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Baltic Sea datums and their unification as a basis for coastal and seabed studies

by

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Abstract

This paper presents examples of application of a common reference datum, such as NAP, within the elevation EVRS reference system for the Baltic Sea. A common reference datum allowed for setting the geographical pattern of occurrence of extreme sea levels in the Baltic Sea. The eastern Baltic coasts exposed to western air masses are vulnerable to extreme hydrological events (the Gulf of Finland, the Gulf of Riga and the Gulf of Bothnia). On the contrary, the Swedish coasts of the central and northern Baltic are the least threatened by extreme sea levels. The south-western coasts of the Baltic Sea (the Bay of Mecklenburg and the Bay of Kiel) cover the basins with the most frequent and the most severe storm falls and extremely low sea levels. Demonstration of the Baltic surface deformation magnitude during a storm event is another example of NAP application. The instantaneous height difference between the north-eastern and south-western coasts was 356 cm, which resulted from the negative impact of pressure (water cushion) induced by a dynamic and deep low-pressure system moving through the Baltic Sea. The common reference datum allowed for visualization of the so-called "theoretical water" distribution which has a wide application in the hydraulic engineering within the coastal zone. In addition, the study provides examples of differences that may be observed during storm events between the real sea-level data and the hydrodynamic model forecast. This is of great practical significance in terms of forecasting storm surges in the Baltic Sea.

Key words: sea level, storm surge, Baltic Sea, vertical datum, Normaal Amsterdams Peil (NAP)

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Introduction

Knowledge of the elevation and oscillations of the sea-level is extremely important to many aspects of different scientific disciplines. Sea charts' users, navigators, hydrographic surveyors, geographers and oceanographers face difficulties in the interpretation of information on water basin depths plotted on these charts as well as in the presentation of studies concerning the sea-level oscillations and storm surges. This issue is especially true for charts of the Baltic Sea basins (Mononen 2008; Baltic Sea Hydrographic Commission 2013; 2014). This results from the fact that there was no single, common, vertical reference datum for sea-level observations among the Baltic states. Due to the requirements of e-navigation, coastal engineering, construction of harbor infrastructure and configuration of other spatial data, a unification of vertical reference systems and their zero datums became necessary. This is particularly important in comparative spatial analysis of coastal zone morphodynamics carried out for different parts of the Baltic, including modelling and forecasting the changes in the shoreline configuration.

In June 2005, the International Hydrographic Organization and the Baltic Sea Hydrographic Commission established the Chart Datum Working Group for the harmonization of reference levels of the Baltic Sea charts. The main task of this working group was to examine possibilities of using the European Vertical Reference System (EVRS) as the main alternative to vertical reference systems on the Baltic Sea charts.

Another task of this group was to establish timetables and preliminary conditions in collaboration with each Baltic state which wishes to use a standardized datum on its sea charts. The Chart Datum WG should prepare recommendations on how the sea-level changes should be shown on paper and electronic navigational charts and in other navigational publications.

In order to standardize the vertical reference systems within the European Vertical Reference System (EVRS) project, the Baltic Oceanographic Observation System (BOOS) joined the Baltic Sea Hydrographic Commission (BSHC). Consultation meetings that gather personnel of the above mentioned groups and representatives of geodetic services of the Baltic states should take place each year until 2020, which is the last year for implementing the common reference system into charts (Łyszkowicz 2001; Mononen 2008; Baltic Sea Hydrographic Commission 2013; 2014).

Review of vertical reference systems functioning in the Baltic states

In all Baltic states, the vertical datum has been based on local mean sea levels (MSL). Different methods are used to obtain mean sea levels (MSL) in various countries, hence methods of determining the datum were different. It is associated with the existing differences in vertical datums between countries.

There are two reference systems in Germany due to the existence of two German states after World War II. One is the *Normall-Null* datum and is binding in Schleswig- Holstein land (since 2000 Normalhöhennull). The datum has always been related to NAP (PN = -5.00 m NN). The other datum HN (Höhen Null) is used in Mecklenburg-Vorpommern and is related to the Kronstadt tide gauge. PN = HN-14 cm level is a MSL for most water gauge stations in that region (Stigge 1989; Koppe 2002).

The DNN (Danish Normal Null) based on sea-level measurements taken in 10 harbors along the coast in the 19th century was launched in Denmark. Apart from DNN, there is also the LN (Local Null) which is a local datum for small islands. Since 1 January 2006, the DVR90 (Dansk Vertikal Reference 1990) is linked with the vertical datum. Similar to the DNN, this datum is based on measurements carried out in 10 Danish harbors in the 1990s and it differs from NAP in just 2 cm (Jakobsen 2008; Geodatastyrelsen 2014).

There were a few vertical datums in Sweden in the 19th and 20th century, which were based on tide gauge observations: RH 1860, RH 00 and RH 70. The datum of RH 00 was accepted as the mean water level in Stockholm in 1900. Since 2005, a new national datum was introduced – Rickets Höjdsystem 2000 (RH 2000). This datum was set up as a Swedish part of the European Vertical Reference System (EVRS) project. Normaal Amsterdam Peil is the reference tide gauge. RH 2000 takes the isostatic land movement into consideration which is corrected by the NKG2005LU model controlled by the Nordic Geodetic Commission. However, it is the MSL which is the reference datum for the production of sea charts. The MSL is calculated on the basis of linear regression of long-term sea-level measurements recorded by tide gauges governed by the Swedish Meteorological and Hydrological Institute (SMHI) (Olsson, Erickson 2005; Svensson et al. 2006; Hammarklint 2009).

There are 3 elevation systems in Finland: NN (Normaali Nolla), N43, N60, the datum of which is based on the tide gauge in Helsinki. The latest system – N2000 – is a Finnish contribution to the European Vertical Reference System (EVRS) project and hence its datum refers to NAP. Due to severe isostatic movements, there is also a "theoretical mean sea level" which is described as a long-term forecast of the mean sea level for practical purposes. This forecast is based on long-term observations of 13 tide gauges mounted along the Finnish coast and every year it is confirmed by the Finnish Meteorological Institute for the next five years (FMI 2013).

On the eastern coast of the Baltic sea (Russia, Estonia, Latvia, Lithuania, Poland), the Baltic Height System (BHS) was used as early as in the 1950s and was updated in 1977. The system is based on long-term observations of the mean sea level at the Kronstadt gauge in 1825-1840 (Gulf of Finland). The estimated difference between the systems based on NAP and BHS is ca. 15 cm (leveling of the Kronstadt system is higher). The elevation system based on Kronstadt is valid in Poland till 2020. However, the recording of the sea levels is referred to NAP (Ekman 1999; Bogdanov et al. 1994).

Sweden and Finland experience a specific issue with the implementation of EVRS in sea charts. Due to intense isostatic movements (up to 0.8-0.9 mm $year^{-1}$) in the northern coasts of the Baltic Sea, the depths are continuously varying due to constant lowering of the mean sea level. This shortens the sea charts' validity. Therefore, the adoption of a common reference datum in sea charts should give the opportunity to deliver correct information on the depths despite the ongoing geological process.

The purpose of the work is an adaptation of the practical realization of the EVRS system along with its NAP vertical datum for a spatial display of parameters of extreme Baltic Sea levels. The work includes the following parameters:

- distribution of the maximum and minimum sea levels,
- the number of storm surges and storm falls,
- distribution of the theoretical 200-year water,
- short-term deformation of the sea surface,
- differences between the sea-level observation data and the HIROMB model.

Materials and methods

Definition of the European Vertical Reference System

EVRS was created based on the implementation of the continental leveling network UELN (United European Leveling Network) project. The purpose of UELN was to create the uniform vertical reference frame for Europe with a resolution of up to 10 cm. The final effect of this work are the results of the continental leveling network alignment called UELN-95/98. The EVRS is realized by geopotential numbers and normal heights of nodal points of the United European Leveling Network 95/98 (UELN 95/98) extended to Estonia, Latvia, Lithuania and Romania , in relation to Normaal Amsterdams Peils (NAP). This practical realization of the EVRS system was called EVRF 2000 (European Vertical Reference Frame 2000).

The European Vertical Reference System (EVRS) is related to the Earth's gravity field and defined as follows (Ihde, Augath 2001; 2002; Łyszkowicz 2001):

- The reference surface is a horizontal surface for which the potential of gravity W_0 is constant:

$$W_0 = W_{0E} = const. \quad (1)$$

and which is at the Normaal Amsterdams Peil (NAP) level.

