Validation of the hydrodynamic part of the ecohydrodynamic model for the southern Baltic*

OCEANOLOGIA, 47 (4), 2005.
pp. 517–541.

KEYWORDS
Baltic Sea
Hydrodynamic model
Model validation

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Received 21 February 2005, revised 28 October 2005, accepted 30 November 2005.

Abstract

The first part of the Baltic Sea ecohydrodynamic model, based on the Princeton Ocean Model (POM), was validated by long-term observations of sea level, salinity and water temperature fluctuations. The modelled sea surface temperature (SST) fields were also compared to satellite images – satisfactory correlation coefficients were obtained. The model bias and efficiency coefficients of the modelled variables in relation to the observed values were determined. The quality of model simulations in relation to measured values was estimated with respect to spatial and seasonal variability in shallow and deep coastal waters as well as in the open sea. The results indicated the high quality of simulations by the hydrodynamic model.

1. Introduction

The ecohydrodynamic model of the Baltic Sea consists of two interacting parts: one is a hydrodynamic module describing the physical aspects of the marine environment, while the other represents biogeochemical processes

* This research was supported by the State Committee for Scientific Research, Poland (grant No 6 P04G 061 17). Editing assistance of the article was provided by BALTDER (EVK3-CT-2002-80005), funded by the European Commission under the 5th Framework Programme.

The complete text of the paper is available at http://www.iopan.gda.pl/oceanologia/

in sea water. It is the development and modification of an earlier model designed at the Institute of Oceanography of Gdańsk University[1].

The hydrodynamic part is a three-dimensional, baroclinic model describing water circulation and takes advection and diffusion processes into consideration. The model is based on the Princeton Ocean Model – POM (Blumberg & Mellor 1987) adapted to Baltic conditions. The horizontal advection calculation was modified (Kowalewski 1997) using TVD (Total Variation Diminishing). The model was validated in the Gulf of Gdańsk on the basis of temperature and salinity measurements in 1994–96 (Kowalewski 1997). The results showed a significant correlation between calculated and measured distributions. The best correlations were obtained for the coastal stations and surface layers. The next validation attempt was undertaken on the basis of measured and simulated temperatures and water salinities at depths below the Ekman layer. Here, the correlation between the above variables turned out to be somewhat lower. Direct measurements of water currents at Władysławowo, at the base of the Hel Peninsula, were also compared to modelled velocities (Kowalewski 1998, Kozłowski 1998).

An environmental experiment was carried out in the Gulf of Gdańsk to determine the spreading of a neutral substance. This enabled the model to be validated in relation to the advection and diffusion of a rhodamine spot (Jędrasik et al. 1999). The direction and range of the spread of rhodamine were accurately predicted. During the experiment two thermal deep-water transects were traced to compare observed and modelled distributions of temperature and salinity in the Gulf of Gdańsk: the simulated and measured values of both parameters were very similar. The modelled locations of the thermocline and halocline along these transects were confirmed by observations. In addition, the sea level variations at two stations – Władysławowo and the North Port of Gdańsk – were compared with readings from 1995. The correlation coefficients between actual and modelled sea level variations were 0.87 and 0.92. Next, the simulated sea level fluctuations at the North Port of Gdańsk, Hel and Władysławowo were compared to the 1998 observations: the respective correlation coefficients were 0.91, 0.89 and 0.87 (Kowalewski 2002). The water level forecast for the Pomeranian Bay based on the Hiromb model gave good agreement between simulations and observations (Kałas et al. 2001), with correlation coefficients from 0.87 to 0.91.

To obtain an adequate approximation of the water exchange between the Vistula Lagoon and the Gulf of Gdańsk (Jędrasik 1999), the bathymetric

[1]The model was designed as part of project No 6 P04E03609, funded by the State Committee for Scientific Research, Poland.

field of the Gulf of Gdańsk was extended to the Vistula Lagoon in a numerical grid with a 1 Nm horizontal space step. To resolve the problem of water inflows from the open sea to the coastal lakes in another application of the model (Jędrasik & Cyberski 2000), the interaction of the Baltic Sea model (5 nm grid) with the Lake Gardno model (1/54 of 1 nm grid, i.e. 34 m) was considered. Model validation was limited to water level fluctuations and surface temperature changes in Lake Gardno.

