Operational hydrodynamic model for forecasting extreme hydrographic events in the Oder Estuary*

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Abstract A 3D operational hydrodynamic model, developed at the Institute of Oceanography, University of Gdansk, was used to forecast extreme hydrographic events in the Oder Estuary. The model was based on the coastal ocean circulation model known as the Princeton Ocean Model (POM); it was adapted to Baltic conditions and to a 48-h numerical meteorological forecast. Wind-driven water backup in the Oder mouth necessitated working out a simplified operational model of river discharge, based on water budget in a stream channel. The model generates 60-h forecasts of water levels, currents, water temperature and salinity in the estuary. As the model adequately approximates hydrographic variability in the estuary, it can be regarded as a reliable tool for storm surges forecasting and for the assessment of Oder water spread in the Baltic. The forecast is rapidly accessed on its designated website, thereby providing assistance in decision-making by emergency situation centres and bodies that are responsible for navigation safety, port operation and environmental and flood protection of coastal areas. It is intended to fine-tune the model so that a better fit between the observed and computed data is obtained.

Keywords Extreme hydrographic events; hydrodynamic model; Princeton Ocean Model; the Oder Estuary

Introduction

The Pomeranian Bay (southern Baltic Sea) sea level shows a substantial variability, resulting from an overlap of various types of periodic oscillations and non-periodic fluctuations. The latter, particularly those related to passages of deep and intense low-pressure systems that may produce 1.0–2.0 m high local storm surges and 0.5–1.5 m deep storm falls, are most dangerous for the navigation safety and for the stability of the sea coast and beaches. The fluctuations in question are caused by wind activity and changes in atmospheric pressure on the sea surface, as shown by Wisniewski *et al.* (2000). Wind and wave may be additive in their effects, i.e. they act in concert to increase or decrease the sea level on the coast, or their effects may be non-additive, as when one factor produces a sea level increase while the action of the other results in a decrease. Along the Polish coast, a dynamic influence of air pressure is particularly strong in the eastern sector of the low, whereas in the western sector a high sea level is mainly a result of an increasing wind activity. Such a complex nature of meteorological effects renders forecasting sea level fluctuations very difficult, particularly in the coastal zone where influences of additional factors should be taken into account as well.

The Pomeranian Bay, a shallow and exposed part of the southern Baltic, is affected by the mixing of fresh and brackish waters. The Oder River, its effluent initially buffered in the Szczecin Lagoon, drains into the Baltic coastal zone via three straits: the Swina, the Dziwna,

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and the Peenestrom. The water exchange via the Swina accounts for three quarters of the total exchange between the lagoon and the sea. The shipping channel running across the lagoon has a great impact on the water circulation in the Oder mouth (Majewski 1974, 1980; Robakiewicz 1993). The water circulation in the Pomeranian Bay is mainly wind-driven. During westerly winds, the coastal current transports the lagoon water, in a narrow band, eastwards. During prolonged domination of the easterlies, advection associated with the Ekman offshore transport moves the Szczecin Lagoon water offshore, thereby causing the Bay's water to upwell in the inshore zone. On entering the Pomeranian Bay, the newly discharged lagoon water spreads along the coast of the Usedom Island (Lass *et al.* 2001). As the Oder River is one of the most polluted rivers entering the Baltic Sea, an accurate forecast of the Oder water dispersal is important for tourism and the functioning of seaside resorts situated along the inner, and particularly outer, coasts of the Oder Estuary.

Numerical modelling has become an essential tool in coastal management as well as environmental and flood protection in the Oder Estuary. The complex hydrodynamic regime of the downstream Oder River was studied by, for example, Buchholz (1989) and Ewertowski (1988, 2000). The hydrodynamic regimes of the Szczecin Lagoon and Pomeranian Bay have been mostly described by 3D models, such as ESTURO (Jasinska and Robakiewicz 1999) and the Warnemünder Ostee Model (WOM) based on the Geophysical Fluid Dynamics Laboratory (GFDL) ocean circulation model (Lass *et al.* 2001). On the other hand, Mohrholz and Lass (1998) analysed water exchange between the Szczecin Lagoon and the Pomeranian Bay by applying a simple barotropic box model.