- Vertical components are differences ΔW_P between the potential W_P of the Earth's gravity field at the selected point P and the gravity potential W_{0E} of the EVRS datum. The potential difference (ΔW_P) is also referred to as the geopotential number C_P:

$$-\Delta W_P = C_P = W_{0E} - W_P \quad (2)$$

Normal heights are equivalent to geopotential numbers;

- EVRS is a system in which the tidal datum system was adjusted according to the resolution of the International Association of Geodesy. The datum of EVRS is realized by NAP. Consequently, the geopotential number of a NAP level is also equal to zero:

$$C_{NAP} = 0 \quad (3)$$

• Parameters and constants describing the vertical system are parameters and constants defined by Geodetic Reference System 1980 (GRS-80). As a result of the adoption of these parameters and constants, the normal gravity potential W_{NAP} at a NAP point is a normal potential of the GRS-80 ellipsoid:

$$W_{NAP}^{REAL} = U_{0GRS80} \tag{4}$$

• The EVRF-2000 (practical realization of EVRS) system is realized by the geopotential number and a corresponding normal height of the reference point number 000A2530/13600 of the UELN network.
• The gravity potential at NAP can be calculated from this equation:

$$W_{NAP} = W_0 + {}_{\Delta}W_{SST} + {}_{\Delta}W_{TG0} \tag{5}$$

All the symbols of equations 1-5 are explained in Figure 1.

Scientific material

Hourly sea-level observation data from 49 tide gauges located along the Baltic Sea coasts were used to achieve the objective. The 51-year period (1960-2010) was the essential measurement period used in scientific analysis. Such a period was chosen as the longest possible period that could provide sea-level data from national meteorological and hydrological institutes of the Baltic states. These institutes are: the Institute of Meteorology and Water Management (IMGW) – Poland, Bundesamt für Seeschifffahrt und Hydrographie (BSH) – Germany, the Danish Meteorological Institute (DMI) – Denmark, the Swedish Meteorological and Hydrological Institute (SMHI) – Sweden, the Finnish Meteorological Institute (FMI) – Finland, the Estonian Weather Service (EWS) – Estonia, the Latvian Environment, Geology and Meteorology Centre (LVGMC) – Latvia and the Environmental Protection Agency (EPA) – Lithuania.

Hourly sea-level data were corrected to a single vertical datum which is NAP in the practical realization of the EVRS system called EVRF 2000

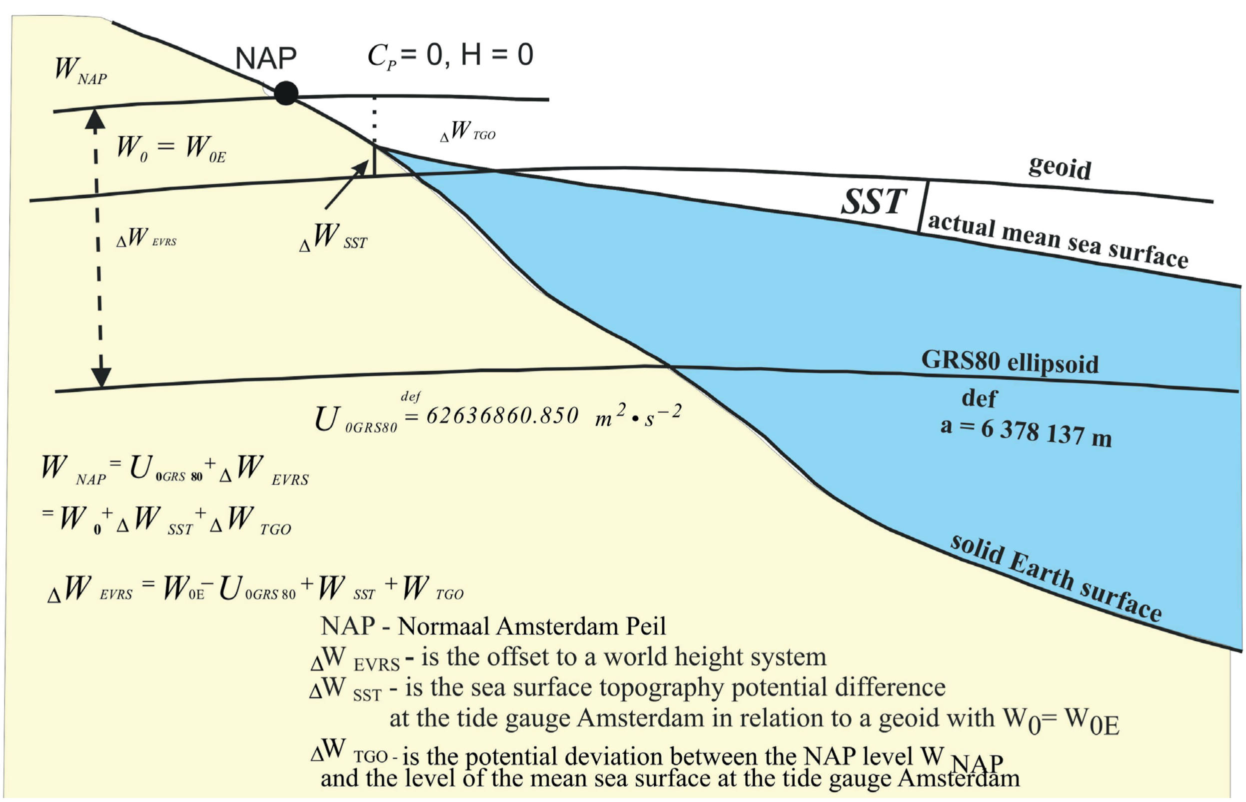

Figure 1
Relations between the EVRS Datum Definition as a World Height System and the EVRF 2000 Datum (NAP) (Ihde 2004 – modified by the authors)

(although there is now a newer, practical realization of the EVRS system, that is EVRF 2007, most of the Baltic and European states have established transformations of their own datum to the previous realization – the EVRF 2000). Basic calculations were performed using the Coordinate Reference Systems (CRS EU), while consulting the relevant institutes of the Baltic states during the data acquisition. Due to intense isostatic movements in Finland and Sweden, the sea-level data from these countries were referred to the MSL for each tide gauge. These calculations enabled a display of the Baltic surface deformations during a specific hour of a given day. However, more important for the determination of the common reference datum was the display of the geographic distribution pattern of extreme sea levels in the analyzed period of time.

To describe the storm event in this paper, an IMGW synoptic chart was used with values of atmospheric pressure, wind velocity and wind direction derived from NOAA's National Climatic Data Center (NCDC) website. The sea-level forecast from the HIROMB model for 9 January 2005, 3:00 UTC (3-hour forecast) was obtained from SMHI.

Quantitative analyses of the storm surges and falls at low sea levels

For the purpose of this study, catalogues of storm surges and storm falls for tide gauges located in the Baltic Sea were used. These catalogues have been developed as part of a project funded by the National Science Centre (Wolski 2011-2014). In order to determine precisely the number of storm surges and storm falls, the following conditions were accepted to recognize the phenomena.

Conditions for the storm surge occurrence:

- the lowest maximum reached by a surge is 70 cm above the NAP datum (occurrence probability for sea levels 70+ cm is ca. 75% per annum for tide gauges located at open waters of the Baltic coast);
- the minimum surge level (rise from the initial level in cm) of 30 cm is reached within 24 hours.

Conditions for the storm fall:

- the minimum sea-level fall is -70 below the NAP datum;
- due to the nature of low sea levels, which can be short-term (storm falls lasting several tens of hours) or long-term (lasting several weeks at eastern atmospheric circulation), there were no time limits introduced in terms of reaching the minimum level of a storm fall.

The annual average of storm surges and storm falls presented herein reflects the total amount of these phenomena in the period of 1960-2010 divided by the number of years of observations.

Description of the storm event

The paper describes the storm event of 17-19 October 1967. As part of this description, the following features of the low pressure system together with storm event parameters were listed for several tide gauge stations located in different places of the Baltic coast:

- p_i – pressure at the center of the depression [hPa],
- the initial sea level [cm] (the sea level prior to the occurrence of an extreme event),
- extreme values of the sea level during the surge and their amplitude [cm],
- rates of the maximum sea-level rise and fall [cm h^{-1}],
- the duration of the sea level ≥ 70 cm, ≥ 100 cm and ≤-70 cm ≤-100 cm in relation to NAP

Values of static and dynamic sea surface deformation, resulting from the impact of the low pressure system moving through the Baltic Sea, were also determined in this study. According to the equation, a pressure drop in the low center Δp = 1 hPa causes a static sea level rise ΔHs ~1 cm (Lisowski 1961; Wiśniewski, Wolski 2009a; 2011a; Weisse, von Storch 2010) (equation 6)

$$\Delta H_S = \frac{\Delta p}{\rho \times g} \tag{6}$$

where:

ΔH_s (cm) – a static increase in the sea level at the center of the low pressure area (static sea surface deformation)

Δp (hPa) – an increase or decrease in the atmospheric pressure in relation to its average value, i.e. 1013.2

ρ – mean water density – 1.010 g cm^{-3},

g – gravity acceleration – 981 cm s^{-2}.