The aim of the present work was to evaluate the quality of the hydrodynamic model as the hydrodynamic module of the ecohydrodynamic Baltic Sea model (Ołdakowski et al. 2005, this volume). In the present paper the validated model took into account the majority of riverine inflow into the Baltic Sea (153 rivers). This evaluation covered a greater number of stations

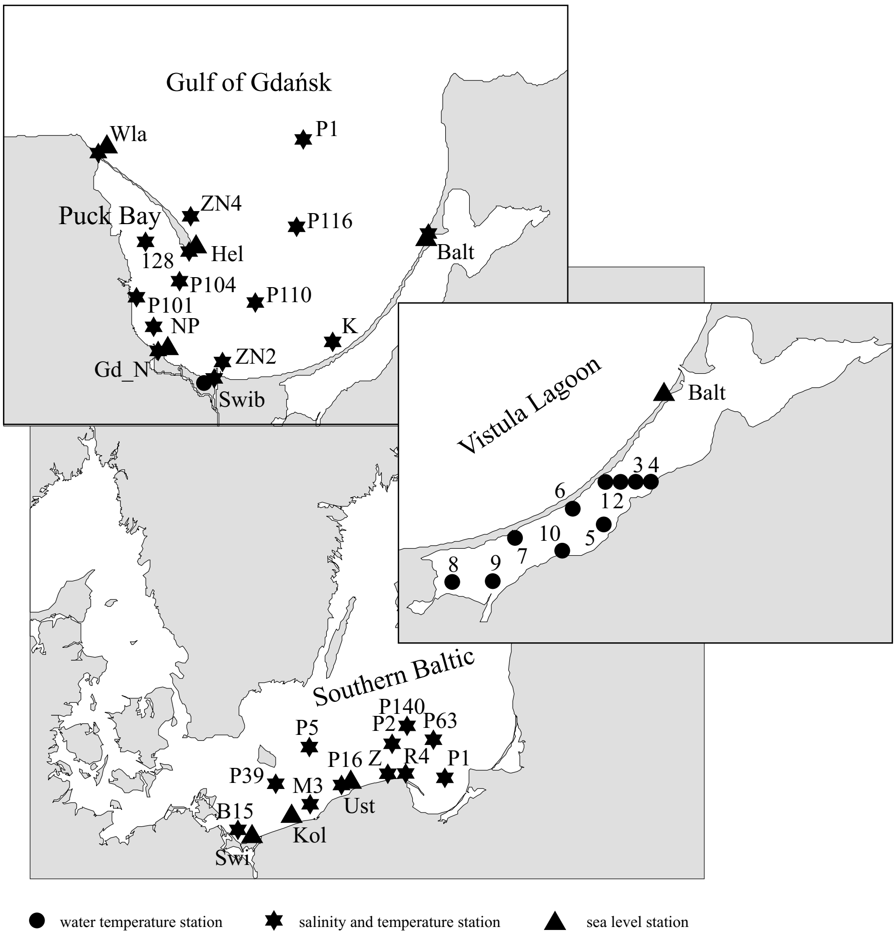

Fig. 1a. Modelled areas; observation stations are indicated

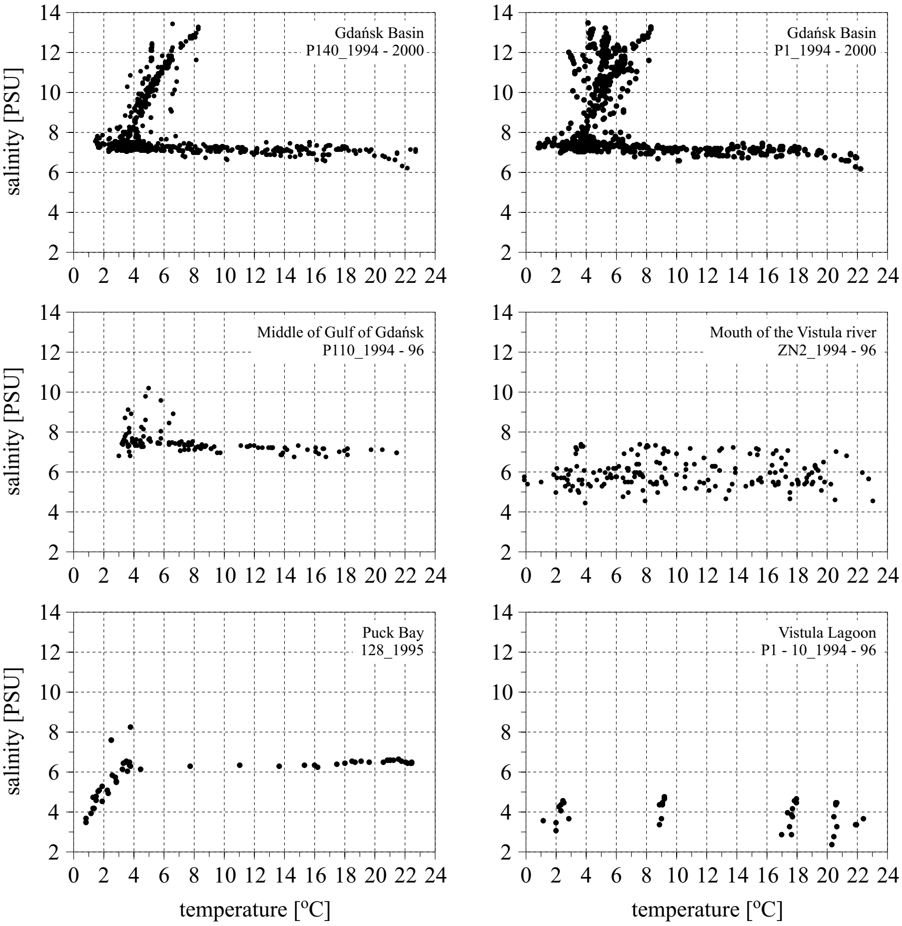

Fig. 1b. *T*-*S* diagrams for the Gdańsk Basin (station P140), the Gulf of Gdańsk (stations P1, P110, ZN2), Puck Bay (station 128) and the Vistula Lagoon (stations P1–P10)

