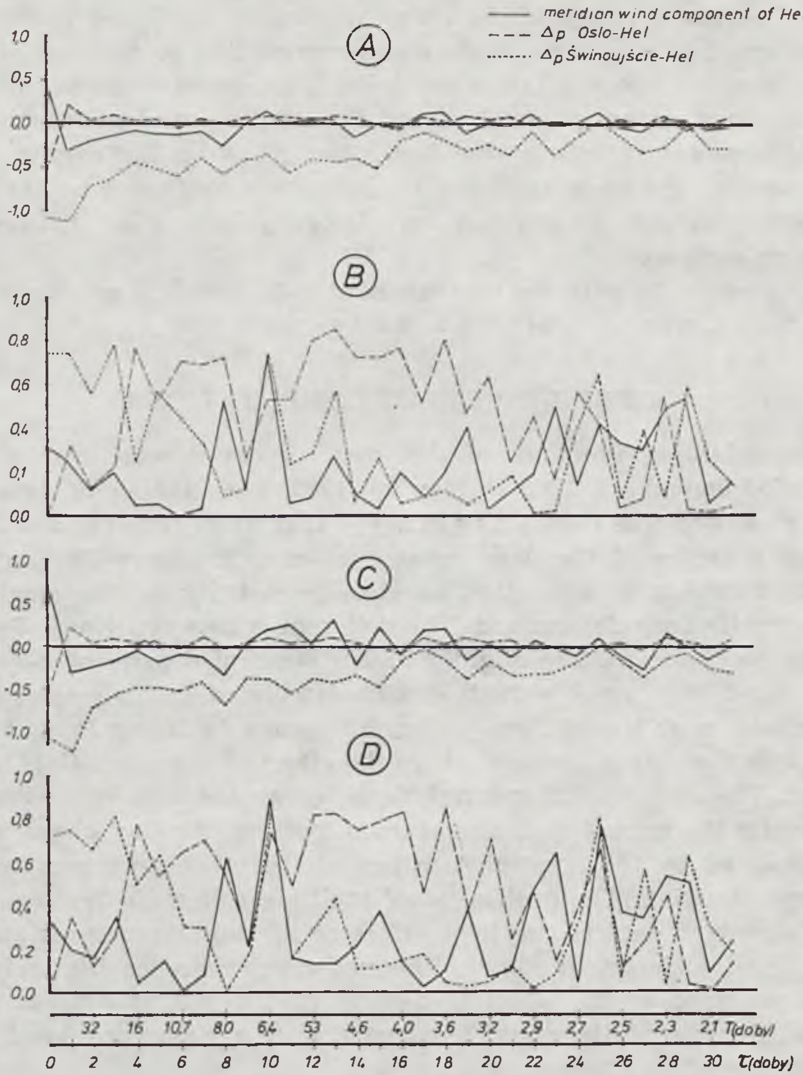

Fig. 4. Weighting functions (A) and partial coherences of input processes (B) for Hel, also weighting functions (C) and partial coherences of input processes (D) for Nowy Port

Ryc. 4. Funkcje wagowe (A) i cząstkowe koherencje procesów wejściowych (B) dla Helu oraz funkcje wagowe (C) i cząstkowe koherencje procesów wejściowych (D) dla Nowego Portu

Finally, the meridian wind component of Hel was accepted in further computations. Fig. 4 shows the weighting functions computed together with partial coherences of the input processes and the output process for Nowy Port and Hel.

The mean errors of both tide gauges in the period in question indicated the same value of $\pm$ 7 cm for correlated inputs. For uncorrelated ones, the respective figures were $\pm$ 10 cm for Hel and $\pm$ 11 cm for Nowy Port. The multiple coherence for Nowy Port, shown in Fig. 3, and a bit higher on average than the other, is not consistent with the mean error computed for both tide gauges with an accuracy up to 1 cm. The water levels from the measurements and computations for the annual period of February 1, 1968 to January 31, 1969, presented in Figs. 5 and 6, illustrate substantial conformity in both graphs. The computations shown refer to correlated inputs only. The system of uncorrelated inputs was not analyzed because of greater divergence with the data measured.