Marine weather and hydrography forecasts are essential for different areas of human life and activities within the Baltic Sea region. The High Resolution Operational Model for the Baltic Sea (HIROMB) model was developed at the Bundesamt für Seeschifffahrt und Hydrographie (BSH) in Hamburg (Germany) and subsequently extended in cooperation with the Swedish Meteorological and Hydrological Institute (SMHI) in Norrköping (Sweden) (Kleine 1994; Eigenheer 1999; Funkquist 2001). It is now run operationally by the SMHI (http://www.smhi.se/oceanografi/oce_info_data/models/hiromb.htm). HIROMB forecasts water levels, currents, salinity and temperature as well as ice thickness, ice concentration and ice drift over the whole Baltic Sea and in its individual parts. The Maritime Institute in Gdansk (Poland) extended the model onto the Polish zone of the Baltic (Kalas *et al.* 2001). At present, the Maritime Branch of the Institute of Meteorology and Water Management (IMWM) in Gdynia (Poland) issues an online daily hydrographic forecast for the southern Baltic Sea (http://baltyk.imgw.gdynia.pl/hiromb/). In Denmark, the Centre for Marine Forecasting at Danish Meteorological Institute (DMI) (http://ocean.dmi.dk/DMI-CMF.htm) supplies daily forecasts of sea current, temperature, salinity and sea ice using the BSH-Cmod (provided to DMI by BSH) and issues storm surge predictions using Mike 21 (provided to DMI by the Danish Hydraulic Institute for Water and Environment, i.e. DHI Water & Environment). Marine forecasts concerning, for example, water level, currents, water temperature and salinity are also supplied by the DHI Water & Environment; available at http://www.waterforecast.com as well.

3D operational hydrodynamic model of the Baltic sea

In this study, a 3D operational hydrodynamic model, developed at the Institute of Oceanography, University of Gdansk (Poland), was applied to forecast extreme hydrographic conditions in the Oder Estuary. Theoretical and numerical solutions of the model were based on the coastal ocean circulation model known as the Princeton Ocean Model (POM), described in detail by Blumberg and Mellor (1987) and Mellor (1996). Adaptation of the model to the Baltic Sea required certain changes in the numerical calculation algorithm, as described in detail by Kowalewski (1997). The open boundary was located between the Kattegat and the Skagerrak to parametrise water exchange between the North and the Baltic Seas. A radiation boundary condition was applied to average vertical flows. If the instantaneous free surface elevation is higher than the pre-set value, the water flows out from the Baltic and the outflow is proportional to the difference between those values. When the sea level in Kattegat is lower, the inflow of water from Skagerrak occurs.

The data inputs necessary for the hydrodynamic model of the Baltic Sea are derived from the operational weather model, the solar radiation model and the model of the Oder discharge (Kowalewska-Kalkowska and Kowalewski 2004). Meteorological data are supplied by the mesoscale operational weather model known as the Unified Model for Poland Area (UMPL), developed by the Interdisciplinary Centre of Mathematical and Computational Modelling, University of Warsaw (Herman-Izycki *et al.* 2002). The solar energy input is calculated for each time step on the basis of astronomical data and meteorological conditions (Krezel 1997). The remaining components of the heat budget on the sea surface are derived from meteorological data and simulated sea surface temperatures (Jedrasik 1997). The climatic monthly mean runoffs of 153 rivers discharging into the Baltic are supplied by the Baltic Environmental Database (BED, http://data.ecology.su.se/models/bed.htm). The initial conditions for hydrodynamic fields were based on the climate temperature and salinity distributions in the Baltic Sea. After the model had been activated, temperature and salinity variations were affected only by the time-dependent changes in meteorological conditions and river inflows, i.e. no hydrological data assimilation was performed. The 3D distributions of water temperature and salinity were prepared using the Data Assimilation System (Sokolov *et al.* 1997) based on the BED data for 1970–1994.

The wind-driven water backup in the Oder mouth necessitated developing a simplified operational model of river discharge, based on water budget in a stream channel (Kowalewska-Kalkowska and Kowalewski in press). Discharge calculations are performed automatically by using water level data from gauging stations along the downstream section of the Oder, available at the IMWM website (http://www.imgw.pl/wl/internet/hydro/biuletyn.jsp).

Two grids with different spatial steps were applied to obtain an adequate resolution and reliable data: one involved 5 nautical mile (nmile) long steps for the entire Baltic Sea, the steps in the other being 0.5 nmile long, applicable to the region that comprises the Pomeranian Bay and the Szczecin Lagoon upstream to Police at the Oder mouth (Figure 1). Calculations run parallel for the two areas, information being exchanged on the common boundary on each common time step.

The 3D hydrodynamic model of the Baltic Sea has been generating time series of water levels, currents, water temperature and salinity for the southern Baltic Sea and the Gulf of Gdansk since 1999. Linking the Oder discharge model with the model of the Baltic Sea into a single system made it possible to also operationally simulate hydrographic conditions for the Pomeranian Bay and the Szczecin Lagoon. Current results of the model are placed daily on the University of Gdansk website (http://model.ocean.univ.gda.pl) as maps of 60-h forecasts of water level, currents, water temperature and salinity for the Pomeranian Bay and the Szczecin Lagoon.