and a longer period of observation (6 years, 1994–96 and 1998–2000) than previous studies. For the present validation, observations were gathered in the southern Baltic, mainly in the vicinity of the Polish coast. Open-sea stations were located in the Gdańsk (P2, P63, P140) and Bornholm Basins (P5) (Fig. 1a). Deep-water measurements were taken in the Gulf of Gdańsk, specifically in the Gdańsk Deep (P1, P110, P116). Shallow-water stations in Puck Bay and the Vistula Lagoon were also covered by the analysis (Fig. 1a). Besides the vertical distributions of temperature and salinity, satellite images of sea-surface thermal fields were compared with the simulated ones. A further modelled parameter – sea level variations – were compared to the readings from tide-gauges located along the Polish coast.

To describe the quality of the model, more advanced statistical measures were applied. Generally, validation included the physical variables of the environment – the sea level fluctuations, and the spatial distributions of salinity and temperature in the deep waters of the Gdańsk Deep, the coastal waters of the Gulf of Gdańsk, the shallower waters of Puck Bay, and the very shallow waters of the Vistula Lagoon (Fig. 1a; Fig. 1b). All these waters belong to the Gdańsk Basin.

2. Methodology

Validation is a comparison of model simulations to observations not applied in other steps of the procedure, such as model calibration, and the ratio of measured to modelled values is expressed as a statistical measure. The simulations were compared to the measured sea level variations at coastal stations, and to temperatures and salinities at stations in the Vistula Lagoon, Puck Bay, the Gulf of Gdańsk, elsewhere in the Gdańsk Basin, and also at some stations along the Polish coast (Fig. 1a). The modelled surface water temperature fields were compared to the thermal fields recorded by satellite imagery. The observation material covered deep and shallow water bodies situated off the coast, in the open sea and near river mouths. The comparisons of model results to the observations covered seasonal cycles in the above-mentioned observation periods.

To compare the modelled sea level variations, the following tide-gauge readings were used: Baltiysk (1994)[2], Świnoujście, Kołobrzeg, Ustka, Władysławowo, Hel and the Northern Port of Gdańsk (1995), and Świnoujście, Władysławowo and the Northern Port of Gdańsk (2000).[3] The water-gauge zero of the 508 cm ordinate as referenced to the sea level in Kronstadt had to be added in order to render the modelled sea levels comparable with observed values. Water temperatures were measured at stations belonging to the monitoring network of the Gdańsk region and the southern Baltic. The modelled surface water temperatures and salinities were correlated with values measured at coastal stations (Hel and Świbno). Monthly surface and near-bottom water temperatures from the Polish part of the Vistula Lagoon were used (April–November 1994–96).[4] 15 satellite images of the southern Baltic[5] were compared to the sea surface temperature (SST) fields in precisely synchronised periods.

[2]Data from the Institute of Oceanology, Kaliningrad, Russia.

[3]Data from the Institute of Meteorology and Water Management, Marine Branch, Gdynia.

[4]Data from the Nature Conservation Inspectorate, Elbląg.

[5]Landsat images obtained from Southampton University, England.

The areas bounded by the relevant geographical coordinates contained the same number of pixels (unit fields). In addition, images with clouds were screened out to eliminate discrepancies with the modelled surface water temperature fields. To avoid over- or underestimating coastal water temperatures, a buffering distance of one pixel perpendicular to the shore was applied along the coastline. Geostatistical analysis of satellite images and modelled SST fields was carried out by IDRISI (www.Clarklabs.org).

2.1. Statistical measures in the model validation

Correlation coefficients and standard deviations were most frequently used in the model validation. The present study revealed a large number of discrepancies, i.e. when the correlation coefficients between the modelled and observed values of the same state variable were higher at different stations, and the standard deviations of the differences between modelled and observed variables increased instead of decreasing. It was therefore necessary to extend the statistical analysis of the relations between observations and model simulations in the sea. Guidance was sought in the paper by Węglarczyk (1998) when there were obvious shortcomings in the hydrological models: e.g. despite the high correlation coefficients yielded by the comparison between observed and modelled values, the modelled values were none the less over- or underestimated. The correlation coefficients appeared to be insensitive to bias.

