Performance of operationally calculated hydrodynamic forecasts during storm surges in the Pomeranian Bay and the Szczecin Lagoon

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The modified hydrodynamic model of the Baltic Sea, developed at the Institute of Oceanography, University of Gdańsk was validated using storm-related sea level fluctuations as well as water temperature and salinity variations in the Pomeranian Bay and the Szczecin Lagoon (southern Baltic). The high resolution (about 300 m) applied to the model for the Szczecin Lagoon area resulted in a much better description of the area's bathymetry, and in an improved fit between the modelled and the observed distributions of the data sets both in the Bay and in the Lagoon. Model quality tests involving 2002–2007 storm surge events showed a better representation of events characterised by rapid water level fluctuations and fast changes of physical water properties. The numerical model's high quality of simulations allows for applying the higher resolution of spatial spacing to the Szczecin Lagoon area also in the operational version of the model.

Introduction

Storm surges represent a particular threat for low-lying coastal areas of the Pomeranian Bay and Szczecin Lagoon (southern Baltic) by producing flooding events, resulting in coastal erosion and causing many problems to inhabitants of the coastal areas. These rapid, non-periodic, short-term sea level fluctuations are associated with cyclonic circulation having its centre within or close to the Baltic Sea, when strong northwesterly to northeasterly onshore winds blow onto land (Zeidler *et al.* 1995). Majewski *et al.* (1983) showed that those winds are associated mainly with passages of lows entering the Baltic Sea from N to W sector, or less frequently from W to SW sector. Moreover, strong northerly air flow occurs when lows travel outside the Baltic Sea, i.e., north of the Gulf of Bothnia or over the central and eastern parts of Europe. Sztobryn *et al.* (2005) identified several types of pressure patterns leading to storm surges at the German and Polish Baltic Sea coast, i.e., northerly air flow over Scandinavia and the Baltic Sea, stormy low pressure systems moving over the central and southern Baltic Sea and storms from the eastern sector. The authors also showed the amount of water in the Baltic Sea ('fill-up') to be of great importance in generating particularly dangerous storm surges. In turn, Jensen and Müller-Navarra
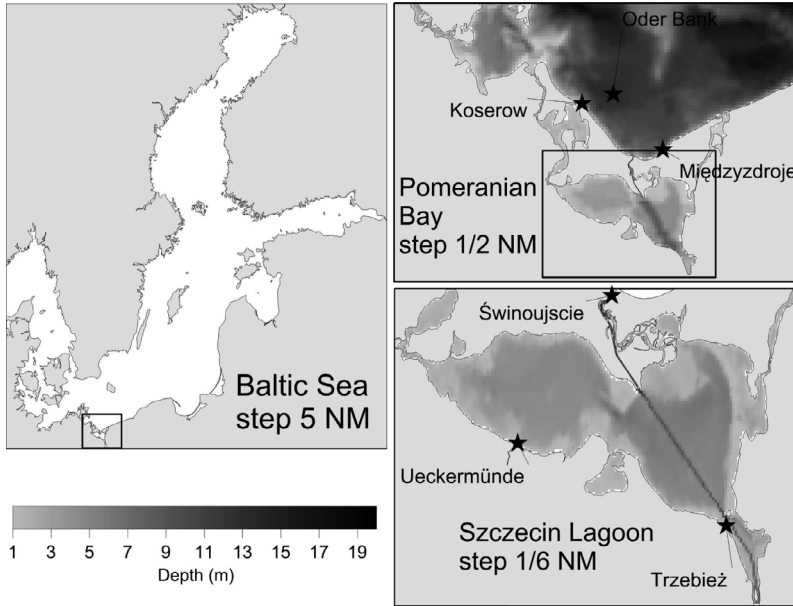
Fig. 1. The modelled regions (Baltic Sea, Pomeranian Bay, Szczecin Lagoon) with station locations (stars).

(2008) pointed out that seiches involving the whole water body of the Baltic Sea can influence the storm water level in the western Baltic. In a recent study, Kowalewska-Kalkowska and Wiśniewski (2009) demonstrated that the most dangerous storm surges at the Pomeranian Bay coasts occur during the passages of deep and intensive low pressure systems near the coast of the southern Baltic, with an extensive system of north-westerly to north-easterly winds.

The shallow, almost non-tidal Pomeranian Bay, with a mean depth of about 13 m and an area of about 6000 km^2, is affected by the intensive wind-induced mixing of fresh and brackish waters (Fig. 1). It receives annually on average 17.6 km^3 freshwater input mainly from the Odra River (Mikulski 1970). In its downstream reach, the Odra opens first into the Szczecin Lagoon, a coastal water body of about 687 km^2 surface area, 2.5825 km^3 water volume and 3.8 m in mean depth (Majewski 1980). Then, it drains into the Pomeranian Bay through three narrow straits: the Świna, the Dziwna and the Peenestrom. The Świna consists of both natural and man-made canals and serves as the most important conduit of the water exchange between the Lagoon and the Bay. According to Mohrholz and Lass (1998), it covers 60%–70% of the mass transport. The Peenestrom and the Dziwna

contribute 15%–20% to the water exchange. The water exchange between the Szczecin Lagoon and the Pomeranian Bay occurs as pulse-like in- and outflow events. Water circulation within the Odra mouth is greatly affected by the shipping channel, 66 km long, 10–11 m deep, and 250-m wide, extending from the Szczecin Harbour along the western Odra to intersect the eastern part of the Szczecin Lagoon, the Great Lagoon and along the Świna Strait — to reach the Pomeranian Bay (Majewski 1980).

The hydrodynamic conditions of the Szczecin Lagoon are driven by wind action, water level differences between the Lagoon and the Pomeranian Bay, fresh water inflow from the Odra, and salt water intrusions through the straits connecting the Lagoon with the Pomeranian Bay (Jasińska *et al*. 2003). As a result of a very low slope of water surface within the whole Odra mouth area, water levels in the Szczecin Lagoon and in the Lower Odra channels are strongly affected by changes in the sea level. During heavy storm surges associated with strong northerly winds, when the sea level in the Bay is higher than that in the Lagoon, the Bay's brackish water enters the Lagoon and raises the water level both there and in the Lower Odra channels (Buchholz 2009, Kowalewska-Kalkowska and Wiśniewski 2009). The influx affects the

Lagoon's physical and chemical characteristics as well. Jasińska and Massel (2007) reported that during storm surge events the brackish Pomeranian Bay water, with a salinity up to 8‰, was advected through the Świna and spread into the Szczecin Lagoon. On the other hand, effect of the instantaneous Odra discharge on water levels in the river's mouth area is of less importance because, even during Odra flood events, the water level increases by only a few centimetres as the flood wave enters the Szczecin Lagoon. However, the increased Odra discharge results in a drop of salinity there. As reported by Mohrholz *et al*. (1998), during the Odra flood event in August 1997 the salinity of the eastern part of the Szczecin Lagoon decreased to 0.15‰.

Due to complex nature of meteorological and hydrological factors affecting hydrodynamics of Baltic coastal waters, numerical modelling has become an essential tool in offshore zone management and flood protection there. Suursaar *et al*. (2002) applied two-dimensional hydrodynamic model for the Gulf of Riga and the Väinameri Sea for examining sea level variations there. The model was then used in studies on the extreme sea level events (Suursaar *et al*. 2003, 2006). Andrejev *et al*. (2004) used a three-dimensional baroclinic prognostic model to study mean circulation and water exchange in the Gulf of Finland, and recently Averkiev and Klevanny (2007) applied successfully the CARDINAL numerical model in analyses of extreme sea levels in St. Petersburg (Russia).