Verification of the model

The model was verified on the basis of observed and calculated data sets for water level, currents, water temperature and salinity in the Oder Estuary, including the southern part of the Pomeranian Bay, the Oder Bank and the Szczecin Lagoon. The routine observed data sets

Figure 1 Regions modelled: the Baltic Sea and Oder Estuary, with station location

for 2002 were obtained from the Szczecin- Swinoujscie Harbour Master's Office and from IMWM as well as from the BSH website. At first, standard statistical parameters were calculated for a given set of observations and numerical simulations. Then, regression analysis and Student's *t* tests for paired averages, as well as the *F* test for two variances, were run to assess the fit between empirical and predicted data series at the significance level of $\alpha = 0.05$.

With respect to the water level series, the correlation between the observed and the predicted data sets was very high both for the Pomeranian coastal gauging stations (Koserow and Swinoujscie) and the Lagoon ones (Trzebiez and Ueckemuende). The best agreement was achieved for the 0-h forecast, but correlation coefficients higher than 0.88 for all the predictions were indicative of high statistical significance (Figure 2). The highest correlation between the observed and the computed data was that at the Trzebiez gauging station. The best fit between average values was obtained for Swinoujscie where the largest underestimation concerned the 12-h forecast (the modelled mean was lower by 1.1 cm than that calculated for the observed data). It was at Trzebiez only that mean values were overestimated, the modelled averages being from 2.5 cm (a 0-h forecast) to 4.3 cm (a 48-h forecast) higher than those actually recorded. With respect to the extreme values, the model generally underestimates the minimum values and overestimates the maxima. Higher differences were visible in data for the Pomeranian Bay stations, compared to those for the Lagoon. The coefficients of variation ranged from 0.03–0.05, the lowest values being those produced by the 0-h forecasts. It should be mentioned that numerical data are relative only, that is, due to the imperfection of the coastal conditions applied to the open boundary in the Skagerrak and Kattegat, it is difficult to refer them to the average sea level. If the constant sea

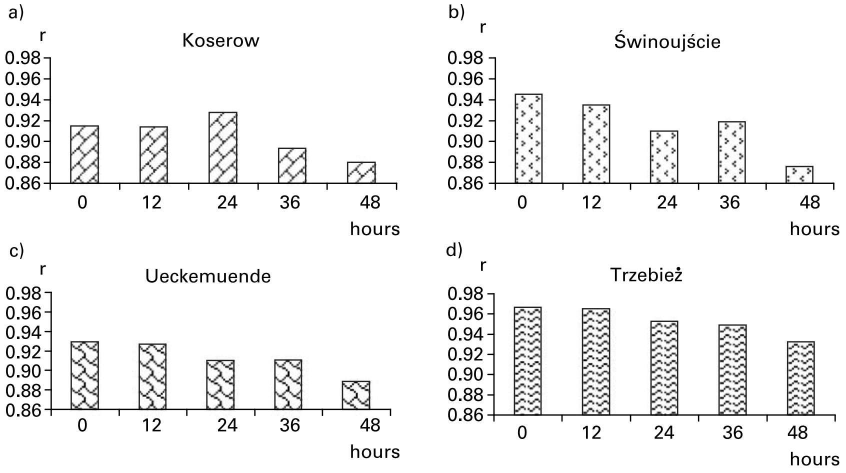

Figure 2 Correlation coefficients (*r*) of correlations between observed and predicted (0- to 48-h forecasts) water levels at individual gauging stations

level were replaced by varying water levels observed at the coastal stations in the vicinity of the open boundary, the prognostic accuracy of the surface elevation would be improved, thus making it possible to calculate the absolute sea levels, for example in relation to "NN Amsterdam 1955".

A very good agreement was also obtained in water temperatures. The correlation coefficients between the empirical and the numerical data sets, both for the Pomeranian Bay and the Lagoon stations, exceeded 0.98, revealing a high statistical significance. Moreover, the modelled mean values were only lower by 0.2–0.9°C than those calculated for the observed data. The lowest underestimation of averages was achieved for the 0-h forecasts. A higher variability was observed at coastal stations.

The observed and calculated salinity values showed a poorer fit; however, the correlation coefficients were statistically significant. On the Oder Bank for the salinity at a depth of 3 m, they ranged from 0.521–0.622, a range of 0.565–0.676 being obtained at 12 m. The model overestimated the mean values by 0.3–0.5 psu. Extreme values were overestimated as well. A lower variability was obtained for the depth of 12 m. The differences between the observed and calculated salinity values could have been brought about by the initial conditions for the hydrodynamic fields. Salinity and temperature distributions calculated by the preceding forecast were used to reinitialise the model and to calculate the next forecast.