The modelled values y were compared with the observed values x, and the differences between them were denoted as the model error:

$$\Delta xy = y - x. \tag{1}$$

The measure based on the error value was the mean square error:

$$E_{rs} = \overline{(\Delta xy)^2}. \tag{2}$$

According to Węglarczyk (1998), the bias of the model was expressed as:

$$Q_m = \overline{\Delta xy} = \overline{y} - \overline{x}, \tag{3}$$

which is a dimensionless value indicating the degree of over- or underestimation of the modelled values in relation to the observed ones. The modified bias, a dimensionless value indicating the over- or underestimation of the ratio of modelled to observed parameters, is the mean value of an observed state variable $\overline{x}$ divided by the mean value of its modelled counterpart $\overline{y}$.

$$Q'_m = \frac{\overline{x}}{\overline{y}}. \tag{3a}$$

The correlation coefficient is calculated as the product of the standardised observed and modelled values:

$$r = \frac{\overline{(x-\overline{x})(x-\overline{y})}}{S_x S_y} = \frac{\operatorname{cov}(x,y)}{S_x S_y} = \frac{\overline{xy} - \overline{x}\,\overline{y}}{S_x S_y}, \tag{4}$$

where x – observed value of state variable; y – modelled value of state variable; cov (x, y) – covariance of observed and modelled values; $\overline{y}$ – mean value of modelled state variable; $\overline{x}$ – mean value of observed state variable; $S_x = \sqrt{\frac{\sum(x-\overline{x})^2}{N}}$ – standard deviation of observed values; $S_y = \sqrt{\frac{\sum(y-\overline{y})^2}{N}}$ – standard deviation of modelled values.

If we assume the mean square error (2) to be the sum of the variance and the bias, and that the formula for the correlation coefficient is the one given by eq. (4), then after adding r^2 to and subtracting r^2 from both sides and rearranging, the expression for the mean square error takes the form (Węglarczyk 1998):

$$E_{rs} = S_x^2 \left[\left(1 - r^2\right) + \left(\frac{S_y}{S_x} - r\right)^2 + \frac{Q_m^2}{S_x^2} \right]. \tag{5}$$

The second term in eq. (5), which describes the correlation between the model error and the value simulated by the model, is the conditional bias and is denoted by C^2.

$$C^2 = \left(\frac{S_y}{S_x} - r\right)^2. \tag{6}$$

The third term in eq. (5) is the unconditional bias, B^2, defined as the ratio of the absolute bias to standard deviation of the observation:

$$B^2 = \frac{Q_m^2}{S_x^2}. \tag{7}$$

Eq. (5) divided by S_x^2, together with definitions (6) and (7), give the expression

$$E = r^2 - C^2 - B^2, \tag{8}$$

for the Nash-Sutcliffe effectiveness coefficient E (Węglarczyk 1998) in the form:

$$E_d = r^2. \tag{9}$$

For the case when there is no bias (6) and (7), E (8) is equal to r^2, and we denote it as the determination coefficient E_d (9). The bias of the model results decreases the effectiveness coefficient and indicates the quality of the model simulation.

Then, the relation between the correlation coefficient and the total square error

$$E_{rc} = \frac{\sqrt{E_{rs}}}{\overline{x}}, \tag{10}$$

is used to express the special correlation coefficient R_s in relation to E_{rc}:

$$R_s = \sqrt{1 - \frac{E_{rs}}{S_x^2 + \overline{x}^2}}. \tag{11}$$

The coefficient R_s is equal to 1 when the mean square error is zero, and its value decreases with increasing E_{rc}. However, when $E_{rs} > S_x^2 + \overline{x}^2$, R_s cannot be applied because of its negative value. R_s better represents the fitting of model simulations to the observed ones than to the total square error, since the denominator in eq. (11) is greater than that in (10), and the coefficient is closer to 1 than the error is to 0.

3. Validation of the hydrodynamic model – results

3.1. Sea level variations

The regression lines obtained from a comparison of simulation and observation results do not run along the figure diagonal (Fig. 2) – the majority of points lie below it. This suggests that the modelled values are underestimated as compared to the measured ones.

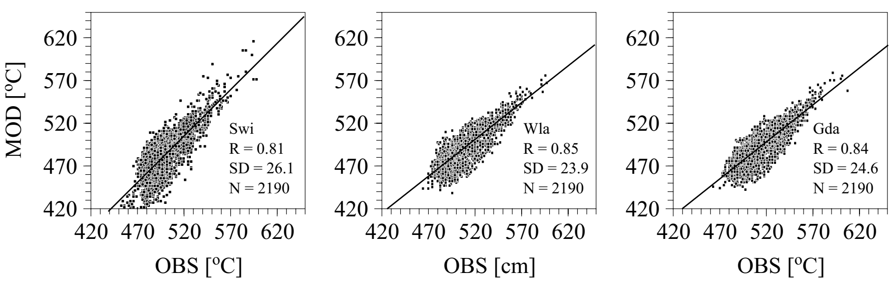

Fig. 2. Relationship between the observed (OBS) and modelled (MOD) sea level fluctuations along the Polish coast (stations: Swi – Świnoujście, Wla – Władysławowo, Gda – Gdańsk) in 2000. (R – correlation coefficient, SD – standard deviation, N – number of observations)