The hydrodynamic regimes of the Szczecin Lagoon and Pomeranian Bay have been mostly described by three-dimensional models, such as ESTURO (Jasińska and Massel 2007) and the Warnemünder Ostsee Model (WOM) (Lass *et al*. 2001). Siegel *et al*. (2005) analysed discharge and transport processes in the western Baltic Sea and in the Szczecin Lagoon using three-dimensional MOM-3 model and two-dimensional FEMFLOW model, respectively. Mohrholz and Lass (1998) applied a simple barotropic box model for the description of water exchange between the Szczecin Lagoon and the Pomeranian Bay. Model simulations of the Odra River spread in the Szczecin Lagoon during the flood in 1997 using three-dimensional TRIM3D model were carried out by Rosenthal *et al*. (1998). The

most advanced model describing the hydrodynamic regime of the Lower Odra River was developed by Ewertowski (1988).

Over the recent years, operational meteorological and hydrodynamic forecasting within the Baltic Sea region has been a target of many numerical studies. The High Resolution Operational Model of the Baltic Sea (HIROMB) was developed at the Bundesamt für Seeschifffahrt und Hydrographie (BSH) in Hamburg and subsequently extended in cooperation with the Swedish Meteorological and Hydrological Institute (SMHI) in Norrköping (Eigenheer 1999, Funkquist 2001). Kałas *et al*. (2001) and Stanisławczyk (2002) validated the forecasts for the Polish coastal zone. The description and validation of the Bundesamt für Seeschifffahrt und Hydrographie, circulation model (BSHcmod) was presented in detail by Dick *et al*. *(*2001). Filinkowa *et al*. (2002) applied the model in the eastern Gulf of Finland. Gästgifvars *et al*. (2008) proved that the Baltic Sea forecast models HIROMB, BSHcmod, and DMI-BSHcmod run by the three institutes SMHI, BSH, and DMI in their daily routine services are well suited to forecast water level changes in the Gulf of Finland.

The three-dimensional operational hydrodynamic model of the Baltic Sea (M3D_UG) built on the coastal ocean circulation model known as the Princeton Ocean Model (POM) was developed in 1995–1997 at the Institute of Oceanography, University of Gdańsk (Kowalewski 1997). At first, the model was generating hydrodynamic forecasts for two areas: the southern Baltic and the Gulf of Gdańsk (Kowalewski 2002). Further modification of the model resulting in development of the Odra discharge model (Kowalewska-Kalkowska and Kowalewski 2006) allowed to issue 60-h hydrodynamic forecasts of water levels, currents, water temperature and salinity for the Pomeranian Bay and Szczecin Lagoon (http://model.ocean.univ.gda.pl). The performance of hydrodynamic forecasts for those regions was described in detail by Kowalewska-Kalkowska and Kowalewski (2005, 2007). The M3D_UG model proved successful in studies on the occurrence of coastal upwelling in the Baltic (Kowalewski and Ostrowski 2005) as well as long-term simulations of current and sea level fluctuations in the Baltic (Jędrasik *et al*. 2008).

This study focused on the improvement of prognostic reliability of the M3D_UG model for the Pomeranian Bay and the Szczecin Lagoon. We present an overview of the main characteristics of the model and a detailed validation of the modified model. In particular, we provide results of statistical analyses applied to assess the quality of the model. We also discuss the performance of hydrodynamic forecasts during storm surges in the Pomeranian Bay and Szczecin Lagoon giving a short description of two storm surge events and carefully examining the accuracy of the model.

Model description

A three-dimensional hydrodynamic model of the Baltic Sea (M3D_UG) is a baroclinic model that describes water circulation with due consideration to advection and diffusion processes. The model is based on the POM that is described in detail by Blumberg and Mellor (1987). Adapting the model to the Baltic Sea required certain changes in the numerical calculation schema, which are described in detail by Kowalewski (1997). The open boundary is located between the Kattegat and the Skagerrak. For the purpose of approximating water exchange between the North and the Baltic Seas, a radiation boundary condition is applied. Monthly averaged climatic vertical distributions of salinity and temperature are also assumed at the open boundary. Hourly readings of sea levels in Göteborg (obtained from Baltic Operational Oceanographic System), are accepted over the whole open boundary. We made this assumption because the tides are strongly suppressed in the Danish Straits and their impact on sea level is negligible along the Baltic Sea coast (Suursaar *et al.* 2003, Jasińska and Massel 2007). Although it is a simplified way of including tides in the Kattegat in the model, it does not produce significant errors.

The meteorological data necessary to operate the hydrodynamic model were obtained from the Unified Model for Poland Area (UMPL) (Herman-Iżycki *et al.* 2002). The solar energy input was calculated on the basis of astronomical data and meteorological conditions (Krężel 1997). Other components of the heat budget at the sea surface were derived from meteorological data and simulated sea surface temperatures (Jędrasik 1997). The initial 3D temperature and salinity distributions were interpolated by the Data Assimilation System (Sokolov *et al.* 1997) based on the data from Baltic Environmental Database (http://ecology.su.se/models/bed.html). The calculations were carried out without assimilation of hydrologic data. The ice dynamics model was not included, but for the water temperature below the freezing point, wind stress equal to zero was assumed. In this way, the impact of the wind in case of ice occurrence is reduced. The model considers the majority of riverine inflow into the Baltic Sea. Because of wind-driven water back-flow in the Lower Odra channels, a simplified operational model of the Odra discharge based on water budget in a stream channel was developed (Kowalewska-Kalkowska and Kowalewski 2006).

A numerical grid with a sigma transformation enables vertical profiles at any point in the sea to be divided into 18 layers regardless of depth. For a better representation of the surface and near-bottom layers, their thicknesses are smaller than those of other layers (Kowalewski and Ostrowski 2005).

In order to obtain adequate resolution and reliable output, three grids with different spatial spacing were applied: 5 nautical miles (NM) for the Baltic Sea, 1 NM for the Gulf of Gdańsk, and 0.5 NM for the Pomeranian Bay and Szczecin Lagoon. However, when the resolution of the model increases, the number of grid points for which calculations are carried out increases as well. Moreover, to satisfy the numerical stability conditions it is necessary to apply shorter computational time steps. Generally speaking, this leads to a sudden increase in the amount of necessary calculations. To increase the effectiveness of calculations, downscaling is usually applied; the downscaling technique involves a coarser grid for calculations applied to a larger basin, a finer grid being applied to an area of interest which needs a more precise solution. Results of the calculations for the larger area were used as boundary conditions for the model of the smaller area.

The M3D_UG model enables multi-level linking of grids with different resolutions; how-

ever, two-way connection between the nested grids is applied instead of typical downscaling. Calculations run parallel for all the modelled areas, information being exchanged on the common boundary on each common time step. All the model variables (temperature, salinity, currents, sea level, vertical and horizontal coefficient of eddy viscosities) as calculated on the border of one area serve as a boundary condition for the other area. The connection is realised by an algorithm which ensures mass and energy conservation. Like in downscaling algorithms, values of the variables being modelled in the larger area are accepted on the local model's boundary. Once a certain number of computational steps has been made in the local grid which corresponds to one temporal step of the coarser grid, values of the local model variables are appropriately averaged in the grid points of the low resolution area located on the common border. A two-way connection between the nested grids is provided, meaning that all calculated variables can be transported from the coarse grids to the finer grids and vice versa.