Application of the model to forecasting extreme events

The good fit between the observed and predicted data was an incentive for checking the accuracy of the model on storm surges that occurred in 2002. A substantial storm surge on the southern Baltic coast, lasting from 19–27 February 2002, was a result of a passage of a deep low-pressure system over the Baltic. Initially, a decrease in water level at the Pomeranian coastal stations was observed on 19 February (Figures 3(a) and (b)). The 18 and 19 February forecasts of that drop for Koserow and Swinoujscie correctly approximated its timing and extent (472 cm in Swinoujscie and 476 cm in Koserow). Beginning on 20 February, the sea level began to rise to reach the maximum on 21 February as a result of the low centre's shift over the southern Baltic. The maximum values (668 cm in Koserow and 635 cm in Swinoujscie) were also predicted with a high accuracy, but the Koserow maximum

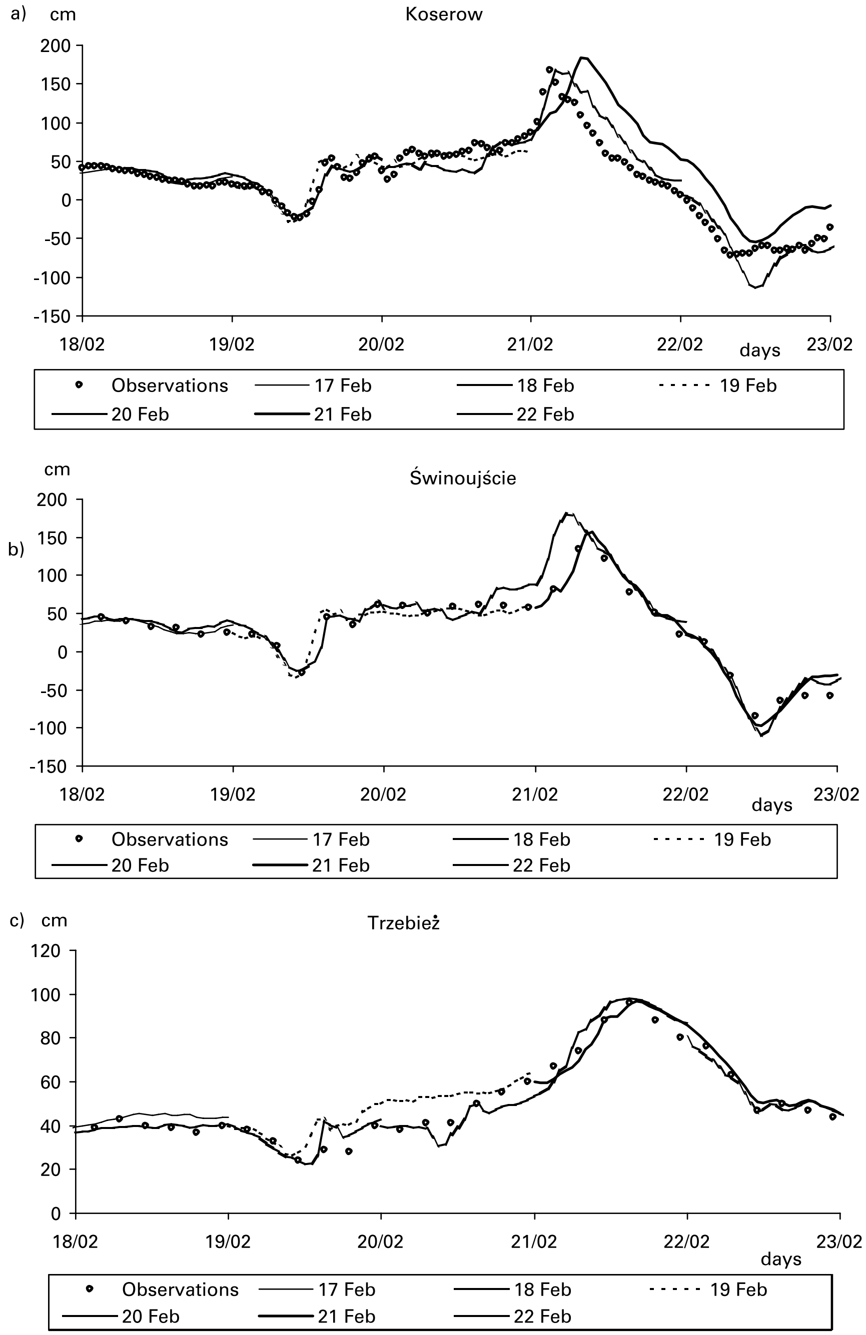

Figure 3 Observed and predicted water level changes in Koserow (a), Swinoujscie (b) and Trzebiez (c), during the storm surge in February 2002; Legend: forecasts of 17, 18, 19, 20, 21, and 22 February