The 1995 simulations of sea-level fluctuations were underestimated at the stations from Świnoujście to Ustka (Fig. 3). From Władysławowo to Gdańsk they were underestimated for the first three months in the year; during the following months they alternated with the observed values. Simulations at Baltiysk were slightly higher than the readings. The measured and calculated curves exhibited the same shape and time of extremes at every station (Fig. 3). However, the extreme values of measurements seldom coincided with the simulated maxima. Series of 4 and 24 h intervals were analysed. As was to be expected, such a sampling frequency did not significantly affect the general picture of sea level variations, at least during the course of the year. The variability in water level at Świnoujście was found to be greater than at the other stations, because of its location on the shallow Pomeranian Bay.

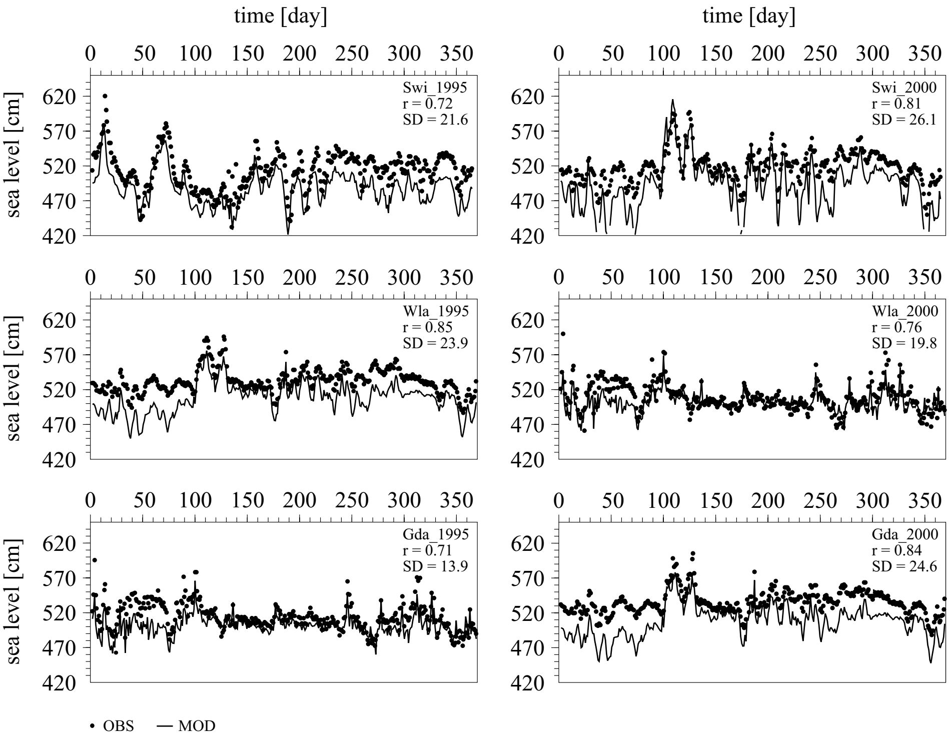

Fig. 3. Observed (OBS) and modelled (MOD) sea level fluctuations at selected coastal stations in 1995 and 2000

The simulated variations in 2000 (Fig. 3) are closer in shape to the measured values and the extreme values. From November till February the simulated levels were much lower than the measured ones at all stations. From April till May and in the second half of September the average measured and simulated levels were almost the same. A roughly semi-annual periodicity was more in evidence in the sea level variations in 2000 than in 1995. The correlations of the observed and simulated fluctuations ranged from 0.69 at Ustka to 0.85 at Władysławowo. Values above 0.8 were noted at Świnoujście, Gdańsk and Baltiysk. Contrary to expectations, the standard deviation increased (instead of decreasing) with the increase in correlation. Sea level fluctuations were modelled best at Kołobrzeg in 1995, and worst at Gdańsk in 2000.

3.2. Water temperature and salinity at the stations in the Gulf of Gdańsk

The model computation gives a good representation of the surface water temperature at the coastal stations at Hel and Baltiysk (Fig. 4) and at

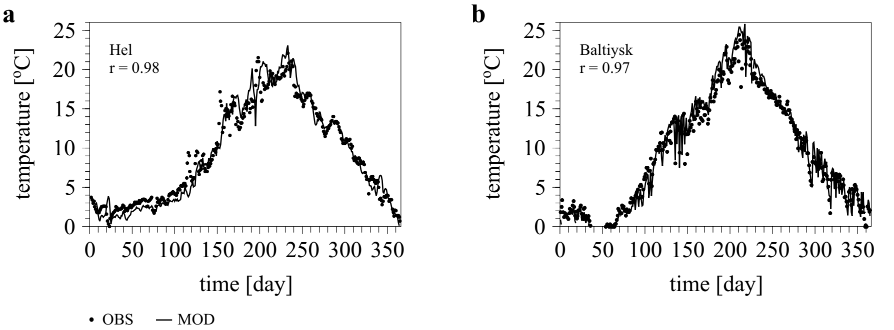

Fig. 4. Observed (OBS) and modelled (MOD) surface water temperature: Hel, 1995 (a) and Baltiysk, 1994 (b)