The low pressure system moving over the sea surface is followed by the dynamic sea surface deformation (ΔH_d). The deformation associated with the baric wave (water cushion) is characterized by positive ordinates in the center and negative ones on the edges of the deformation (Lisowski 1961; Wiśniewski, Wolski 2009a; 2011a, Wolski & Wiśniewski 2014) (equation 7)

$$\Delta H_d = \frac{\Delta H_S}{1-\left(\frac{V_L}{\sqrt{g \times H_m}}\right)} \tag{7}$$

where:
ΔH_d (cm) – dynamic sea surface deformation,
V_L (m s^{-1}) – travelling velocity of the air pressure system,
H_m (m) – average depth of sea

In addition to the analyzed storm event, a temporal course of sea-level changes, wind velocities and wind directions along with a synoptic chart with the plotted trajectory of the main low pressure system moving through the sea were demonstrated.

Visualization of the extreme parameters of the Baltic Sea levels in ArcGIS

ArcGIS was the basic tool used for the visualization of extreme parameters of the Baltic Sea levels in this paper. The tool displayed a distribution of maximum and minimum sea levels, a distribution of 200-year water, the number of storm surges and storm falls and a deformation of the Baltic Sea level during storm events as well.

Kriging was the main ArcGIS module that was a basis for spatial analysis. It is widely used and recommended in environmental studies in the preparation of charts created on the basis of data interpolation (McGrath et al. 2004; Urbański 2012). Kriging uses a weighted average of a subset of adjacent points to obtain a specific interpolation point using an equation (Badura et al. 2012):

$$Z^*(x_0) = \sum_{i=1}^{n} w_i Z(x_i) \tag{8}$$

where:
$Z^*(x_0)$ – value of interpolation at point x_0
$Z(x_i)$ – real value at the measured point (sea level at a tide gauge)
w_i – kriging weight
n – the number of points considered in kriging (12 for the analyses herein).

The main advantage of kriging used for spatial analyses in this study is the feature that causes the isolines drawn by this method to show a clear trend of diversification in the investigated parameter (Badura et al. 2012).

Probability of the theoretical sea level (statistical distributions)

In the analysis of extreme sea levels, it is essential to know the high water-level stages, which may happen once every specific number of years, e.g. once every 50, 100, 150 or 200 years. This period is called the return period (T) and is expressed as follows :

$$T = \frac{100}{p\%} \, [\,years\,] \tag{9}$$

where:
T – mean return period
p – probability (%).

The study determined the theoretical water level for the 200-year return period for both the maximum and minimum sea levels.

Calculations of the extreme water-level exceedance probability consists in the proper choice of theoretical probability distributions, followed by selection of methods assessing the parameters of a given distribution, using the statistical data.

Theoretical, maximum levels

In this study, the probability of theoretical, maximum sea levels for 49 tide gauge stations from different coastal regions of the Baltic Sea was determined. The analyses used the maximum, annual sea levels from the period of 1960-2010. To determine the theoretical level with the 200-year return period, the Gumbel distribution and the maximum likelihood method were used. Double exponential Gumbel's distribution is described by the following formula (Gumbel 1958):

$$f(x) = \frac{1}{\hat{a}} e\left[-\frac{x-b}{\hat{a}} - e\left(-\frac{x-b}{\hat{a}}\right)\right] \tag{10}$$

where:
$\hat{a}$ – scale parameter (determines the dispersion of the distribution along the x-axis),
b – location parameter (determines the location of

the distribution on the x-axis)
e – the base of the natural logarithm

The estimation of the adopted distribution to the available measured data consists in the determination of estimators of the distribution parameters â and b. Estimators were determined by the maximum likelihood method.

Theoretical, minimum sea levels

The Pearson type III distribution, the standard one in hydrology (Kaczmarek 1970), was used to determine the theoretical, minimum sea levels:

$$f(x) = \frac{\alpha^{\lambda}}{\Gamma(\lambda)} e^{-\alpha(x-\varepsilon)} (x-\varepsilon)^{\lambda-1} \tag{11}$$

where:
α, ε, λ – distribution parameters which should meet the following requirements: $x \geq \varepsilon$ (the lower limit of the distribution), $\alpha > 0$, $\lambda > 0$
$\Gamma(\lambda)$ – gamma function of the variable λ

The parameters of the Pearson type III distribution were also assessed by the maximum likelihood method.

In this study, the consistency of the assumed theoretical distribution with the empirical distribution (observation series of sea levels) was examined using the Kolmogorow normality test.

All calculations referring to the probability were carried out in Matlab.

Results and discussion

Examples of the application of the common reference datum for the Baltic Sea

Geographical pattern of extreme sea-level occurrence in the Baltic Sea

Studies carried out as part of the project (Wolski 2011-2014) resulted in the determination of the following regularities in the occurrence of extreme sea levels in the Baltic Sea:

1. Eastern coasts of the Baltic Sea, which are exposed to the inflow of western air masses related to western atmospheric circulation, including

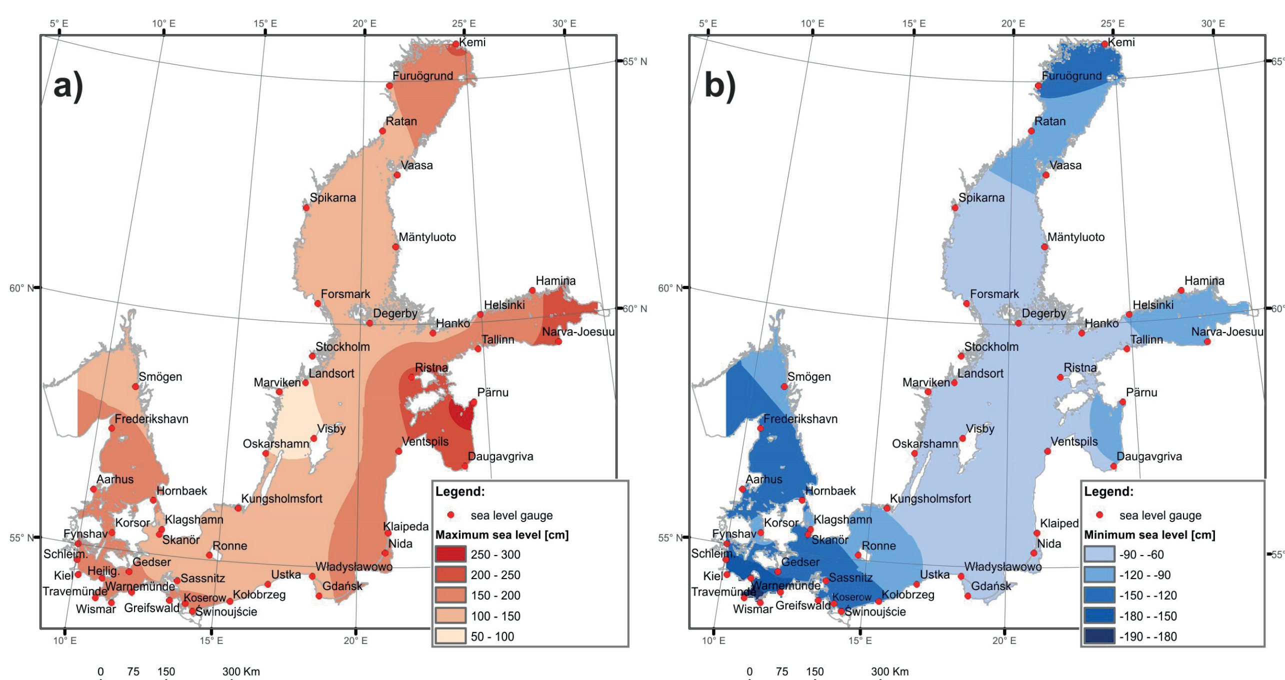

Figure 2

Distribution of extreme sea levels in the Baltic Sea in the period of 1960-2010; a) maximum sea levels, b) minimum sea levels (source: Wolski et al. 2014) the dominant tracks of pressure systems, are particularly threatened by extreme hydrological events. This mostly applies to the Gulf of Riga along with Pärnu Bay, the Gulf of Finland, and the Gulf of Bothnia. These water basins experience the largest numbers of storm surges, the longest duration of high sea levels (≥ 70 cm) and the highest water levels in general (Figs 2 and 3). On the contrary, the Swedish coasts of the central and northern Baltic are the least endangered by extreme sea levels within the Baltic Sea basin. This is primarily explained by their eastern exposure, which represents the opposite direction to the inflow of western air masses and the propagation of low pressure systems. In the conditions of western circulation, the filling of the Baltic Sea increases and the inclination of water surface toward the eastern coasts of the Baltic Sea increases as well. This characteristic regularity is in line with the results of studies by Averkiev and Klevanny (2007, 2010), Suursaar et al. (2003, 2009), Johansson et al. (2001), Wolski et al. (2014), according to which the eastern coasts of the Baltic (the Gulf of Riga and the Gulf of Finland and part of the Gulf of Bothnia) are exposed to dangerous storm events and extreme sea levels induced by deep low-pressure systems that move through the investigated area and by strong landward winds.