was predicted, by the 20 February forecast, to happen 3 h after the real maximum, and – by the 21 February forecast – 5 h after. On the other hand, the maximum in Swinoujscie was predicted, by the 20 February forecast, to occur 2 h before the real maximum, while the 21 February forecast predicted it to happen 2 h after it. The rapid drops of sea level in Swinoujscie and Koserow to 415 and 428 cm, respectively, on 22 February, resulting from the shift of the low over Scandinavia, were also approximated well. The timing and extent of the minimum in Swinoujscie were very accurately predicted. In Koserow, the minimum was calculated with a 4-h lag by both forecasts (21 and 22 February). In addition, the 22 February forecast underestimated the minimum.

During the storm surge discussed, the Szczecin Lagoon stations showed much weaker water level fluctuations that followed, with a delay, changes in the sea level. From 19–21 February, a constant increase of the water level until the maximum of 596 cm (Trzebiez) was observed. That maximum occurred 8 h after the sea level maximum was recorded at the Pomeranian Bay stations. The forecasts of both 20 and 21 February accurately predicted that phase of the storm in terms of the timing and the amplitude of the surge (Figure 3(c)). During the next few days, the ensuing decrease of the water level in the Oder Estuary was also accurately predicted by the model. Figure 4 illustrates the 3D operational numerical model prediction of water level changes in the Pomeranian Bay and the Szczecin Lagoon during the February storm surge.

During the February 2002 storm, changes in other physical variables were recorded as well. The 19 and 20 February forecasts accurately predicted the extent of the eastward spread of the Lagoon water along the Wolin Island coast, caused by the prolonged prevalence of the westerlies (Figure 5); however, the predicted values were underestimated by about 1.0 psu at Miedzyzdroje. The following day, the reversed slope of the free surface of water caused the inflow of brackish water from the Pomeranian Bay into the Szczecin Lagoon. Salinity simulations of 21 and 22 February clearly predicted the inflow by indicating the presence of saline water in the central part of the Szczecin Lagoon. The salinity on the coasts of Wolin Island, predicted on 21 and 22 February, was overestimated by about 1.0 psu. During the storm, the calculated water temperatures along the Wolin Island and Szczecin Lagoon coasts

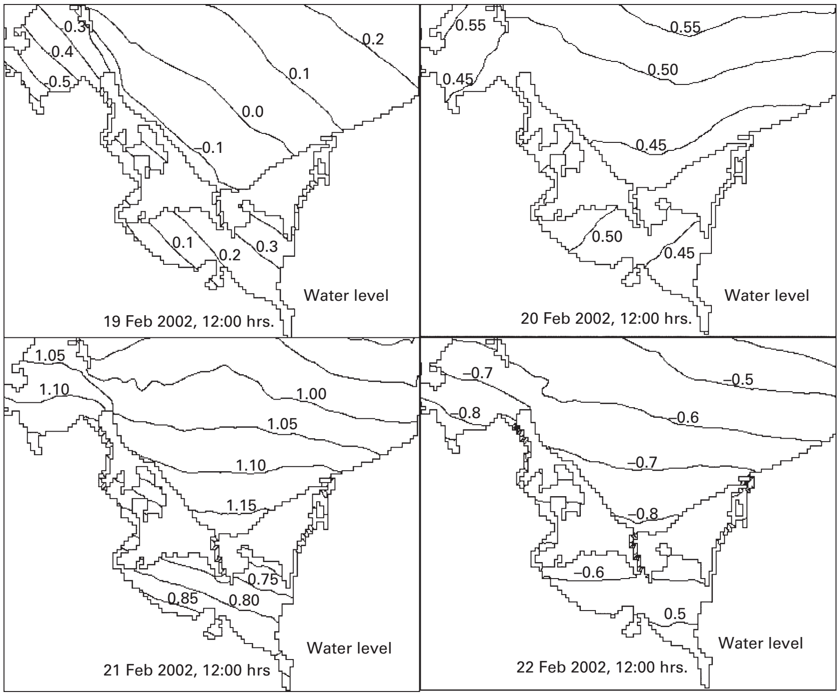

Figure 4 Water levels during the storm surge in February 2002, as simulated with the 3D operational numerical model of the Oder Estuary (slope of the free surface of water in metres)