From the diagram of the weighting functions shown in Fig. 4 it appears that the maximum absolute values of these functions are related to the zero value of the argument τ for the Oslo—Hel gradient and the Hel meridian wind component. The Świnoujście — Hel gradient has the maximum absolute value of the weighting function for $\tau = 1$. This result agrees well with the spectral characteristic of the processes analyzed. The negative and positive values of the weighting functions are present because of the complex process of the effect of anemobaric fields on water levels, in both frequency and time systems, and also due to the system chosen for the preparation of these data as input characteristics.

Additional computations of water levels were conducted for Nowy Port with the Oslo—Hel gradient, Hel meridian wind component, and daily mean sea levels at Hel as input characteristics. The mean error of the water levels calculated with respect to the data measured was $\pm$ 3 cm. The computation illustrated in Fig. 7 shows that the water levels computed for one tide gauge can easily be extended to other stations of an area considered, with very little additional work. The generalization of the system assumed for the entire area is coupled with the appropriate choice of the input processes, which include local anemobaric and hydrological parameters together with data on the effect of larger fields of air pressure. It should be noted that the conditions of water level variation of the Hel tide gauge, when used for Nowy Port forecasts, are more complex than those of the weather stations located along the south coastline of the Gulf of Gdańsk.

The daily mean sea levels were taken in computations as they are simple to use in predictions, have been used for many years in numerous bibliographical sources dealing with such computations, and also because