For the purpose of this work, the model for the Pomeranian Bay and the Szczecin Lagoon was modified. Preliminary evaluation of the model's accuracy showed a satisfactory fit between the modelled and observed distributions of data sets. Although the present version of the model (v0) (available on the Internet) generates relatively good simulations overall, salinities of the Pomeranian Bay and Szczecin Lagoon are overestimated by more than 1‰ (Kowalewska-Kalkowska and Kowalewski 2005, 2006, 2007). Hence some simulations in this study were run to improve prognostic reliability of the model. Firstly, a more accurate bathymetric map of the Pomeranian Bay was applied and the course of the coastline was slightly corrected manually. In that version, as before, the spatial spacing of about 1 km (0.5 NM) was applied both to the Pomeranian Bay and Szczecin Lagoon (v1). For subsequent simulations (v2), two grids differing in spatial resolution were used: one with about 1 km spacing, applied to the Pomeranian Bay, and the other with about 300 m (1/6 NM) spacing, applied to the Szczecin Lagoon (Fig. 1). That operation resulted in a much better description of the coastline and the area's bathymetry; in par-

ticular, widths of the narrow straits connecting the Lagoon with the Pomeranian Bay (the Świna, the Dziwna, and the Peenestrom) were close to their real size.

The bathymetric grid for the new area was prepared based on available bathymetric data and nautical charts of the area. Despite the relatively high resolution (300 m), the bathymetric chart required manual modifications. Since the straits connecting the Szczecin Lagoon with the Pomeranian Bay were in many places narrower than the grid's spatial resolution, manual corrections were necessary to ensure water exchange between these basins. As demonstrated in the model validation, water exchange between the Bay and the Lagoon was too limited. Therefore, the grid was altered, the alteration consisting of deepening and widening the straits where the water transport was most limited. Thus, a new version of the model (v3) emerged; it did not differ from v2 in resolution, the only difference involving the manner in which the bathymetry and the coastline was approximated.

Model validation

Validation of the model was based on the observed and calculated data series of water level, water temperature, and salinity in the Odra mouth area, including the coastal zone of the Pomeranian Bay, the Oder Bank, and the Szczecin Lagoon from 2002–2007. The water level readings for Świnoujście and Trzebież were collected by the Harbour Master's Offices in Świnoujście and Trzebież at 1-h and 4-h resolutions, respectively, and with reference to NN Amsterdam 1955 (the land survey datum of Poland). Hourly sea level and temperature data for Koserow and Ueckermünde as well as water temperature and salinity data on the Oder Bank were acquired from Bundesamt für Seeschifffahrt und Hydrographie (from BOOS and http://www.bsh.de/). As reported by Stigge (1994) and Kałas *et al.* (2001), to obtain consistency between Polish and German levelling, the correction of –6 cm for the German stations was considered. The daily water temperature and salinity data for Międzyzdroje and water temperature for Trzebież were obtained from

the Institute of Meteorology and Water Management. The data on water temperature and salinity in the Szczecin Lagoon were also available from the Regional Inspectorate of Environmental Protection in Szczecin.

Statistical characteristics of the model performance comprise calculations of the model error, the absolute bias of the model, the standard deviation of the differences between the modelled and observed values, the correlation and determination coefficients, and the Nash-Sutcliffe coefficient of effectiveness, using formulas described by Węglarczyk (1998) and Jędrasik *et al.* (2008). Moreover, according to the US NOAA standards (Gästgifvars *et al.* 2008) the frequency of water level forecasts that fit the limit of ±15 cm difference from the readings was calculated. It should be mentioned that the calculated water level data are relative only, that is, due to the imperfection of the conditions applied to the open boundary in the Skagerrak and Kattegat, it is difficult to refer them to the average sea level and to calculate the absolute sea levels, for example with reference to NN Amsterdam 1955. In case of comparing water level simulations with the measurements, the mean sea levels have been adjusted to the same level, i.e., the modelled values were fitted to the mean sea level in Koserow by subtracting the values 10.12, 11.79, 11.83 and 11.80 cm from all simulated data of version v0, v1, v2 and v3, respectively.

With respect to the water level series, the modification of the numerical bathymetric grid of the Baltic involving adjustment of depths and shoreline in the area of the Island of Rügen in version 1 (v1) allowed to improve the agreement between the modelled and the observed readings as measured at coastal stations in the Pomeranian Bay and the Szczecin Lagoon. The correlation coefficients between the observed and computed data increased to over 0.92 (Table 1). The highest correlation was obtained for the Trzebież gauging station, where the coefficient correlation reached the value of 0.938. In turn, standard deviations of differences between measurements and calculations decreased and coefficients of effectiveness slightly increased. As a result, more than 90% of all the forecasts fitted within the limit of ±15 cm difference from the readings (Table 2). The smallest errors were noted for the

Trzebież gauging station. The high resolution grid applied to the Szczecin Lagoon in version 2 (v2), and thus narrowing the straits connecting the Szczecin Lagoon with the Pomeranian Bay, resulted in a decreased water exchange between the two areas. However, correlation coefficients between the numerical and observed readings as measured at the Szczecin Lagoon gauging stations decreased, ranging from 0.814 in Trzebież to 0.828 in Ueckermünde. Further, standard deviations of differences between measurements and calculations increased and coefficients of effectiveness significantly decreased. The comparison of simulated water levels with measurements showed that only 65% and 80% of forecasts for Trzebież and Ueckermünde, respectively, fitted into the ±15 cm limit. Moreover, changes in the water level in the Lagoon, as calculated by the model, proved too slow, as compared with the observations. Further modification of the bathymetry grid and the shoreline in version 3 (v3) allowed to improve significantly the agreement between the calculated and observed water levels in the Szczecin Lagoon. As a result, the correlation coefficients between the empirical and numerical data sets reached 0.941, standard deviations decreased and coefficients of effectiveness significantly increased. In turn, over 95% of forecasts found to be within the range of ±15 cm of the observed water levels. Very good agreement was also obtained for the Pomeranian Bay stations, where 91% and 93% of forecasts for Świnoujście and Koserow, respectively, matched actual water levels within the range of ±15 cm.

With respect to water temperature (Table 1), the modification of the model resulted in the improvement of agreement between the modelled and observed distributions of data sets. In version 1 (v1), the model produced a very good fit between the observed and predicted water temperatures both in the Pomeranian Bay and Szczecin Lagoon. The modelled mean values were calculated with accuracy of ±0.5 °C. The best correlation was achieved for the open waters of the Pomeranian Bay, but correlation coefficients higher than 0.98 for all stations were indicative of high statistical significance. Coefficients of effectiveness were almost equal to coefficients of determination; indicating good quality of model

Table 1. Statistical descriptors of model performance with respect to water level, water temperature and salinity at selected stations in 2002–2007. n = number of data, Q_m = bias of model, SD = the standard deviation of the differences between modelled and observed values, r = correlation coefficient between observed and numerical values, E = the Nash-Sutcliffe coefficient of efficiency.