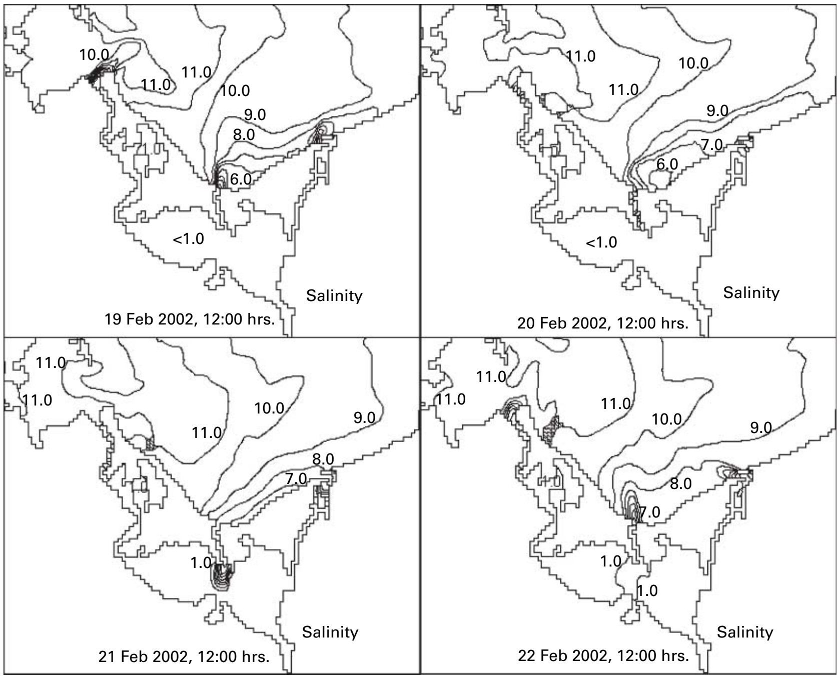

Figure 5 Salinity (psu) during the storm surge in February 2002, as simulated with the 3D operational numerical model of the Oder Estuary

was about 1.0°C higher and about 1.0°C lower, respectively, than those subsequently shown by actual measurements.

During 20–27 March 2002, another low-pressure system passed over the Baltic Sea and caused a storm surge on its southern coasts. Initially, on 20 March, the water level dropped along the Pomeranian Bay and the Lagoon coasts. The forecasts of 19 and 20 March (Figures 6(a) and (b)) overestimated that minimum (511 cm in Swinoujscie and 507 cm in Koserow). Then, the sea level increased, the increase being well approximated by the forecasts of 21 and 22 March. On 23 March, the storm-surge-caused water level reached its maximum of 590 cm in Koserow and 597 cm in Swinoujscie. The agreement between the empirical maximum timing and extent of the surge and the forecasts of 22 and 23 March was good; however, the 23 March forecasts approximated the maximum values more accurately. They were underestimated slightly by the 22 March forecasts, whereas the 23 March predictions produced some overestimates at both gauging stations. The continuing drop in sea level over the following days was accurately predicted by the model.

During that storm surge, the Szczecin Lagoon water level fluctuations were weaker and were accurately predicted by the model. At the beginning, as in the coastal Pomeranian Bay stations, the 19–21 March forecasts overestimated the water level drop during the night of 20 March when 531 cm was recorded at Trzebiez (Figure 6(c)). Then, the subsequent increase in Lagoon water level, occurring with a time lag relative to the sea level maximum in Swinoujscie, was well approximated by the 22 and 23 March forecasts. The accuracy of the maximum water level prediction at Trzebiez (588 cm during the night of 23 March) was also good. During the next few days, the ensuing drop of the water level was accurately simulated by the model. Figure 7 illustrates all the storm phases as predicted by the 3D operational numerical model.