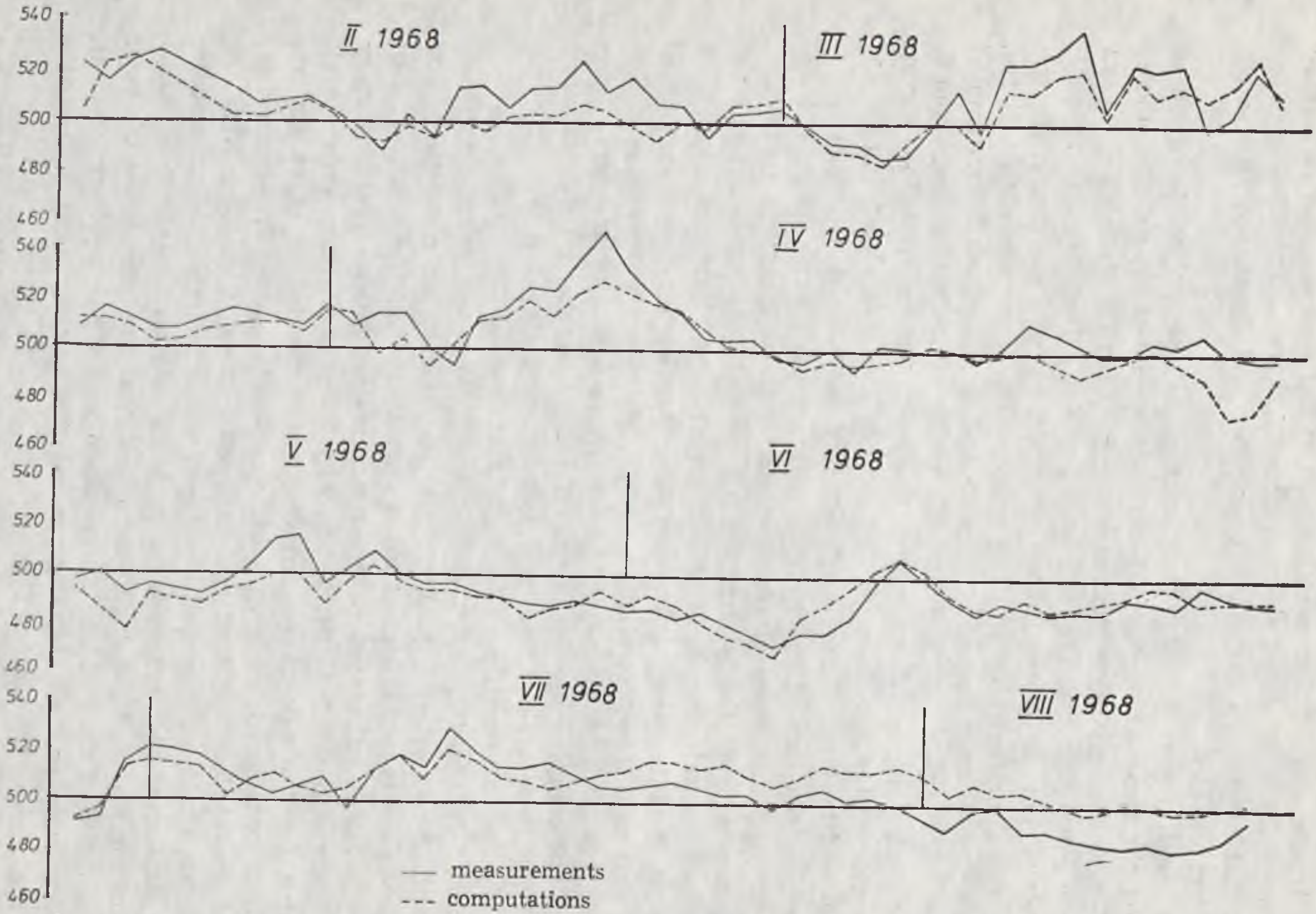

Fig. 5. Daily mean sea levels in Nowy Port computed by weighting functions of anemobaric parameters and measurements for the period from February 1968 to August 1968

Ryc. 5. Średnie dobowe poziomy morza w Nowym Porcie obliczone funkcjami wagowymi elementów anemobarycznych oraz dane pomiarowe z okresu luty 1968—sierpień 1968