Station	n	v0				v1				v2				v3			
		Q_m	SD	r	E	Q_m	SD	r	E	Q_m	SD	r	E	Q_m	SD	r	E
Water level (m)																	
Świnoujście	8715	–0.003	0.094	0.912	0.817	–0.003	0.086	0.924	0.846	–0.006	0.092	0.916	0.823	–0.003	0.089	0.921	0.837
Koserow	43151	0.000	0.089	0.922	0.840	0	0.081	0.934	0.868	0	0.081	0.933	0.867	0	0.082	0.933	0.866
Trzebież	8735	–0.004	0.079	0.926	0.835	–0.005	0.071	0.938	0.866	0.119	0.118	0.814	0.262	0.029	0.068	0.941	0.857
Ueckermünde	36495	–0.046	0.079	0.924	0.776	–0.052	0.074	0.933	0.783	0.058	0.109	0.828	0.590	–0.024	0.067	0.941	0.866
Water temperature (°C)																	
Międzyzdroje	2191	–0.074	1.069	0.988	0.976	–0.023	1.051	0.989	0.977	–0.009	1.068	0.988	0.977	–0.003	1.040	0.989	0.978
Koserow	18153	0.005	0.917	0.990	0.980	0.043	0.912	0.990	0.980	0.058	0.911	0.990	0.980	0.039	0.911	0.990	0.981
Oder Bank (3 m)	29670	–0.244	0.794	0.992	0.982	–0.198	0.772	0.992	0.983	–0.183	0.781	0.992	0.983	–0.194	0.771	0.992	0.983
Oder Bank (12 m)	26480	0.363	0.945	0.987	0.970	0.413	0.928	0.988	0.970	0.420	0.920	0.988	0.971	0.404	0.918	0.988	0.971
Trzebież	2190	–0.178	1.563	0.979	0.959	–0.161	1.481	0.982	0.963	0.018	1.505	0.981	0.962	–0.275	1.502	0.981	0.961
Ueckermünde	35855	–0.541	1.198	0.989	0.970	–0.530	1.198	0.989	0.970	–0.393	1.117	0.992	0.975	–0.445	1.101	0.992	0.975
Salinity (‰)																	
Oder Bank (3 m)	29465	1.119	0.803	0.669	–4.184	0.752	0.673	0.675	–1.785	0.698	0.682	0.671	–1.602	0.689	0.687	0.692	–1.586
Oder Bank (12 m)	25402	0.927	0.773	0.692	–10.438	0.540	0.587	0.656	–3.994	0.500	0.584	0.652	–3.641	0.512	0.597	0.659	–3.858
Międzyzdroje	2191	0.614	1.277	0.265	–1.879	0.398	1.263	0.207	–1.517	0.238	1.303	0.198	–1.516	0.139	1.354	0.206	–1.657

simulations. Further simulation (v2) with spatial spacing of 300 m applicable for the region of the Szczecin Lagoon allowed to achieve better agreement between empirical and numerical water temperatures only in Ueckermünde. The most recent version of the model (v3) produced high quality results for the majority of stations, as indicated by the lowest variability, highest correlation and highest effectiveness. The highest fit between the observed and the computed data was achieved for water temperature in the Oder Bank at a depth of 3 m. For all the stations, water temperature simulations were either slightly higher or lower as compared with the measured values. In rare cases, modelled and observed water temperatures differed by a few degrees; these differences could have been related to the meteorological forecast of the UMPL weather model that included the climatic sea temperature. Additionally, slightly higher standard deviations of differences between measurements and calculations as well as worse correlation obtained for Trzebież could be a result of inconsistent approximation of the Odra water temperature, which base on mean weekly air temperature.

With respect to salinity, the modification of the bathymetric grid of the southern Baltic (v1), resulted in a reduction of the salinity overestimation by an average of 0.22‰ in the coastal zone of the Pomeranian Bay and 0.4‰ on the Oder Bank (Table 1). Moreover standard deviations of differences between measurements and calculations decreased both for the coastal zone of the Bay and its open waters. Coefficients of effectiveness significantly increased in relation to the previous version but remained still negative. In version 2 (v2), the application of the high resolution grid to the Szczecin Lagoon resulted in a reduction of the salinity overestimation and

a rise in the coefficient of effectiveness. Further modification of the model in version 3 (v3) allowed to decrease salinity overestimation to a certain degree, however on the Oder Bank salinities remained still overestimated by an average of 0.51‰–0.69‰ as compared with the observations. The comparison of salinity simulations by the modified model and the actual measurements showed a better fit than that achieved by the previous versions of the model. In v3, the calculated correlation coefficients for the Oder Bank ranged from 0.659 to 0.692, 0.206 being the coefficient for Międzyzdroje. A lower variability and a better correlation between the observed and computed data was achieved for open waters of the Pomeranian Bay.

Application of the modified model to storm surge

In 2002–2007 at the Pomeranian Bay coasts, the alarm levels [≥ 80 cm above mean sea level (MSL = 500 cm at the tide gauge with respect to NN Amsterdam 1955)], as recorded in Świnoujście, were exceeded during 22 storm surges; the level of 100 cm above MSL was exceeded during 12 of them. The highest sea level of 143 cm above MSL was observed on 1 November 2006. In the Szczecin Lagoon (Trzebież), the alarm level (≥ 60 cm above MSL), was exceeded during 33 storm events. The highest level (97 cm above MSL) was observed on 25 January 2007. Most of the surges were recorded during November–February. The exceptionally mild ice winter 2006/2007 was the most stormy winter season during the period discussed; the level of 100 cm above MSL, as recorded in Świnoujście, was exceeded during 6 storm surges. In contrast, during the moderate ice winters 2002/2003 and 2005/2006 (Schmelzer *et al*. 2004, Schmelzer and Holfort 2009), the sea levels were remaining below the warning states. Occasionally, the warning level in the Szczecin Lagoon was exceeded.

Temporal variations of hydrodynamic conditions in the region, as approximated by the modified model, may be visualised for a case involving a heavy storm surge that occurred on 22–25 November 2004. During that event, the passage

Table 2. Frequencies (%) of water level forecast with error less than ±15 cm. *n* = number of data.

Station		Model version			
	n	v0	v1	v2	v3
Świnoujście	8715	89.5	91.8	90.1	91.2
Koserow	43151	91.1	93.4	93.3	93.3
Trzebież	8735	93.7	95.4	65.4	95.2
Ueckermünde	36495	89.4	90.4	80.4	95.1

of a deep low-pressure system was moving from the North Sea over the central part of the Baltic and then south-eastward (Fig. 2). Initially on 22 November, a decrease in sea level at the Pomeranian coastal stations was observed (Fig. 3a and b). The 21 and 22 November forecasts fairly accurately predicted the timing and extent of that drop (26 cm below MSL in Koserow and 29 cm below MSL in Świnoujście); only the 21 November forecast predicted the minimum with a 3-h lag. Then on 23 November, the sea level in the Pomeranian Bay increased rapidly up to 135 cm above MSL in Świnoujście and 131 cm above MSL in Koserow. That rise in the sea level was fairly accurately approximated by the 22 and 23 November forecasts. The analysed event also shows a good agreement between the empirical maximum timing and the extent of surge at the Pomeranian Bay coasts and the forecasts for 22 and 23 November; only the 22 November forecast slightly underestimated the maximum
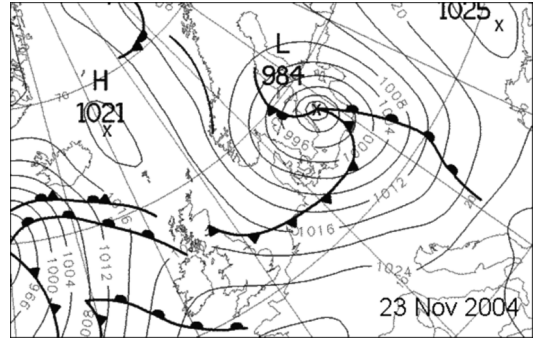
Fig. 2. Synoptic situation on 23 November 2004 (published with permission, ©British Crown copyright 2004, the Met Office).