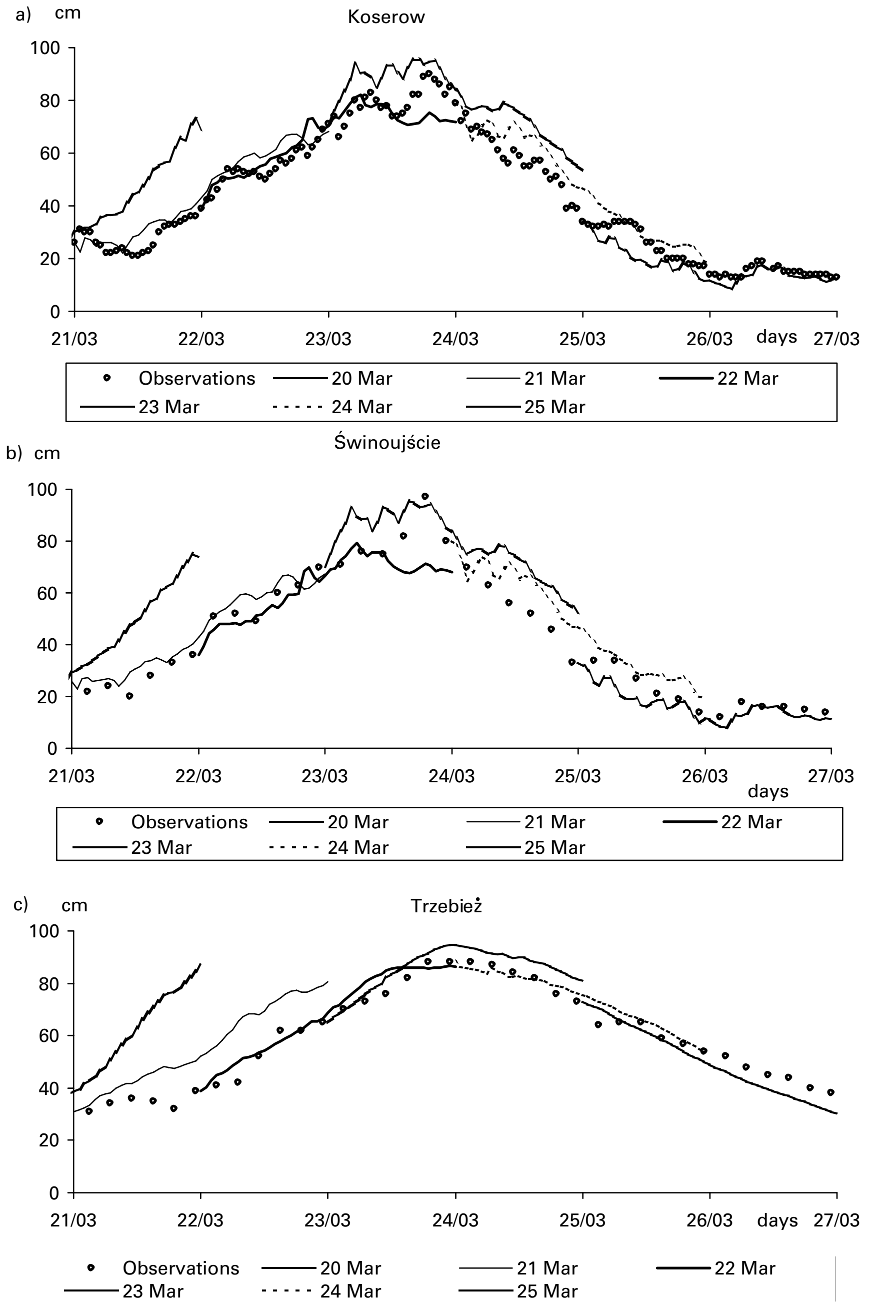

Figure 6 Observed and predicted sea level changes in Koserow (a), Swinoujscie (b) and Trzebiez (c) during the storm surge in March 2002. Legend: forecasts of 20, 21, 22, 23, 24, and 25 March

In the second half of March 2002, due to the prevalence of westerly winds, the Lagoon waters were spreading eastwards along the Wolin Island coasts. However, the storm-driven change of wind direction to NW–NE forced the sea water intrusion into the Szczecin Lagoon, which was well approximated by the model in the forecasts of 23–25 March (Figure 8). On 26 March, the change of wind direction to S–SW and the sea level drop on the