Świbno (not shown). The correlation between simulations and observations ranged from 0.96 to 0.98. Values at Świbno were the lowest because of the influence of the Vistula river water. Fluctuations due to seasonal variability were recorded at all three stations.

In the southern part of the Vistula Lagoon the surface water temperature distributions showed very good conformity between simulations and measurements from April 1994 till November 1996 (Fig. 5). In winter, no temperature measurements were carried out. At all stations the consistency of the calculations with observations, expressed as a correlation coefficient, was > 0.9. The correlations were best at stations 1–4 (0.97–0.98), and the correlation coefficients at stations 6–10 ranged from 0.92 to 0.96.

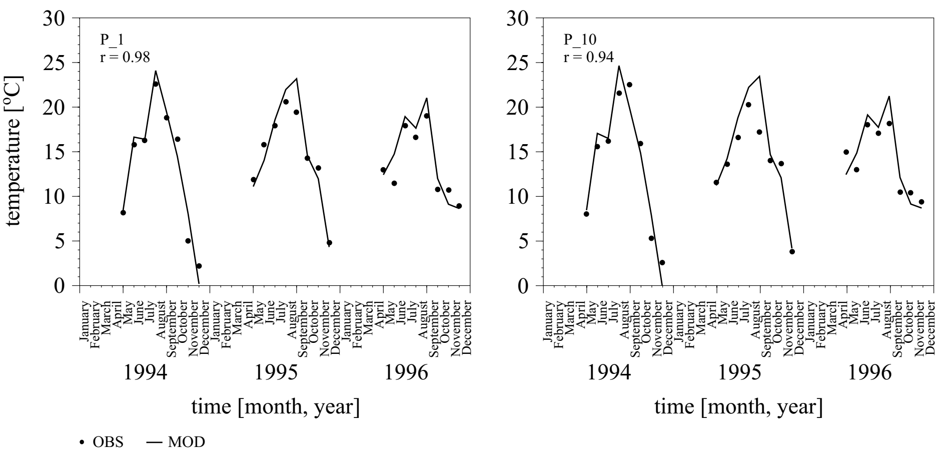

Fig. 5. Observed (OBS) and modelled (MOD) surface water temperature (stations 1, 10; Polish part of the Vistula Lagoon; 1994–96)

Vertical distributions of temperature and salinity were measured not only at coastal stations, but also at station 128 in Puck Bay from January till August 1996. Salinity values were about 7 PSU and did not significantly differ in the first half of the year. Temperature distributions were homogeneous and more distinctly stratified in summer (Fig. 6). The summer (August) thermocline at station 128, somewhat above 20 m depth, was poorly simulated by the model. Similarly, measurements showed a decrease in the near-bottom salinity (c. 40 m).

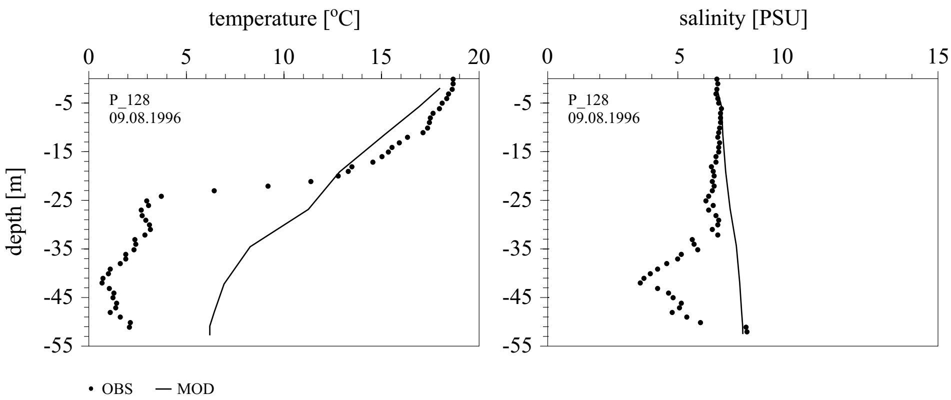

Fig. 6. Vertical distributions of temperature and salinity (station 128; Puck Bay; summer 1996)