2. South-western coasts of the Baltic Sea: the Bay of Mecklenburg and the Bay of Kiel are water basins of the most frequent and the deepest falls as well as of the extremely low sea levels (≤ -70 cm) (Fig. 2, Fig. 3). The eastern exposure of these bays and their small depth favor the water outflow from their basins by fast-moving mesoscale low moving through the Baltic Sea from SW to NE. At the same time, only large north-eastern gulfs of the Baltic Sea have higher values of parameters such as the incidence of high sea levels, the heights of their maxima and the number of storm events than the Bay of Mecklenburg and the Bay of Kiel, which is a peculiar phenomenon among the Baltic basins.
3. Extreme phenomena, related to water dynamics, increase from the open sea waters of the Baltic Sea (Baltic Proper) to the innermost parts of its bays (the Gulf of Bothnia, the Gulf of Finland, the Gulf of Riga, the Bay of Mecklenburg and the Bay of Kiel). This regularity is caused by the so-called bay effect, i.e. the impact of geomorphological and bathymetrical configuration of the coastal zone on the water dynamics. This effect causes an increase in extreme sea levels and an increase in the time of their occurrence at bay stations of the Baltic Sea from the seaside boundary of

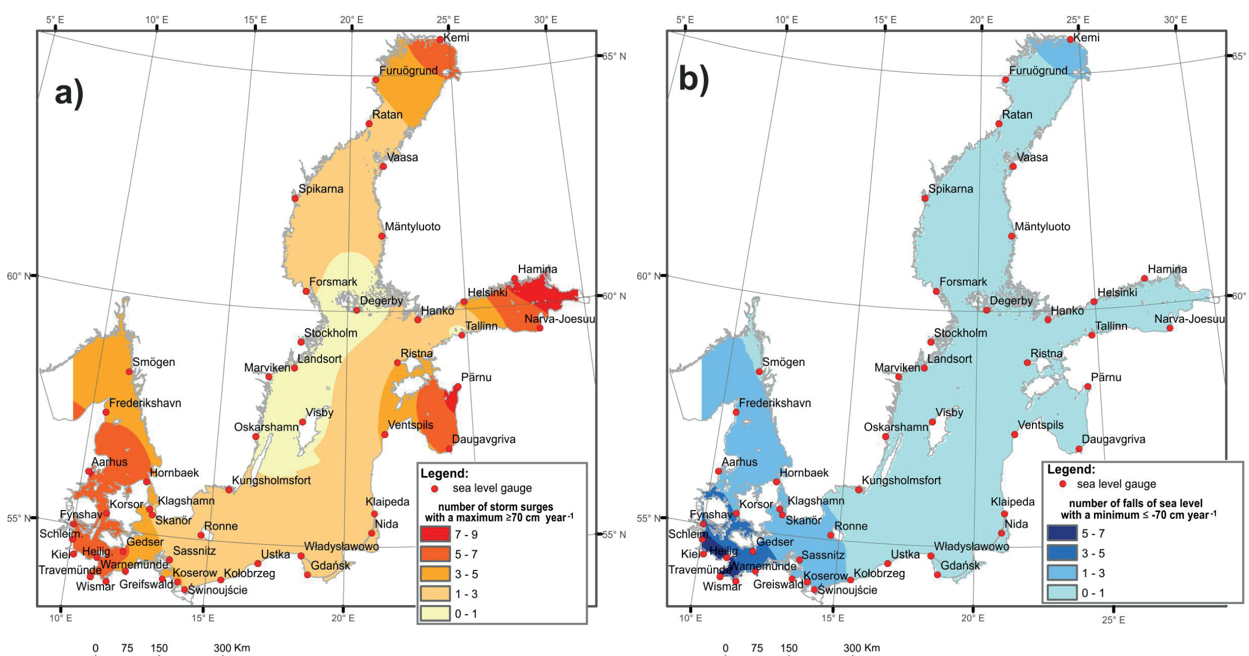

Figure 3

a) The number of storm surges with the maximum ≥ 70 cm referring to NAP per year (annual average value from the long term 1960-2010); b) The number of falls with the minimum ≤ -70 cm referring to NAP per year (annual average value from the long term 1960-2010) a given bay toward its farthest, innermost, cut-into-the-land point (the tip of the bay) (Figs 2 & 3). Narrowing of the bays is one of the main causes of this phenomenon. A specific volume of water removed or added to a bay narrowing and a shoal may result in a more extreme water level compared to a wider, seaside part of a bay. This interpretation is in line with the results provided by Sztobryn et al. (2005, 2009), who described storm surges and falls in the Bay of Mecklenburg and in the western part of the Polish coast. According to the author, the probability of occurrence of extreme sea-level events in the above-mentioned regions decreases eastward due to the coastline configuration and the bathymetry of the Bay of Mecklenburg (the bay becomes narrower and shallower toward the west). This regularity was also described by Ekman and Mäkinen (1996) as well as Johansson et al. (2001), who argue that the highest sea levels are expected in the innermost parts of the bays: the Gulf of Finland and the Gulf of Bothnia. This was also confirmed in the study by Meier (2006), who predicted the occurrence of the highest and extreme sea-level values at the end of the century (years 2071-2100). These events would occur within the eastern coasts of the Baltic, the Gulf Finland, the Gulf of Riga and the Gulf of Bothnia and, to a lesser extent, in the western Baltic.

Spatial distribution of the theoretical water along with its determined probability of occurrence along the Baltic Sea coast

Long-term forecasting of the probability of extreme sea levels is crucial not only for the determination of the nature of storm surges. Such forecasts are required in engineering of the coastal zone, the foundation of hydraulic engineering structures, the determination of harbor quay ordinates and flood dykes and dams. Probability of occurrence of extreme sea levels is also applied to land development of urban and industrial parts of the coastal zone (e.g. to exploitation safety of nuclear power plants and LNG terminals etc.).

The methods of determining the probability of extreme sea levels were described in the publications of Wróblewski (1992) and Jednorał et al. (2008). The research methodology in this regard was presented in detail in the study by Wiśniewski and Wolski (2009b) in relation to the Polish coast as well as in the paper presenting the calculations conducted by these authors concerning the comparison of the Polish and Swedish coast of the Baltic Sea (Wolski, Wiśniewski 2012). Authors of the other paper revealed that the height of the theoretical water for upper quantiles depends on the location of a tide gauge in relation to the open sea. Suursaar and Sooäär (2007) and Suursaar et al. (2009) applied the Gumbel distribution to analyze the wind velocity, wave height and extreme sea levels at the Estonian coast. They found that the empirical return periods of both the maximum wind velocities and wave heights can be fairly well matched to the theoretical distribution and hence very well predict the extreme values. On the other hand, the application of the Gumbel distribution for forecasting the highest sea levels during the most severe storm surges yields unsatisfactory results for tide gauges located in bays of specific morphometric features (tide gauge in Pärnu, Pärnu Bay). In the case of such places, extreme sea-level values deviate from the distribution curve and the return period should be replaced by hydrodynamic modelling when forecasting in such basins.

In addition, the use of a standardized datum for the Baltic Sea permits a display of the theoretical water distribution with the determined probability of its occurrence. The paper demonstrates the spatial distribution of the theoretical water with the 200-year return period determined on the basis of annual maximum and minimum sea levels from the period of 1960-2010 (Fig. 4).

The distribution of the theoretical 200-year water levels (Fig. 4) is similar to the geographical distribution pattern of extreme sea levels in the Baltic Sea (Fig. 2 and Fig. 3). This relationship is well-founded since the theoretical levels were calculated on the basis of real annual extremes. The most extreme theoretical 200-year maximum levels (> 240 cm NAP) would occur in the innermost parts of the Gulf of Riga, the Gulf of Finland and to a lesser extent in the Bay of Bothnia. The lowest water levels of the theoretical 200-year minimum water occur in the Bay of Mecklenburg and the Bay of Kiel (< -160 cm). However, the Swedish coasts of the central Baltic have the lowest theoretical 200-year water levels (< 140 cm NAP for the maximum theoretical levels and > −80 cm for the minimum theoretical levels). Due to their transitory location between the North Sea and the central Baltic, the Danish Straits (Skagerrak, Kattegat, Sund, Belts) are the regions with intermediate theoretical 200-year water levels, because the Danish Straits hydraulically balance the water levels between the North Sea and the Baltic Sea.