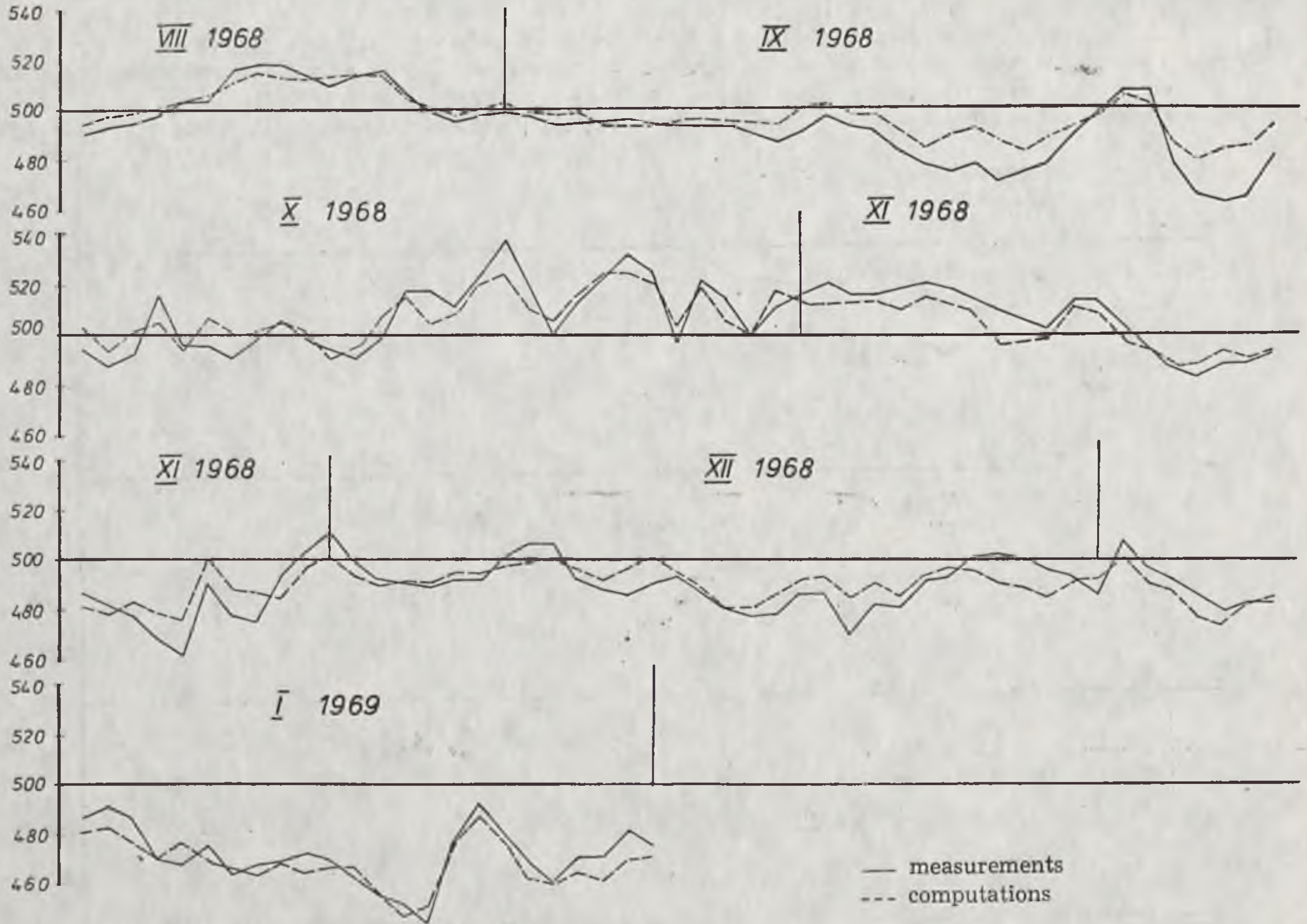

Fig. 6. Daily mean sea levels in Nowy Port computed by weighting functions of anemobaric parameters and measurements for the period from August 1968 to January 1969

Ryc. 6. Średnie dobowe poziomy morza w Nowym Porcie obliczone funkcjami wagowymi elementów anemobarycznych oraz dane pomiarowe z okresu sierpień 1968 — styczeń 1969

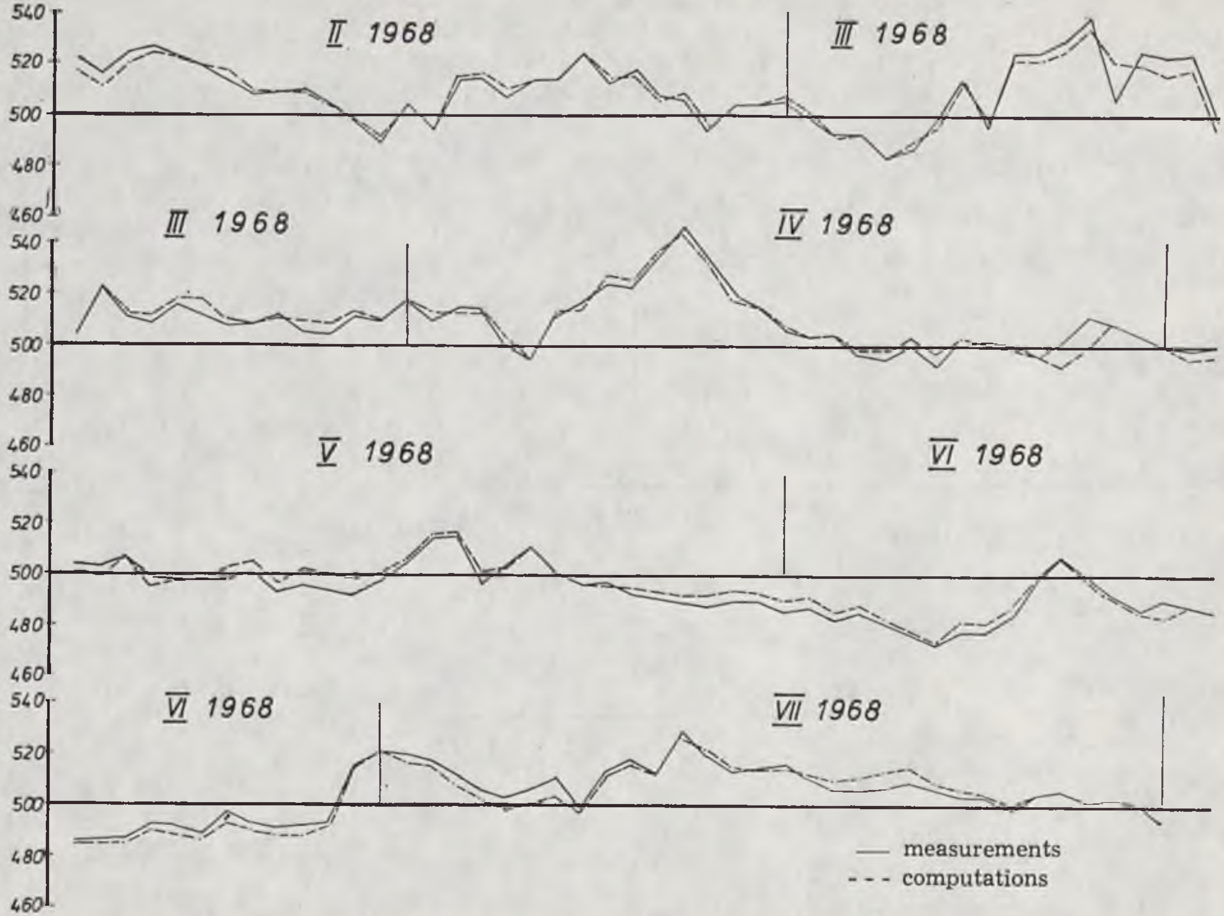

Fig. 7. Daily mean sea levels in Nowy Port computed by the sea level and anemobaric parameters weighting functions for Hel and measurements for the period from February 1968 to July 1968