To validate the vertical distributions of water temperature and salinity, eight stations were chosen in the Gulf of Gdańsk: the Gdańsk Deep (P1), the central part of the Gulf of Gdańsk (P110), the coastal deep-water body near the Hel Peninsula (ZN4), the shallow-water bodies near the Vistula Lagoon (K) and off the Vistula estuary at 15 m depth (ZN2), and also the coastal stations NP, P101 and P104 in the western Gulf of Gdańsk. Simulated and observed vertical distributions were compared seasonally from February 1995 till November 1996 and were preceded by a one-year simulation in 1994. In 1995 the calculated spring distributions of temperature at all stations were closer to the observed ones (Fig. 7). Summer profiles carried out in August, corresponding to the calculations and measurements, represent the summer stratification. The structural conformity in the deep-water bodies (P1, P110, ZN4) indicates that the model correctly describes the process of significant heat convection. Slight differences in the vertical distribution at stations ZN2 and K resulted from the influence of inflowing Vistula water. The autumnal distributions were weakly marked. Stratification was less distinct in deep water bodies and absent in the shallow ones. In 1995 the correlation between calculations and

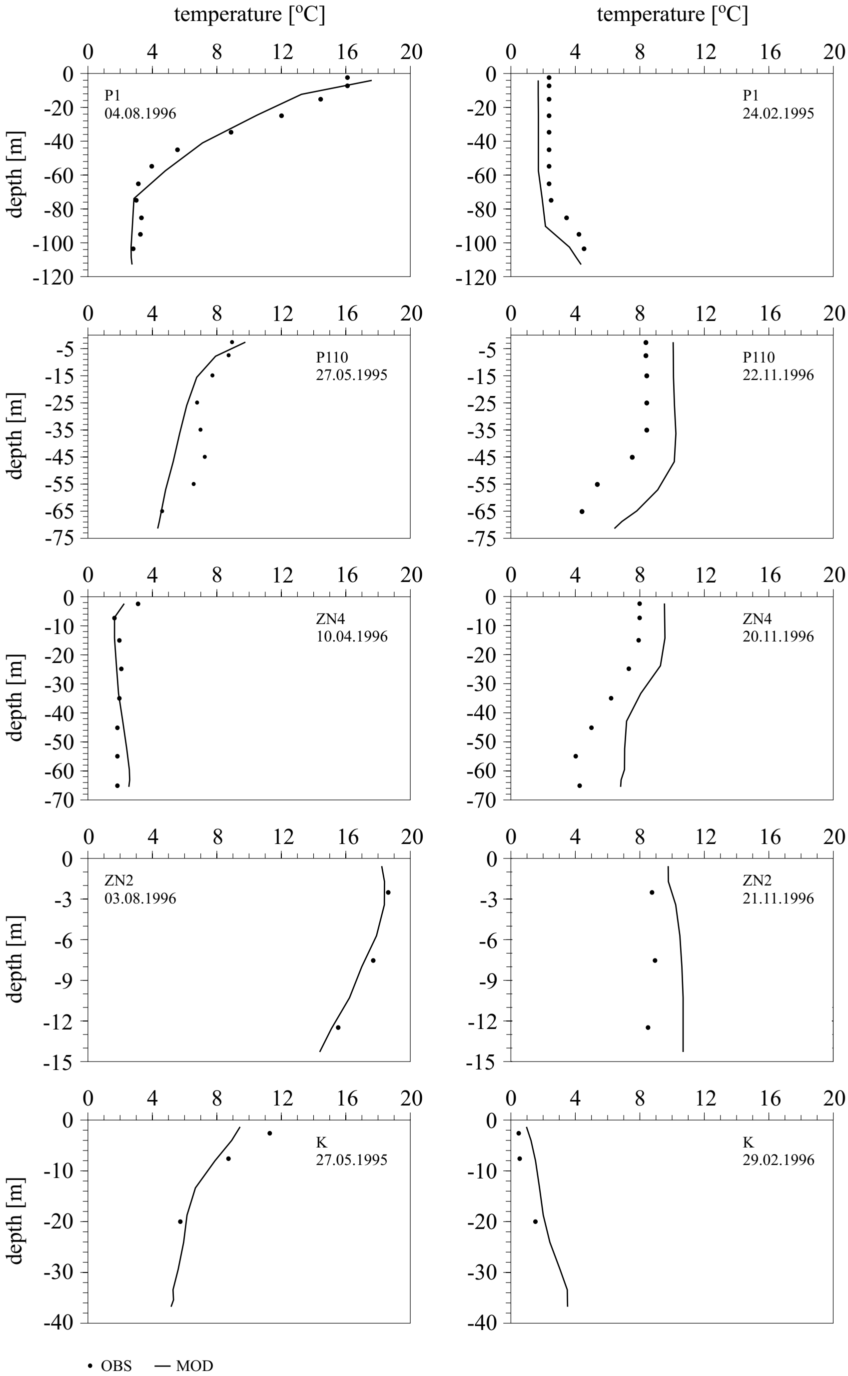

Fig. 7. Observed (OBS) and modelled (MOD) vertical distributions of water temperature at selected stations in the Gulf of Gdańsk: P1, P110, ZN4, ZN2 and K in different seasons between 1995 and 1996