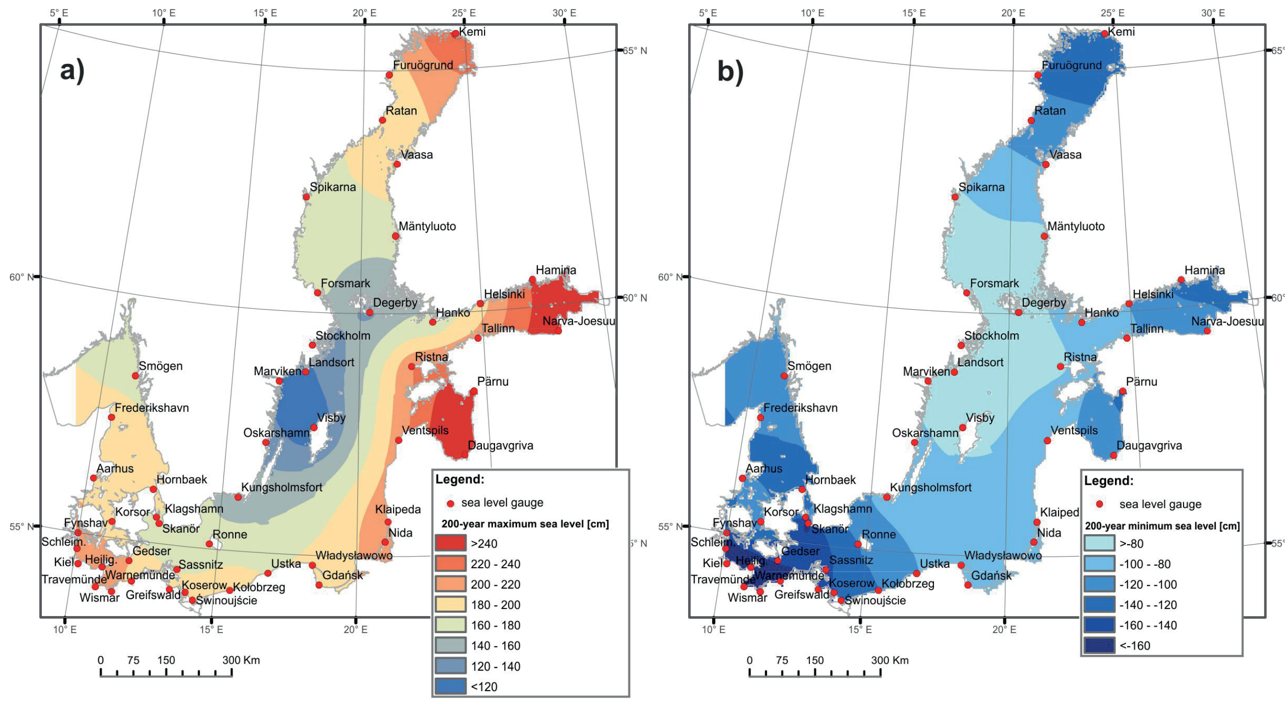

Figure 4

Distribution of theoretical water with the 200-year return period: a) theoretical 200-year maximum water level, b) theoretical 200-year minimum water level

Comparison of the sea levels derived from the HIROMB model and those observed during the extreme storm event

The growing interest in modeling and forecasting of the changing sea levels and storm events in the Baltic Sea region has been observed for many years. Authors of numerous scientific papers describe the effects of hydrodynamic models applied to predict sea levels for different basins of the Baltic Sea. The analysis of tide gauge records from the Baltic sites was conducted in the framework of the project on a 1 cm geoid in Poland. These records showed strong common features, which were further used to derive the model of the Baltic Sea level fluctuations. It was shown that the model well represents both the global and regional features of the Baltic Sea level fluctuations (Kryński, Zanimonskiy 2004). In another project (Project IMGW KLIMAT 2013), a research team developed scenarios of sea-level changes for the main tide gauge stations on the Polish coast for selected scenarios of greenhouse gas emissions, taking into account the effects of circulation and the expected changes in the global sea level by IPCC. Kowalewska-Kalkowska and Kowalewski (2005; 2007) apply the ecohydrodynamic model M3D_UG to forecast not only the sea levels but also salinity, currents, biogenic salts in Pomeranian Bay, the Bay of Gdańsk and the southern Baltic. The issues related to the sea-level modeling in the Gulf of Riga, including extreme sea levels, were researched by Suursaar et al. (2002, 2003, 2007). Meier (2006) applied two regional models of the ocean (RCO) and atmosphere (RCAO) to forecast extreme sea levels along the Baltic coast until 2100. Averkiev and Klevanny (2007, 2010) conducted research on modeling of the most dangerous trajectories of the low pressure systems in terms of storm hazard in the area of St. Petersburg. Gräwe and Burchard (2012) made predictions for wave height during a storm surge in the western Baltic along the German, Danish and Swedish coasts by applying the General Estuarine Transport Model (GETM). The analysis revealed a linear correlation between the storm surge height and filling of the western Baltic basin.

The 3D baroclinic HIROMB (High Resolution Operational Model for the Baltic Sea) model is one of the most popular hydrodynamic models and the only one so complex to operate in the entire Baltic Sea. Apart from sea levels, also currents, salinity, surface temperature, ice concentration and ice drift can be forecasted using HIROMB. Particular Baltic countries (and their hydrological and meteorological institutes) adopted the HIROMB model as a common operational system to their regional conditions in the coastal zone (Poland, Denmark and Finland since 1999). The model output data are archived and all HIROMB projects' participants have access to the complete database via FTP. The website – Ocean Web – has also been created to display real time sea-level forecasts together with the validation (Funkquist & Kleine 2007; SHMI, Ocean Web 2014).

In this paper, HIROMB model forecasts were collated with the results of sea-level observations during a severe storm associated with mesoscale and deep low Gudrun which moved over the Baltic with a high speed on 8-9 January 2005 (Table 1, Fig. 5). This comparison refers to a specific time – 9 January 2005, 03:00 UTC, which is the time when the greatest inclination of the Baltic surface occurred between the western (Skänor, Sund end: -139 cm in relation to NAP) and north-eastern basins (Pärnu, Gulf of Riga: +271 cm NAP) and amounted to 410 cm (Fig. 5a). The collation incorporates a model based on the real sea levels derived from 49 tide gauges (Fig. 5a) and the HIROMB model which is based on the forecast for points located in the location of these tide gauges (Fig. 5b). The final effect of the collation is a chart showing the difference between the observed and forecasted sea levels (Fig. 5c).

Taking into consideration the absolute difference model (Fig. 5c) of the analyzed storm event, it appears that in the areas of sea levels higher than the NAP datum (the Gulf of Bothnia and the Gulf of Finland in particular), the forecasted sea level was higher than the observed one. This means that the HIROMB model overestimated the sea levels higher than 0 for these gauges and the error value itself was significant, reaching -68 cm (tide gauge in Hamina, Table 1). Errors were smaller for tide gauges located at the open sea (the central and southern Baltic), where values did not exceed 30 cm. On the other hand, the HIROMB model most frequently underestimated these values for low sea levels observed. The western Baltic is a good example, where very low sea levels dominated and absolute differences between the observed and forecasted values amounted up to 40 cm (tide gauge in Sassnitz, Table 1, Fig. 5c).

This example proves that the use of a standardized reference datum for the Baltic Sea levels allows the evaluation of the accuracy of operational hydrodynamic models, which is of great practical importance for forecasting of storm surges.

Short term deformation of the Baltic Sea surface

Adaptation of the common reference datum to the Baltic waters not only allows you to determine the geographical pattern of extreme sea levels around the Baltic Sea or to assess the accuracy of hydrodynamic models in forecasting the storm surges, but it also provides multiple possibilities of demonstrating the Baltic surface deformations at a given time of the day. An example of the storm event is presented below. It took place on 17-19 October 1967 when rapid deformations of the Baltic Sea waters occurred due to the deep and fast-moving low pressure system.

Synoptic situation

On 17 October 1967, a deep and dynamic low pressure system moved from the British Isles to Jutland in just 12 hours, where it reached 971 hPa in its center (12:00 hrs UTC, 17/10) (Fig. 6). In the next 12 hours, the center of the low had moved at an average speed of 80 km h^{-1} via southern Sweden and the northern Baltic over the Åland Islands and reached 966 hPa (0:00 hrs UTC, 18/10). During further several hours, the low moved via southern Finland to the White Sea area (12:00 hrs UTC,

Table 1

Collation of the greatest differences between the observed and forecasted (HIROMB model) values of the sea level for selected tide gauges during the storm event of January 9, 2005, 03:00 UTC.