values. The subsequent drop in the sea level over the following days was properly mimicked by the model. The forecasts accurately predicted also the occurrence time of the minimum values on 25 November, however the minimum levels of 51 cm below MSL in Świnoujście and 58 cm
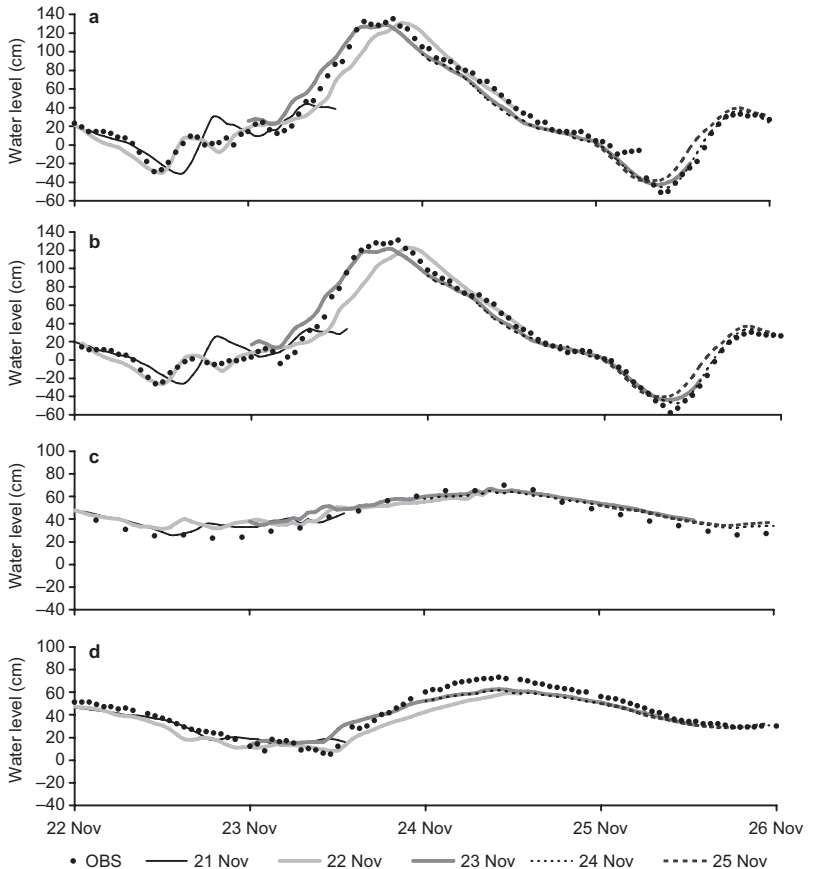

Fig. 3. Observed and predicted (60-h forecasts from 21, 22, 23, 24, and 25 Nov.) water level changes in (**a**) Świnoujście, (**b**) Koserow, (**c**) Trzebież and (**d**) Ueckermünde, during the November 2004 storm surge.
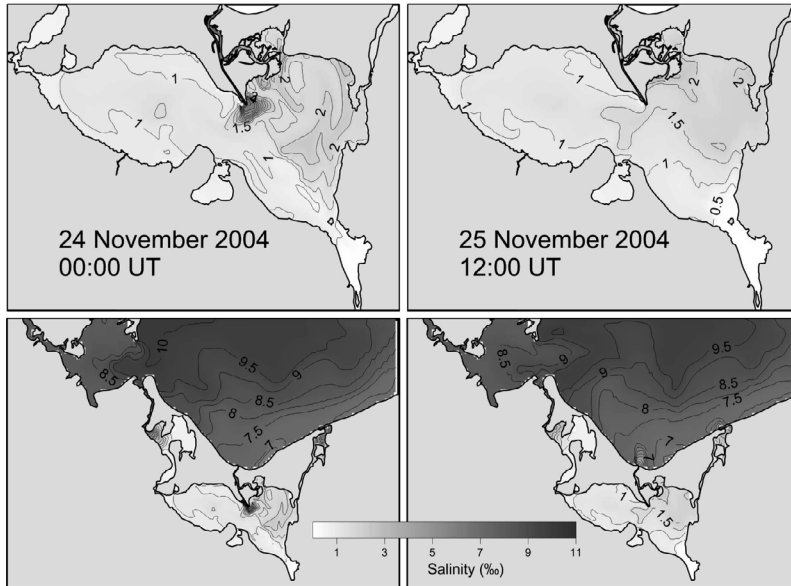
Fig. 4. Salinity (‰) during the November 2004 storm surge, as simulated with the M3D_UG model for the Pomeranian Bay and Szczecin Lagoon.

below MSL in Koserow were slightly overestimated by the model.

During that storm surge, the related Szczecin Lagoon water level fluctuations were weaker and delayed in time (Fig. 3c and d). At the beginning, the Lagoon water level decreased, the decrease being well approximated by the 22 and 23 November forecasts. Then, the subsequent rise in water level was also properly simulated by the model. On 24 November, the storm-surge-caused water level reached its maximum of 70 cm above MSL at Trzebież and 73 cm above MSL at Ueckermünde. The accuracy of the maximum water level prediction at these two gauging stations was good, however, the 23 and 24 November forecasts for Ueckermünde produced some underestimates. Over the following days, the observed drop of the water level was simulated by the model with high accuracy.

During the November 2004 storm surge, changes in other physical variables were recorded as well. On 23 November, the increase in the sea level and strong northerly winds resulted in the intrusion of brackish water from the Pomeranian Bay into the Szczecin Lagoon. The salinity simulations prepared for 23 and 24 November properly reflected the inflow by showing the presence of saline water in the northern, and then in the central parts of the Lagoon (Fig. 4). On 25 November, the decrease in the sea level under

the prevailing south-westerly winds caused the discharge of the Lagoon water into the Bay and spread of that water north-eastward off the Bay's coast. As compared with the measurements, the salinity predictions were very accurate in this respect; overestimates produced by the model did not exceed 0.5‰ on the Oder Bank and 0.6‰ at the coasts of the Wolin Island. On the other hand, the water temperature simulations reflected a typical autumn pattern with the continuous water cooling. The water temperature in the Bay was warmer than in the Lagoon by about 2.0–3.0 °C (Fig. 5). The agreement between the calculated water temperature and those measured in the Pomeranian Bay and the Szczecin Lagoon was very good; differences on average did not exceed ±1.0 °C. Only in Międzyzdroje the simulated water temperatures were about 0.8 °C higher than the measured values.

During 19–26 March 2007, another substantial storm surge at the Pomeranian Bay coasts was observed. It was a result of the passage of a low-pressure system from the Adriatic Sea over Romania and then over northern Poland (Fig. 6). Initially, on 19 March, the water level dropped along the Pomeranian Bay coasts to 64 cm below MSL in Świnoujście and to 63 cm below MSL in Koserow (Fig. 7a and b). The 19 March forecast overestimated slightly both values. Then, the sea level increased, the increase being well approxi-
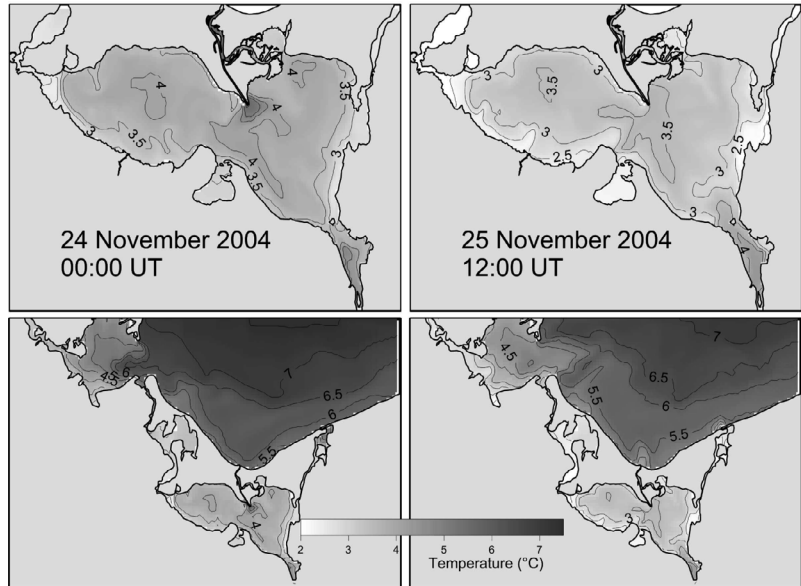
Fig. 5. Water temperature (°C) during the November 2004 storm surge, as simulated with the M3D_UG model for the Pomeranian Bay and Szczecin Lagoon.