Ryc. 7. Średnie dobowe poziomy morza w Nowym Porcie obliczone funkcjami wagowymi poziomów morza i elementów anemobarycznych dla Helu oraz dane pomiarowe z okresu luty 1968 — lipiec 1968 r.

the dynamic conditions of water level variations in the Baltic are very specific. It is a well known fact that data filtration and the elimination of short-period oscillations by means of a discrete-type averaging filter is less effective than using a filter with a consecutive mean value [5, 12]. The filter used in this study transmits some short-period oscillations, especially tides. In the case of the Gulf of Gdańsk tidal amplitudes are ~ 1 cm, and thus are of no practical importance. The seiche oscillations, both local and in the Baltic proper occur seldom with similar amplitudes, and thus the filtration employed is sufficient to smooth out the data.

The water level differences arising from the subtraction of daily mean values from those obtained for the four—hour time increment for Hel were analyzed spectrally (FFT) to better learn the variation of water levels with respect to their mean values. The time series data number was $LX = 2048$ as the respective period analyzed was January 1, 1968 to December 7, 1968.

The results of the computations are shown in Fig. 8. It follows from this diagram that the subtraction of the daily mean values has practically eliminated the long-period oscillations of $T > 200$ hours. For smaller periods $T \leqslant 200$ hours no clear periodicity appears apart from the semi-diurnal tide M_2 and S_2, which manifests itself not too strongly for $T=12.8$ hours (due to the discrimination of computations).

The substantial decrease in the long-period oscillations as compared with the spectrum of Fig. 3 can be attributed to the lack of significant seasonal differences between the analyzed data.

5. CONCLUSIONS

The method of computations presented is highly effective in prediction applications. The data obtained for weighting functions point to the experience of applying a linear system of constant parameters to determine the relationship between anemobaric input processes and the output process of water level variations postulated elsewhere [6, 13, 16], but with a different application.

The computations show that, in the interval of oscillations analyzed, the basic variation of water levels in the Gulf of Gdańsk can be found, by using two components of horizontal air pressure gradients and the meridian wind component. The results obtained for daily mean water levels can be improved in a modified system. Studies in this field are being conducted.

The transition to time increments of 4 hours or even shorter under the Baltic conditions requires that the selection criteria for input proces-