Tide gauge	Sea level		Absolute differences between the observed and forecasted sea level
	Observed	Forecasted	
Ristna	+217 cm	+172 cm	45 cm – underestimation
Hamina	+138 cm	+206 cm	68 cm – overestimation
Kemi	+41 cm	+97 cm	56 cm – overestimation
Helsinki	+145 cm	+188 cm	43 cm – overestimation
Sassnitz	-100 cm	-60 cm	40 cm – underestimation

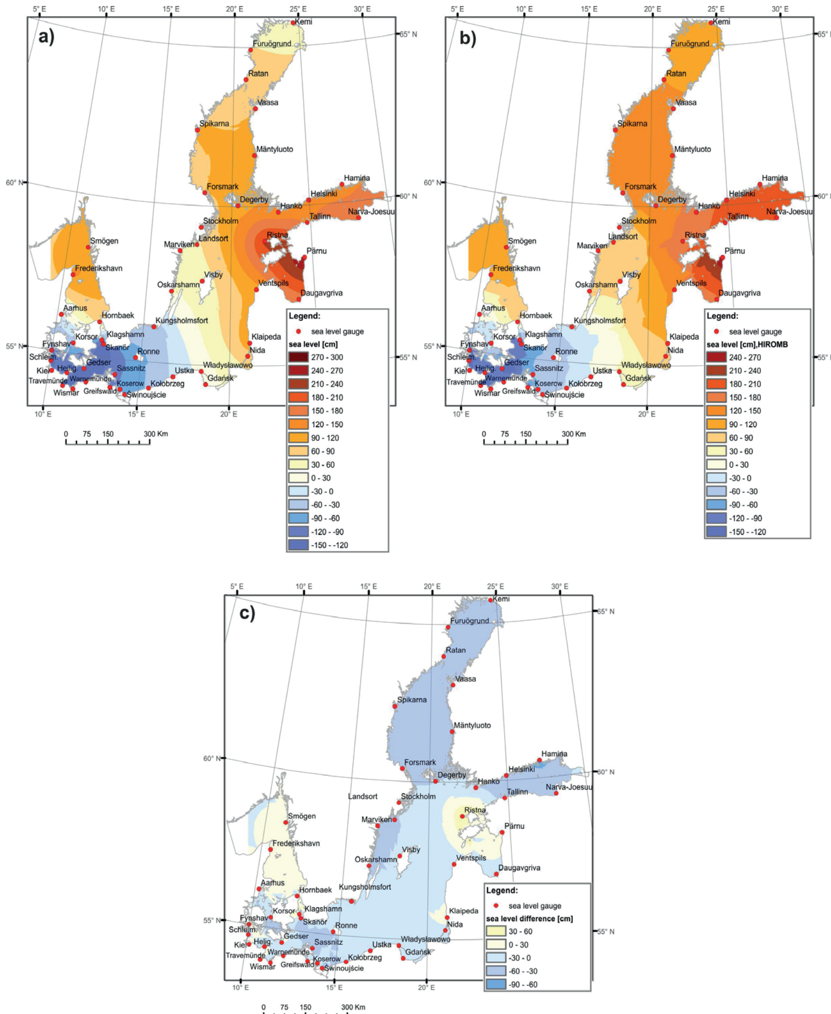

Figure 5

Baltic sea surface models for 9 January 2005, 03:00 UTC: a) on the basis of real sea levels (49 tide gauges); b) on the basis of the HIROMB model (49 points); c) absolute differences between sea levels in cm

18/10). Storm winds and the negative pressure effect (baric wave) generated by this baric system caused incredibly severe seiche-like sea-level oscillations of the Baltic Sea waters (quick changes in the inclination of the Baltic Sea surface).

Characteristics of sea-level changes within particular basins of the Baltic Sea

Western Baltic

However, from the morning of 17 October 1967, tide gauge stations in the western Baltic recorded a constant decline in the sea level which lasted till the morning hours of the next day (18 October). The negative pressure of the dynamically moving and deep low-pressure system together with south-westerly winds of 10-30 m s^{-1} velocity (up to 31 m s^{-1} recorded in Gedser) caused a deformation of the sea surface, decreasing the sea level at the western coasts and increasing at the northern and north-eastern basins of the Baltic Sea. The sea level of -170 cm was recorded in Wismar and Warnemünde (at 0:00 UTC and 3:00 UTC, respectively), -141 cm in Gedser (Denmark), -134 cm in Świnoujście and -129 cm in Skanör (Sweden). The rate of sea-level lowering reached the values ranging from 24 to 54 cm h^{-1} (Table 2). In the early afternoon of 18 October, the western Baltic was on the rear side of the low pressure system and hence it came under the influence of weaker north-westerly and north winds (below 10 m s^{-1}). Tide gauge stations of the western Baltic had switched from the negative to the positive phase of the storm surge and they were recording a rapid increase (34-76 cm h^{-1}) in the sea level at the

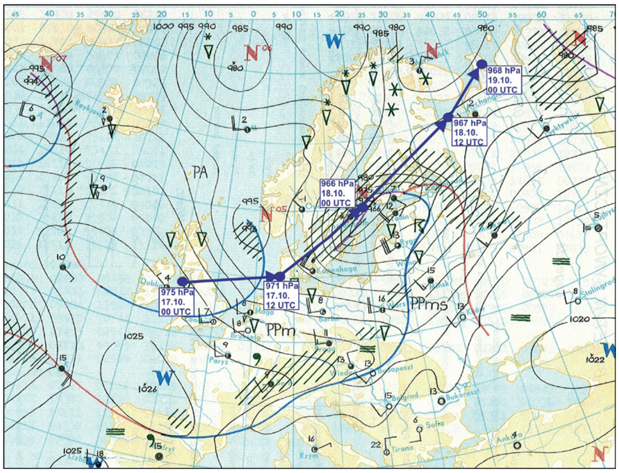

Figure 6

The course of the low pressure system on 17-19 October 1967 together with the main synoptic situation on 18 October.1967, 0:00 hrs UTC (source: Synoptic Bulletin PIHM with modification of the authors).

time until maximum values were reached: +128 cm in Skanör (10:00 UTC, 18 October), +86 cm in Świnoujście (12:00 UTC), +91 cm in Wismar (15:00 UTC), +98 cm in Gedser and +76 cm in Warnemünde (17:00 UTC). Such a rapid drop followed by a rapid rise of the sea level in the western Baltic could not be induced by winds alone. The influence of the negative pressure of the concentric low (so-called water cushion occurring below the low pressure) was the dominant factor here. During the next two days (19 and 20.10), seiche-like oscillations were occurring and disappearing in the western Baltic (sea levels were oscillating below or close to the tide gauge datum with south and south-westerly winds of up to 15 m s^{-1} velocity) (Figs 7 & 8, Table 2).

Danish Straits

Due to the tidal nature of sea-level fluctuations, stations located in the Danish Straits showed an earlier extreme, which was associated with the moving low: 93 cm in Hornbaek (Sund; 22:00 UTC, 17 October), 82 cm in Smögen (Skagerrak; 2:00 UTC, 18 October) (Table 2). Wind velocity in Skagerrak and Sund increased from 4 to 25 m s^{-1} on 17 October. Sea levels recorded at the tide gauges in Sund were similar to those recorded in the western Baltic (Fig. 8).

Southern Baltic

The pattern of sea-level oscillations at the tide gauges in the southern Baltic varied despite similar wind conditions in this water basin. From 17 to 18 October, the wind velocity increased from 7 to 31 m s^{-1} while changing the direction from southern and

Table 2

Features of the low pressure system and parameters of the storm surge analyzed in the period of 17-20 October 1967

Station	Features of the low pressure system		Recorded sea level										H_s (cm)	ΔH_d (cm)
	p_L (hPa)	V_L (m s^{-1})	Initial sea level (cm)	Max (cm)	Min. (cm)	Amplitude (cm)	The maximum rate of sea level change (cm h^{-1})		Duration of the sea level [hour]					
							Rise	Decrease	≥70 cm	≥100 cm	≤ -70 cm	≤-100 cm		
Smögen			20	82	-28	110	30	30	2	-	-	-		
Skänor			19	128	-129	257	76	54	8	5	8	6		
Wismar			-3	91	-170	261	58	24	6	0	17	12		
Warnemünde			-1	76	-170	246	38	33	3		11	8		
Gedser			1	98	-141	239	39	38	6	-	12	11		
Świnoujście			6	86	-134	220	34	54	2	-	4	2		
Kungsholmsfort			13	98	-78	176	41	39	6	-	3	-		
Kłajpeda			28	195	+1	194	31	47	14	8	-	-		
Visby			36	85	+13	72	13	14	4	-	-	-		
Pärnu	966	22.2	91	264	+30	234	102	110	68	40	-	-	47.6	143
Ristna			42	165	+29	136	20	24	40	8	-	-		
Sztokholm			27	90	+9	81	14	18	8		-	-		
Tallinn			63	135	+20	115	17	17	34	7	-	-		
Helsinki			50	103	10	93	15	15	26	6	-	-		
Hamina			44	134	-16	150	21	24	30	16	-	-		
Narva			72	180	+16	164	26	30	54	29	-	-		
Degerby			25	72	16	56	6	10	1	-	-	-		
Vaasa			35	57	14	43	5	6						
Kemi			40	50	-12	62	7	6	-	-	-	-		