mated by the forecasts from 19 and 20 March. On 21 and 22 March, the storm-surge-caused water levels reached their maximum heights. In Świnoujście, the timing of the maximum level of 86 cm above MSL, as calculated by the 20 and 21 March forecasts, was predicted with high accuracy, however, the model generated some overestimates. In Koserow, the observed maximum level of 99 cm above MSL was recorded during the night of 22 March. The 21 March forecast predicted that maximum fairly accurately, whereas the 20 March forecast produced some overestimates and approximated it some hours before the real maximum. Over the following days, the slow drop in the sea level at the Pomeranian Bay coast was reproduced fairly accurately by the model; however some underestimates were produced on 22 March at both gauging stations.

During the storm surge discussed, the Szczecin Lagoon stations showed weaker water level fluctuations that followed, with a delay, changes in the sea level. From 19 to 22 March, a constant increase of the water level until the maximum of 76 cm above MSL in Trzebież and 96 cm above MSL in Ueckermünde was observed (Fig. 7c and d). That phase of the storm surge was accurately reflected by the model. The timing and extent of maximum values as calculated by the 21 and 22 March forecasts were also
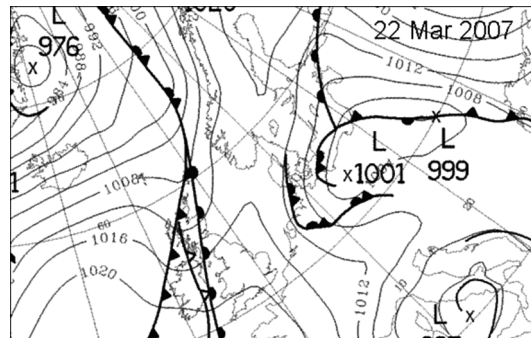

Fig. 6. Synoptic situation on 22 March 2007 (published with permission, ©British Crown copyright 2007, the Met Office).

predicted with a high accuracy, only for Ueckermünde the maximum level was underestimated by the 21 March forecast. During the next few days, a slow and gentle drop of the water level at the Lagoon gauging stations was very accurately mimicked by the model.

Due to the prolonged prevalence of southwesterly winds, the Lagoon waters entering the Pomeranian Bay through the Świna Strait were spreading eastwards along the Wolin Island coast (Fig. 8). Although salinity simulations accurately reflected the extent of the eastward spread of the Lagoon water, the model usually overestimated the measured values in the Bay by about 0.7‰–1.2‰. However, the storm-driven change
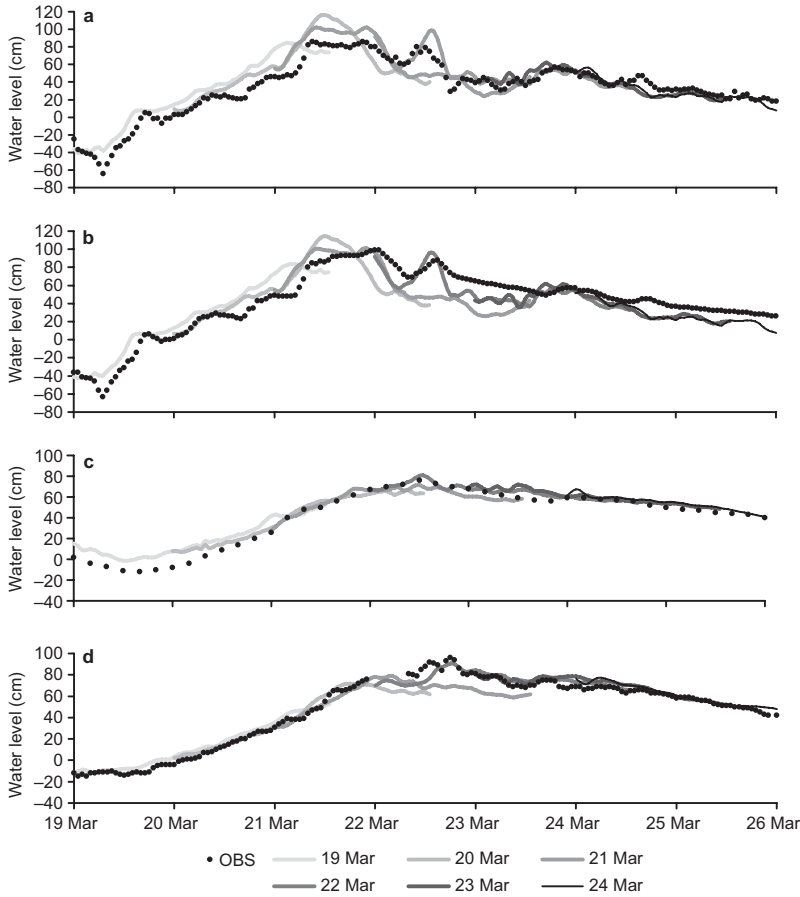
Fig. 7. Observed and predicted (60-h forecasts from 19, 20, 21, 22, 23 and 24 March) water level changes in (a) Świnoujście, (b) Kose-row, (c) Trzebież and (d) Ueckermünde, during the March 2007 storm surge.
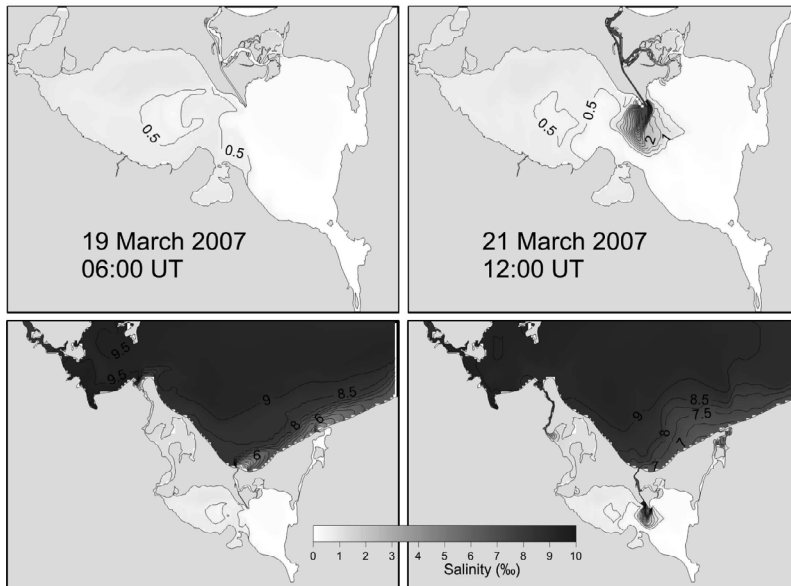