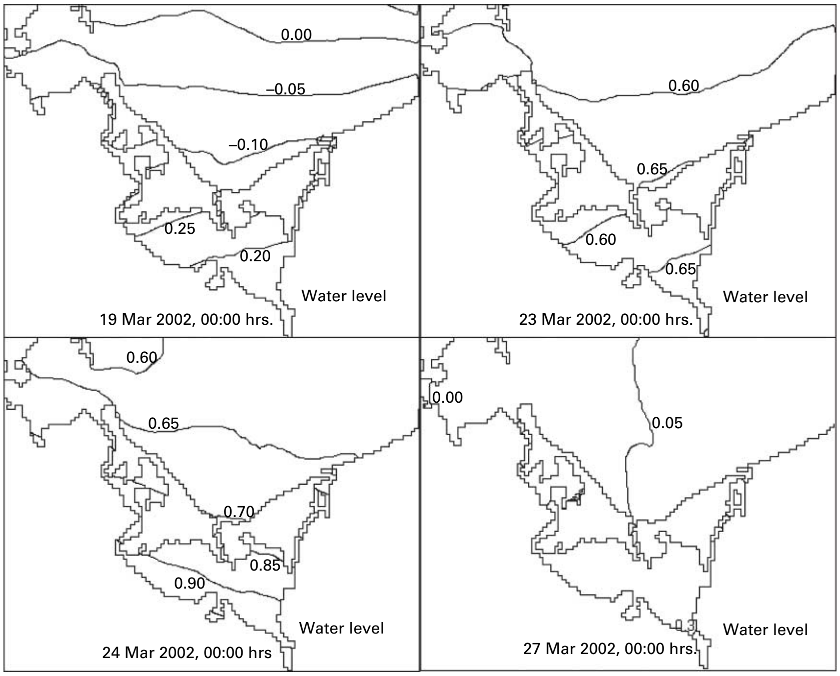

Figure 7 Water levels during the storm surge in March 2002, as simulated with the 3D operational numerical model of the Oder Estuary (slope of the free surface of water in meters)

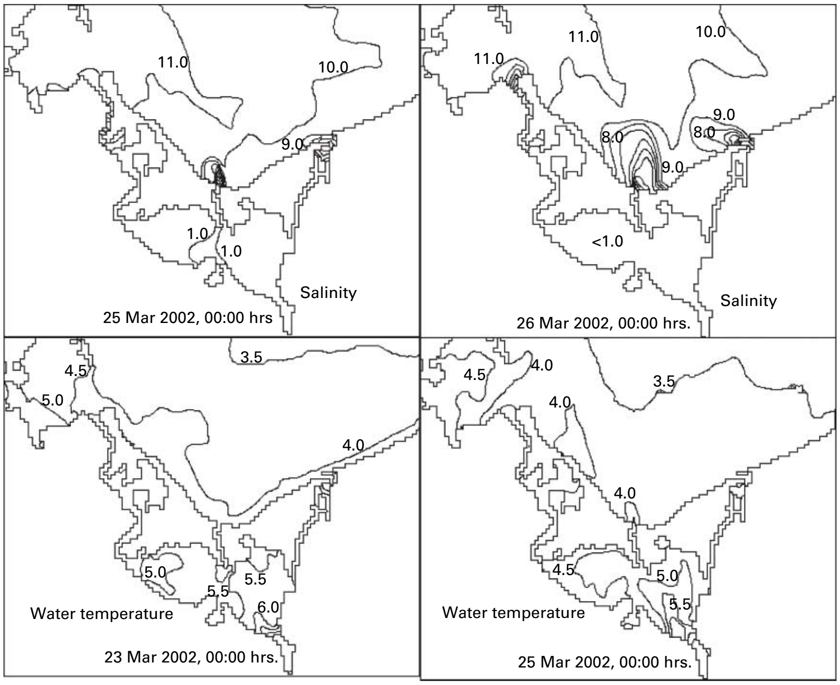

Figure 8 Salinity (psu) and water temperature (°C) during the storm surge in March 2002, as simulated with the 3D operational numerical model of the Oder Estuary

Pomeranian Bay coast resulted in the discharge of the Lagoon water into the Bay and northwards off its coast. Although the 26 March forecast was very accurate in this respect, the model usually overestimated the true (measured) values on the Bay coasts during the storm by about 2.0 psu. On the other hand, the water temperature forecasts reflected a typical spring pattern with continual water warming and increasing impact of fresh warmer water entering the Pomeranian Bay via the Swina, Dziwna and Peenestrom. During the storm, the simulated water temperatures on the Oder Estuary coasts were by about 1.0°C lower than the measured values.

Conclusions

When adapted to Baltic conditions, the 3D operational hydrodynamic model, based on the coastal ocean circulation model, generates 60-h forecasts of water levels, currents, water temperature and salinity in the Southern Baltic, Gulf of Gdansk, Szczecin Lagoon and Pomeranian Bay.

A good fit between the observed and computed data allows us to regard the model as a reliable tool for forecasting storm surges and for the detection of Oder water spread. The model correctly predicts hydrographic situations involving high-amplitude and rapid water level fluctuations and fast changes of physical properties of the water.

A quick website access to the hydrographic forecast (http://model.ocean.univ.gda.pl) allows potential users to predict the day-by-day course of processes that may affect different areas of human life and activities, e.g. navigation, port operations, flood protection of coastal areas, estimation of the hazard of coastal pollution due to the Oder River impact, tourism and recreation. In addition, the model may prove of assistance in studies on coastal processes in the estuary.

A better fit between the observed and computed data can be achieved by including instantaneous salinity and temperature data as well as those on sea levels on the open boundary, meteorological conditions, river discharges and their temperatures. Reliance on a more accurate bathymetric map of the Pomeranian Bay's coastal zone and inclusion of data provided by satellite thermal images and measurement buoys may further improve the prognostic reliability of the model.

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