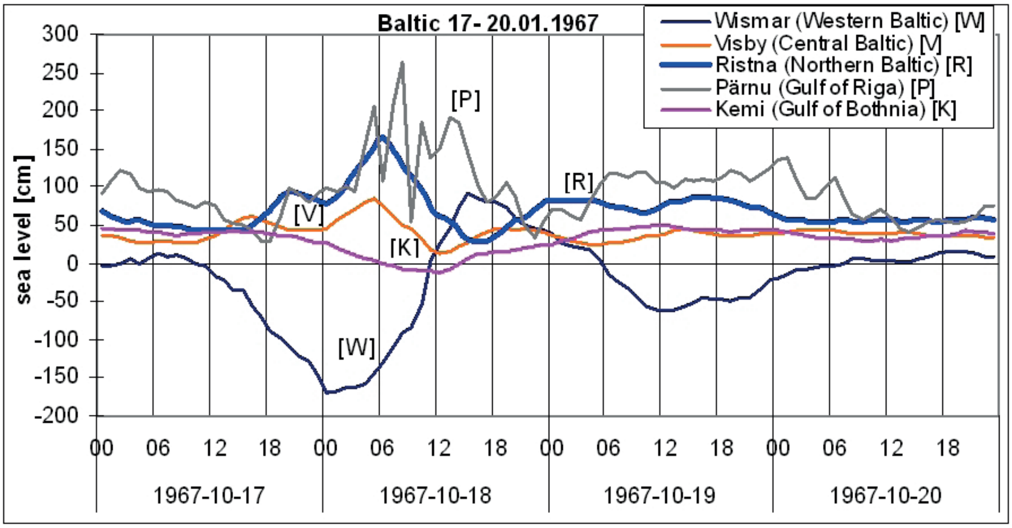

Figure 7

Changes in the sea level for representative stations in the main basins of the Baltic Sea on 17-20 October 1967

south-western to western over the night. The pattern of changes in the sea level in Kungsholmsfort was similar to the surge in the western Baltic with a distinguishable negative and positive phase. The minimum of -78 cm was reached at 3:00 UTC 18 October, while the maximum of +98 cm already 7 hours later (10:00 UTC, 18 October 1967). On the other hand, Klaipeda located on the eastern coast experienced only a positive phase of the surge, reaching the maximum of +195 cm at 5:00 UTC (18 October 1967), while the pattern of sea-level oscillations was similar to tide gauges in the northern Baltic (Ristna) and the Gulf of Riga (Pärnu). However, a very clear deformation and a height difference in the southern Baltic surface occurred together with its inclination from the eastern (high levels) to the western coasts (low levels) (Fig. 9). This deformation is associated with the negative pressure of the fast-moving low pressure system and wind activity which raised the water level on the eastern coasts of the southern and northern Baltic. Once the maximum was reached in Klaipeda, rapid lowering of the sea level began (max fall rate was 47 cm h^{-1}) and the wind velocity decreased to 10 m s^{-1} (Table 2, Fig. 8).

The central and northern Baltic

During the sea level fall in the western Baltic, tide gauges on the central and north-eastern coasts of the Baltic recorded surges on 17 and 18 October. The wind velocity was increasing and its direction was changing as well (1-15 m s^{-1} in Ristna and 125 m s^{-1} in Stockholm). Once the center of the low left the northern Baltic and entered southern Finland (0:00 UTC, 18 October), the tide gauge stations reached their maximum sea levels, which is an opposite situation to the western Baltic stations, where minimum levels were recorded (Visby in the central Baltic reached the maximum of +85 cm at 5:00 UTC, 18 October). Hanko in the northern Baltic reached the maximum of +107 cm (4:00 UTC, 18 October), Stockholm – +90 cm (5:00 UTC), Ristna – +165 cm (6:00 UTC; at the initial level of +42 cm). In the following hours of 18 October, there was a rapid sea-level fall (max fall rate was 14-24 cm h^{-1}) with a moderate, north-westerly wind of up to 15 m s^{-1} velocity. On 19 and 20 October, the northern Baltic experienced a persistence of higher sea levels in Ristna (50-80 cm) and Hanko (30-80 cm) due to a filling of the northern Baltic (Fig. 8).

The Gulf of Finland and the Gulf of Riga

A positive phase of the storm surge in the Gulf of Finland followed with a little delay and the main maxima of sea levels occurred in the morning and at midday of 18 October: Tallinn +135 cm (10:00 UTC, 18 October), Hamina +134 cm (12:00 UTC), Narva +180 cm (12:00 UTC). It should be added, however, that secondary maxima at these stations occurred on 17 and 19 October, which is before and after the main maximum. A clear harmonic character of the sea-level oscillations was revealed, which occurs with a high degree of filling of the basin and moderate winds (a similar situation was observed

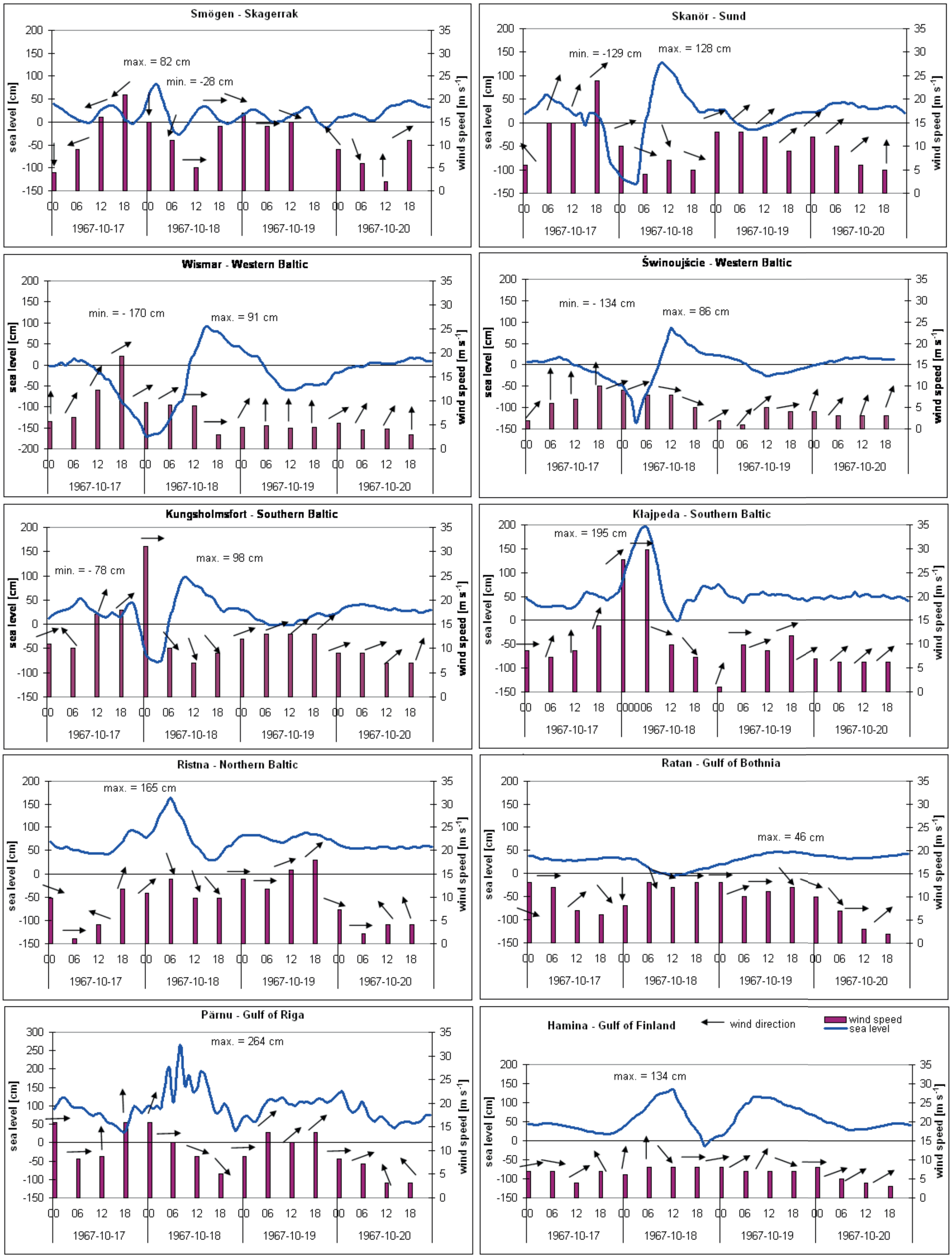

Figure 8

Distribution of wind direction and velocity together with changes in the sea level in particular basins of the Baltic Sea in 17-20 October 1967