Fig. 8. Salinity (‰) during the March 2007 storm surge, as simulated with the M3D_UG model for the Pomeranian Bay and Szczecin Lagoon.
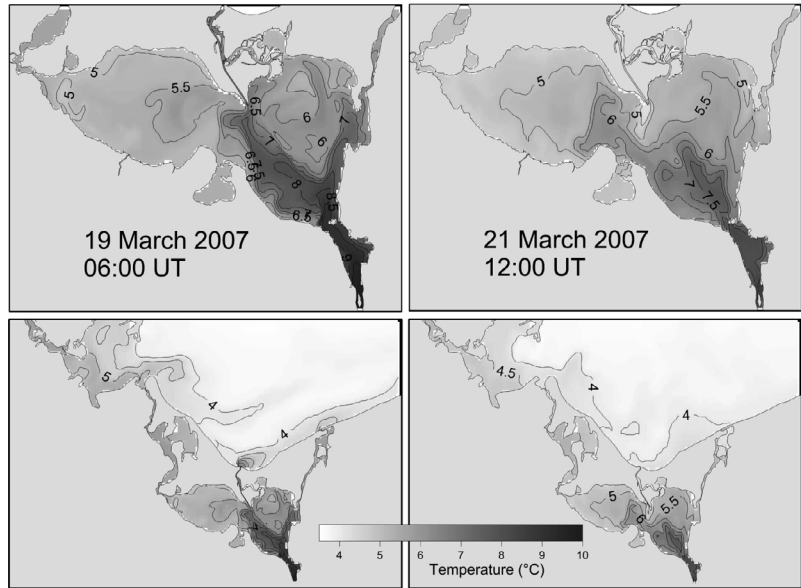
Fig. 9. Water temperature (°C) during the March 2007 storm surge, as simulated with the M3D_UG model for the Pomeranian Bay and Szczecin Lagoon.

in wind direction to the northeast forced the sea water intrusion into the Świna Bay, which was clearly reflected by the model in the simulation of 20 March. During the next two days salinity simulations precisely predicted the inflow in the Szczecin Lagoon by indicating the presence of saline water in the northern and then in the central parts of the Lagoon. On 23 March, the change of wind direction to the east and the related sea level drop at the Pomeranian Bay coast resulted in the discharge of the Lagoon water into the Bay and the spread of this water along the coast of Usedom Island. As compaed with the measurements, during the storm surge discussed the model usually overestimated the measured values by an average of 0.8‰ on the Oder Bank and by about 1.1‰ at the Pomeranian Bay coasts. On the other hand, the water temperature forecasts reflected a typical spring pattern with continuous water warming and increasing impact of the warmer and fresh Odra River water that first entered the Szczecin Lagoon and was then discharged to the Pomeranian Bay via the Świna, Dziwna, and Peenestrom (Fig. 9). The 21 and 22 March water temperature simulations showed an intrusion of colder, brackish waters into the Lagoon as well. During the storm surge, the simulated water temperatures on the Oder Bank and in Międzyzdroje were on average 0.4 °C lower than the measured values while

in Koserow were accurate in this respect. In the Szczecin Lagoon, water temperatures were overestimated by the model, by an average of 0.3 °C in Ueckermünde and 1.5 °C in Trzebież.

Conclusions

In this study, we used a modified version of the hydrodynamic model of the Baltic Sea (M3D_UG) to describe hydrodynamic conditions during the 2002–2007 storm surges in the Pomeranian Bay and the Szczecin Lagoon. We applied a more accurate bathymetric map of the Pomeranian Bay. We also reduced the spatial spacing for the Szczecin Lagoon to about 300 m to improve the description of the modelled area's bathymetry, particularly to reflect the true dimensions of the narrow straits connecting the Szczecin Lagoon with the Pomeranian Bay.

The statistical parameters applied in the analysis made it possible to estimate the degree of improvement of the modified model's quality. With respect to the water level series, results of the correlation analysis showed the high resolution grid for the Szczecin Lagoon resulted in an initial decrease of the correlation between the measured and observed data. Because the water exchange through the straits connecting the Lagoon with the Bay was reduced too much

in the model, frequency of the water level forecast with the estimated error of less than ±15 cm decreased as well. A further modification of the bathymetry grid and the shoreline allowed to improve the agreement between the predicted and observed water levels. Validation of the most recent version of the model revealed an improvement of its performance for both the Pomeranian Bay and the Szczecin Lagoon; with over 90% of all the forecasts differing from the readings no more than ±15 cm. The model performed slightly better in the Lagoon than in the Bay where water level variations are much greater.

The model produced a very good representation of water temperature. Although the simulations produced by the previous version of the model were very faithful, the modified version produced even better results, as indicated by the statistical descriptors used to assess the model's performance. With respect to salinity, first modification of the numerical bathymetry of the Baltic resulted in a reduction of the salinity overestimation, particularly in the Pomeranian Bay. Further modification of the model (involving a high-resolution grid in the Szczecin Lagoon) produced better approximation of the true bathymetry, which reduced the overestimation of both the water exchange between the two areas and the salinity in the Szczecin Lagoon. Salinity was better simulated in the offshore than in the inshore part of Bay, the inshore part being characterised by more dynamic mixing of fresh and saline waters.

Comparisons between the observed water levels, temperatures, and salinities on the one hand and those calculated by the modified model during storm surges showed an improved fit, relative to the previous version of the model. When the water level varied extensively, and when physical properties of the water changed rapidly (e.g., as observed during the storm surges discussed in detail), the model described the rapid water level fluctuations correctly and satisfactorily reflected coastal processes (i.e., the influx of saline Pomeranian Bay's water into the Szczecin Lagoon and the Lagoon water plume in the Bay). The high quality of simulations generated by the modified model allowed applying the spatial spacing of about 300 m for the Szczecin Lagoon in the operational version of the model, too.

Since the model is well suited for forecasting hydrodynamic conditions in the Pomeranian Bay and the Szczecin Lagoon, a fast online access to the daily 60-h hydrodynamic forecast (http://model.ocean.univ.gda.pl) offers an opportunity to predict the extent of processes that may cause problems to inhabitants of the coastal areas. Therefore, it is intended to fine-tune the model to improve its prognostic reliability; the work carried out at present focuses on assimilation of sea level data from coastal stations, water temperatures and salinities from measuring buoys, and sea surface temperatures from satellite images.

References

Andrejev O., Myrberg K., Alenius P. & Lundberg P.A. 2004. Mean circulation and water exchange in the Gulf of Finland — a study based on three-dimensional modelling. *Boreal Env. Res.* 9: 1–16.

Averkiev A.S. & Klevanny K.A. 2007. Determining cyclone trajectories and velocities leading to extreme sea level rises in the Gulf of Finland. *Russ. Meteorol. Hydrol.* 32: 514–519.

Blumberg A.F. & Mellor G.L. 1987. A description of a three-dimensional coastal ocean circulation model. In: Heaps N.S. (ed.), *Three-dimensional coastal ocean models*, Am. Geoph. Union, pp. 1–16.

Buchholz W. 2009. The Oder estuary — hydrological, hydraulic and developmental considerations. *Polish J. Environ. Stud.* 18: 26–34.

Dick S., Kleine E., Müller-Navarra S.H., Klein H. & Komo H. 2001. *The operational circulation model of BSH (BSHcmod) — Model description and validation.* BSH Reports 29, Rostock, Hamburg.

Eigenheer A. 1999. Quality assessment of the HIROMB simulation. *Bull. Maritime Inst. Gdańsk* 26: 27–37.

Ewertowski R. 1988. Mathematical model of the Odra estuary. *AIPCN-PIANC Bull.*, Bruxelles 60: 95–114.