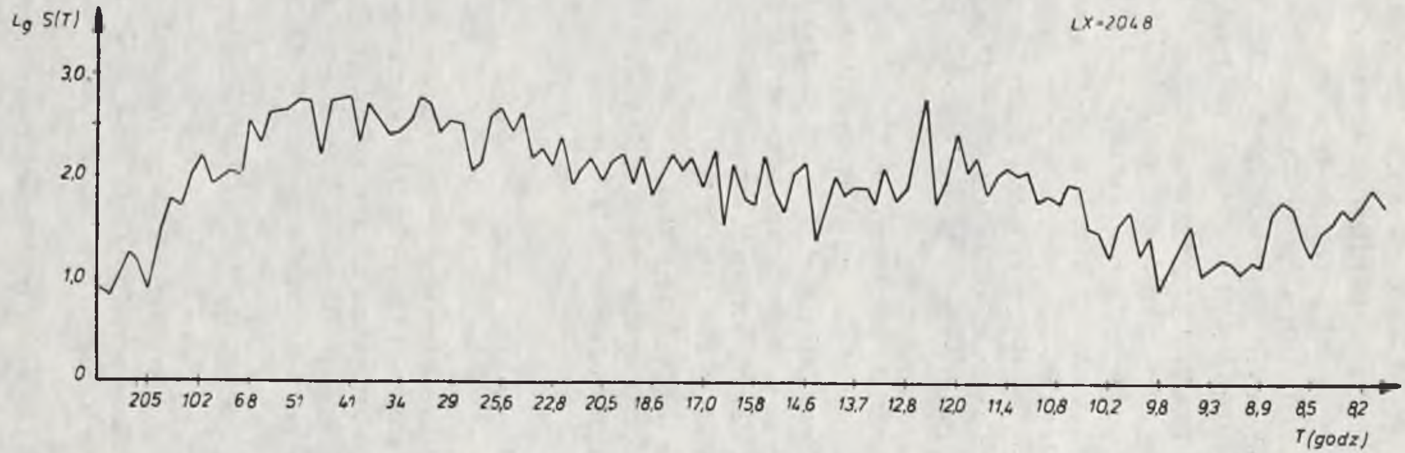

Fig. 8. Spectral density of the differences between sea levels taken every four hours and daily mean values for Hel tide gauge during the period from January 1,1968 to December 7, 1968

Ryc. 8. Widmowa gęstość różnic pomiędzy poziomami morza z krokiem kwantowania 4 g. a średnimi dobowymi dla mareografu helskiego w okresie 1 I 1968—7 XII 1968 ses be examined again against the background of daily mean level computations. A probabilistic forecast of the differences between the daily mean sea levels and those of four-hour intervals can also be given by methods of random variables, used already in Polish oceanographic studies [8].

An important feature of the system presented is its flexibility and the possibility of employing various versions of weighting function computations together with different systems of correlated and uncorrelated input processes. Depending on the degree of approximation of geophysical processes analyzed to mathematical assumptions, the appropriate improvement of time series is possible. The computed weighting functions of a correlated system can be very useful in the analysis of sea-atmosphere interaction, since they represent the effect of various anemobaric parameters with the exclusion of the remaining factors studied.

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OBLICZENIE ŚREDNICH DOBOWYCH POZIOMÓW MORZA ZATOKI GDAŃSKIEJ NA PODSTAWIE FUNKCJI WAGOWYCH

Streszczenie

Praca zawiera obliczenie średnich dobowych poziomów morza Zatoki Gdańskiej na podstawie funkcji wagowych dla mareografów w Nowym Porcie i Helu. Pierwszym krokiem obliczeń było wyznaczenie elementów anemobarycznych posiadających istotną koherencję z obliczanymi poziomami morza. Wyniki doboru procesów wejściowych do przyjętego systemu obliczeń wykazane są na ryc. 2, a rozmieszczenie analizowanych stacji pomiarowych przedstawia ryc. 1. Po przeprowadzonych obliczeniach przyjęto jako procesy wejściowe składową poziomą gradientu ciśnienia Oslo—Hel i Świnoujście—Hel oraz składową południkową wiatru dla Helu. Widmowe gęstości procesów wejściowych i wyjściowych oraz wielokrotną koherencję między tymi procesami przedstawia ryc. 3. Na podstawie widmowych gęstości analizowanych serii realizacyjnych obliczonych metodą FFT określono funkcje przejścia, a następnie funkcje wagowe przyjętego systemu obliczeń. Ponieważ przyjęcie skorelowanych procesów wejściowych dawało lepsze odtworzenie procesu wyjściowego, podano wyniki obliczeń tylko dla tego założenia. Funkcje wagowe oraz cząstkowe koherencje w modelu trzy wejścia jedno wyjście przedstawione są na ryc. 4. Wyniki obliczeń poziomu morza w porównaniu do danych z pomiarów przedstawione są na ryc. 5, 6 i 7. Obliczenia poziomów morza w Nowym Porcie na podstawie poziomów morza i składowej południkowej wiatru dla Helu oraz gradientu Oslo—Hel wykazały bardzo dobrą zbieżność obliczeń z danymi pomiarowymi, udowadniając, że obliczenie poziomów w jednym punkcie akwenu może być łatwo przeniesione na inne punkty, tworząc system umożliwiający przestrzenną i czasową predykcję poziomów morza Zatoki Gdańskiej. Wyniki tych obliczeń pokazuje ryc. 7. Na ryc. 8 naniesiono wyniki obliczeń widmowych gęstości różnic pomiędzy średnimi dobowymi a danymi o poziomach morza z krokiem kwantowania 4 godz. Dane te ilustrują działanie przyjętego filtra średniodobowego oraz wykazują możliwość probabilistycznej predykcji zmiennej losowej analizowanych różnic poziomu morza.

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