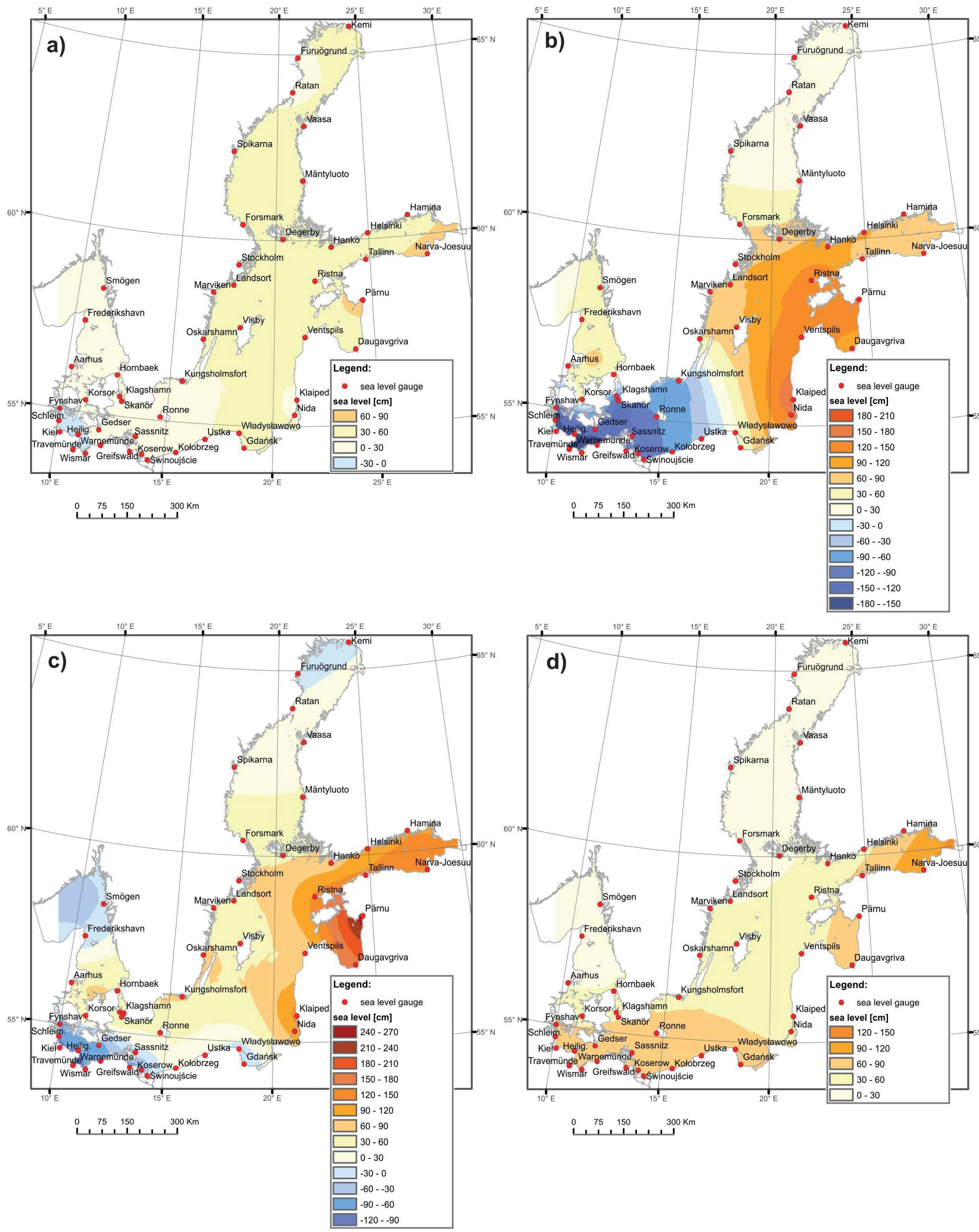

Figure 9

The image of instantaneous sea levels of the Baltic Sea: a) 17 October 1967, 12:00 UTC; b) 18 October 1967, 04:00 UTC; c) 18 October 1967, 08:00 UTC; d) 18 October 1967, 16:00 UTC when a surge wave moved several times toward the southern coast and back). The initial situation in the Gulf of Finland was characterized by slightly higher sea levels – a rise from +40 cm in Hamina to +72 cm in Narva. The record rate of the sea level rise (102 cm h^{-1}) and fall (110 cm h^{-1}) was noticed in Pärnu located in Pärnu Bay which is part of the Gulf of Riga. This resulted from the location of the bay in relation to the trajectory of the low and dominant winds (south-western exposure of the bay). This station recorded the highest maximum during the investigated storm surge, i.e. +264 cm (8:00 UTC, 18 October). This extreme rate of oscillations and the maximum sea level were recorded for Pärnu in the conditions of the south-westerly wind blowing with a velocity of 8-18 m s^{-1}. On the other hand, the initial level of the surge was +91 cm (0:00 UTC, 17 October). The course of sea-level oscillations in Pärnu Bay was characterized by several short-term fluctuations – similarly to the Gulf of Finland (Fig. 8).

The Gulf of Bothnia

Changes in the sea level observed in the Gulf of Bothnia were of a different nature. The low pressure system that caused seiche-like oscillations in the western, southern and central Baltic bypassed the Gulf of Bothnia from the south and did not cause the water level rise. Therefore, tide gauge stations located in the area recorded sea levels in the range of 0-50 cm. On 18 October, sea levels in the gulf fell to tide gauge zero (the effect of the negative phase of the wave on the edge of the low pressure system) (Fig. 8).

Summing up the studied storm event, it should be emphasized that the dynamic entry of the low pressure system (V≈80 km h^{-1}) into the southern and central Baltic and the development of the "water cushion" was reflected in the positive phase of the surge for tide gauges in the central and northern Baltic and the Gulf of Finland and the Gulf of Riga (Visby, Ristna, Pärnu, Hamina). At the same time, the negative phase occurred in the western and southern Baltic (Wismar, Kungsholmsfort) and in the Gulf of Bothnia (Kemi, Ratan). This process of developing the sea surface deformation continued from 17 October, 18:00 UTC to 18 October, 6:00 UTC (the forced wave which corresponded to the pressure depression of 966 hPa moving through the water basins). During the following hours of 18 and 19 October 1967, the seiche-like oscillations of the sea level occurred, which disappeared the next day – 20 October (Figs 7-9). The greatest height difference occurred at the time when the center of the low pressure system began to encroach on the land of southern Finland (after 18 October 1967, 0:00 UTC). An inclination of the sea surface developed, from the north-east to the south-west coast of the Baltic Sea. Changes in the angle of the inclination are shown in the instantaneous sea-level charts (Fig. 9). The chart of 17 October 1967, 12:00 UTC (Fig. 9a) displays the initial phase of the storm – an increase in the deformation. Charts of 18 October 1967, 4:00 and 9:00 UTC (Fig. 9b and 9c) demonstrate the culmination of the surge in the northern and central Baltic, the Gulf of Riga and the Gulf of Finland as well as the lowest sea levels recorded in the western and southern Baltic. At 8:00 UTC of 18 October, the greatest, instantaneous amplitude of the Baltic Sea levels was observed, i.e. 356 cm (+264 cm in Pärnu, the Golf of Riga and -92 cm in Wismar, the western Baltic). The chart of 18 October 1967, 16:00 UTC (Fig. 9d) shows a moment of leveling the water levels in the Baltic Sea. Such a huge deformation could not be created with the sole participation of wind (drift currents and wind set-ups). The negative pressure of the fast-moving low was the deciding factor responsible for the deformations in the Baltic surface. Attention should be paid to the fact that the extreme sea-level fluctuations occur when the speed of the low pressure system is close to the velocity of a swell in the sea surface $\sqrt{gH}$ (as was the case with the storm surge on 17-19 October 1967).

Summary

The knowledge of sea-level changes is very important, both in terms of science and practical application. Data are one of the basic information necessary when conducting the research on the hydrodynamics and morphodynamics of the coastal zone. In addition, a long-term forecast of extreme sea levels is crucial for coastal engineering, land development and all activities related to the integrated coastal zone management (ICZM).

It turns out, however, that there are some difficulties with interpretation of data recorded by tide gauges in different parts of the Baltic coast.

There was not a single common, geodetic reference datum for sea-level observation among the Baltic countries. Fast standardization of the vertical reference systems and their datums is a must. It is hoped that the Baltic Sea Hydrographic Commission (BSHC), which was established by the International Hydrographic Organization (IHO), will quickly complete the tasks aimed at standardizing the

reference systems, assessing the possibilities of using the European Vertical Reference System (EVRS) as the main geodetic reference system for the Baltic charts and choosing the method of demonstrating the sea level and its variability.

The review of geodetic reference systems available in particular countries and demonstrated in this paper might be useful for spatial analysis of the sea-level data derived from various parts of the Baltic Sea. Adaptation of EVRS with the NAP reference level, performed in this paper to display parameters of extreme sea levels of the Baltic Sea for the period of 1960-2010, allowed for a detailed spatial analysis of the investigated phenomenon. The use of the standardized reference datum allowed for the visualization of the so-called "theoretical water" distribution in the 200-year return period and the assessment of the accuracy of operational hydrodynamic models, which is of great practical importance in terms of storm surge forecasting.

The sea level rise is the reason for a landward shift of the wave breaking zone, which induces an increased activity of abrasion, very often leading to catastrophic events such as breaking the spits, disappearance of beaches and storm floods in seaside towns and villages. These events are always associated with huge economic losses (Musielak 2006). To determine the real hazards related to extreme sea levels, it is important to systematically monitor and forecast the elevation of the sea surface (Wiśniewski, Wolski 2009a; Wolski et al. 2014). This makes the correct interpretation of the morphodynamic shore development possible and allows the selection of suitable protection measures.

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