Filinkova O., Ivanov G., Klevanny K. & Müller-Navarra S. H. 2002. Comparison of observed water levels and BSHcmod model forecasts in the eastern Gulf of Finland. *Environ. Chem. Phys.* 24: 198–205.

Funkquist L. 2001. HIROMB, an operational eddy-resolving model for the Baltic Sea. *Bull. Maritime Inst. Gdańsk* 29: 7–16.

Gästgifvars M., Müller-Navarra S., Funkquist L. & Huess V. 2008. Performance of operational systems with respect to water level forecasts in the Gulf of Finland. *Ocean Dynamics* 58: 139–153.

Herman-Iżycki L., Jakubiak B., Nowiński K. & Niezgódka B. 2002. UMPL — numerical weather prediction system for operational applications. In: Jakubiak B. (ed.), *Research works based on the ICM's UMPL numerical weather prediction system results*, Wyd. ICM,

Warszawa, pp. 14–27.

Jasińska E., Robakiewicz M. & Staśkiewicz A. 2003. Hydrodynamic modelling in the Polish zone of the Baltic Sea — an overview of Polish achievements. *Oceanologia* 45: 107–120.

Jasińska E. & Massel S.R. 2007. Water dynamics in estuaries along the Polish Baltic coast. *Oceanol. Hydrobiol. Stud.* 36: 101–133.

Jensen J. & Müller-Navarra S.H. 2008. Storm surges on the German Coast. *Die Küste* 74: 92–124.

Jędrasik J. 1997. A model of matter exchange and flow of energy in the Gulf of Gdańsk ecosystem — overview. *Oceanol. Stud.* 26: 3–20.

Jędrasik J., Cieślikiewicz W., Kowalewski M., Bradtke K. & Jankowski A. 2008. 44 years hindcast of the sea level and circulation in the Baltic Sea. *Coastal Eng.* 55: 849–860.

Kałas M., Staśkiewicz A. & Szefler K. 2001. Water level forecast for the Pomeranian Bay from the HIROMB Model. *Oceanol. Stud.* 30: 39–57.

Kowalewska-Kalkowska H. & Kowalewski M. 2005. Operational hydrodynamic model for forecasting extreme hydrographic events in the Oder Estuary. *Nordic Hydrol.* 36: 411–422.

Kowalewska-Kalkowska H. & Kowalewski M. 2006. Hydrological forecasting in the Oder Estuary using a three-dimensional hydrodynamic model. *Hydrobiologia* 554: 47–55.

Kowalewska-Kalkowska H. & Kowalewski M. 2007. Modeling water exchange in the Oder River mouth area. *Oceanol. Hydrobiol. Stud.* 36: 55–67.

Kowalewska-Kalkowska H. & Wiśniewski B. 2009. Storm surges in the Odra mouth area during the 1997–2006 decade. *Boreal Env. Res.* 14: 183–192.

Kowalewski M. 1997. A three-dimensional, hydrodynamic model of the Gulf of Gdańsk. *Oceanol. Stud.* 26: 77–98.

Kowalewski M. 2002. An operational hydrodynamic model of the Gulf of Gdańsk. In: Jakubiak B. (ed.), *Research works based on the ICM's UMPL numerical weather prediction system results*, Wyd. ICM, Warszawa, pp. 109–119.

Kowalewski M. & Ostrowski M. 2005. Coastal up- and downwelling in the southern Baltic. *Oceanologia* 47: 453–475.

Krężel A. 1997. A model of solar energy input to the sea surface. *Oceanol. Stud.* 26: 21–34.

Lass H.U., Mohrholz V. & Seifert T. 2001. On the dynamics of the Pomeranian Bight. *Cont. Shelf Res.* 21: 1237–1261.

Majewski A. 1980. *Zalew Szczeciński*. Wyd. Kom. i Łącz., Warszawa.

Majewski A., Dziadziuszko Z. & Wiśniewska A. 1983. *Monografia powodzi sztormowych 1951–1975*. Wyd. Kom. i Łącz., Warszawa.

Mikulski Z. 1970. Wody śródlądowe w strefie brzegowej południowego Bałtyku. *Prace PIHM* 98: 25–41.

Mohrholz V. & Lass H.U. 1998. Transports between Oder-haff and Pomeranian Bight — a simple barotropic box model. *Dtsch. Hydrogr. Z.* 50: 371–383.

Mohrholz V., Pastuszak M., Sitek S., Nagel K. & Lass H.U. 1998. The exceptional Oder flood in summer 1997 — riverine mass and nutrient transport into the Pomeranian Bight. *Dtsch. Hydrogr. Z.* 50: 129–143.

Rosenthal W., Wolf T., Witte G., Buchholz W. & Rybaczok P. 1998. Measured and modelled water transport in the Odra Estuary for the flood period July/August 1997. *Dtsch. Hydrogr. Z.* 50: 215–230.

Schmelzer N., Strübing K., Stanisławczyk I. & Sztobryn M. 2004. *Die Eiswinter 1999/2000 bis 2003/2004 an der deutschen Nord- und Ostseeküste. Ice conditions in the Szczecin Lagoon and Pomeranian Bay during the winters 1999–2002*. BSH Reports 37, Hamburg, Rostock.

Schmelzer N. & Holfort J. 2009. *Eiswinter 2004/2005 bis 2008/2009 an den deutschen Nord- und Ostseeküsten. Ice Winters 2004/05 to 2008/09 on the German North and Baltic Sea Coasts*. BSH Reports 46, Hamburg, Rostock.

Siegel H., Seifert T., Schernewski G., Gerth M., Ohde T., Reißmann J. & Podsetchine V. 2005. Discharge and transport processes along the German Baltic Sea Coast. *Ocean Dynamics* 55: 47–66.

Sokolov A., Andrejev O., Wulff F. & Rodriguez Medina M. 1997. *The data assimilation system for data analysis in the Baltic Sea*. Systems Ecology Contributions 3, Stockholm University.

Stanisławczyk I. 2002. Validation of HIROMB model using an extreme hydrometeorological event. *Environ. Chem. Phys.* 24: 168–170.

Stigge H.-J. 1994. Die Wasserstände an der Küste Mecklenburg-Vorpommerns. *Die Küste* 56: 1–24.

Suursaar Ü., Kullas T. & Otsmann M. 2002. A model study of the sea level variations in the Gulf of Riga and the Väinameri Sea. *Cont. Shelf Res.* 22: 2001–2019.

Suursaar Ü., Kullas T., Otsmann M. & Kõuts T. 2003. Extreme sea level events in the coastal waters of western Estonia. *J. Sea Res.* 49: 295–303.

Suursaar Ü., Kullas T., Otsmann M., Saaremäe I., Kuik J. & Merilain M. 2006. Cyclone Gudrun in January 2005 and modelling its hydrodynamic consequences in the Estonian coastal waters. *Boreal Env. Res.* 11: 143–159.

Sztobryn M., Stigge H.-J., Wielbińska D., Weidig B., Stanisławczyk I., Kańska A., Krzysztofik K., Kowalska B., Letkiewicz B. & Mykita M. 2005. *Storm surges in the southern Baltic Sea (western and central parts)*. BSH Reports 39, Hamburg, Rostock.

Węglarczyk S. 1998. The interdependence and applicability of some statistical quality measures for hydrological models. *J. Hydrobiol.* 206: 98–103.

Zeidler R., Wróblewski A., Miętus M., Dziadziuszko Z. & Cyberski J. 1995. Wind, wave, sea level and storm surge regime at the Polish Baltic coast. *J. Coastal Res.* 22: 33–54.