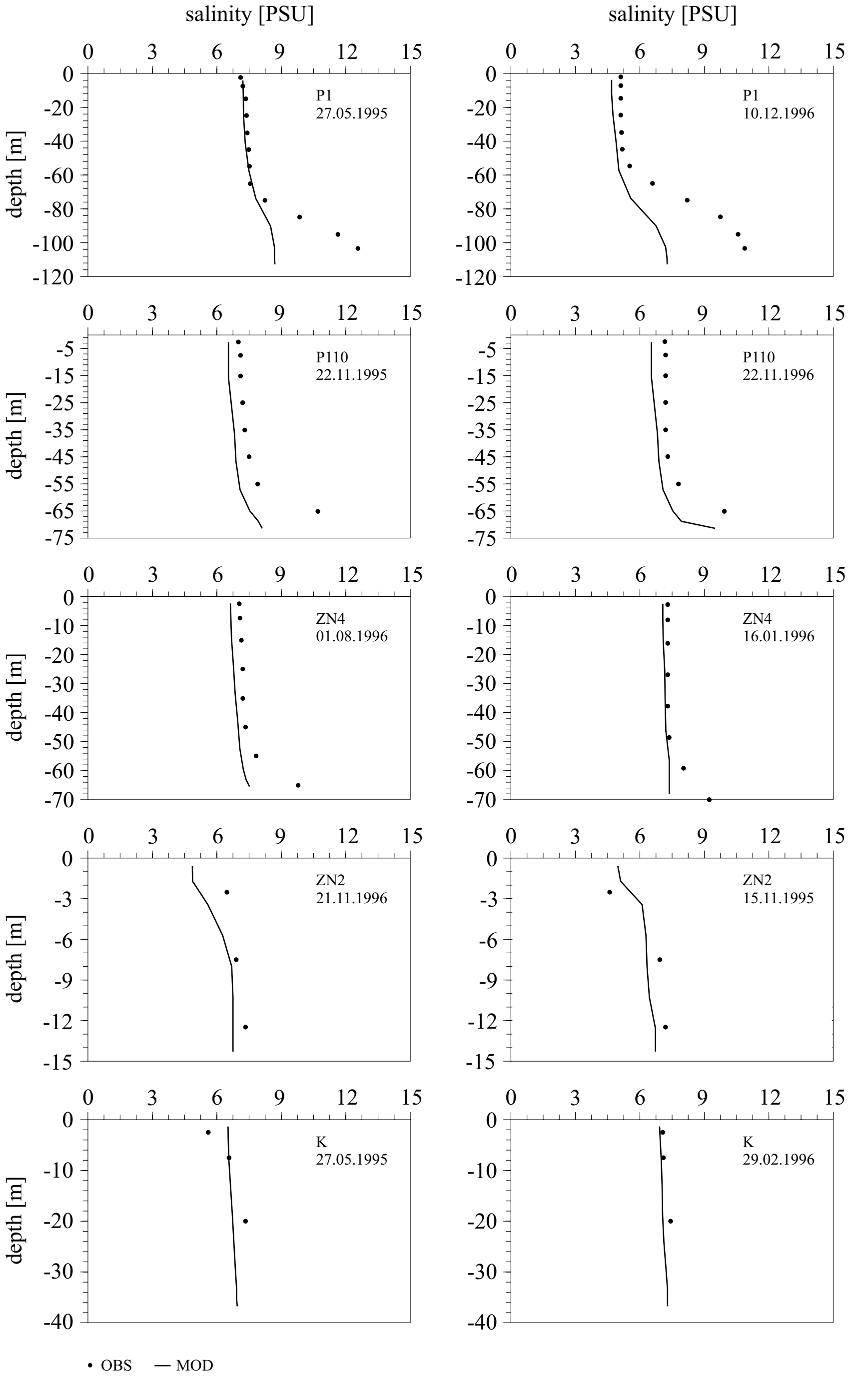

Fig. 8. Observed and modelled vertical distributions of salinity at selected stations in the Gulf of Gdańsk: P1, P110, ZN4, ZN2 and K in different seasons between 1995 and 1996

measurements was much better. The simulations carried out in the next year overestimated temperatures by more than 1°C. In the winter seasons, the thermal system was reversed, especially in 1996, but in 1995 temperatures were largely homogeneous. In 1995 all the simulations underestimated temperatures by 0.2–0.5°C. In 1996 the calculated spring distributions of temperature at both the shallow and the deep stations were closer to the observed ones.

Spring salinity distributions (Fig. 8) showed a high correlation between observations and simulations as far as the halocline (70–80 m). The only exception was station P1, where salinity simulations in the near-bottom layer were underestimated. In 1995 the calculated summer distributions of salinity were in line with the observations in the upper layer, but in 1996 they were underestimated by c. 0.3 PSU. In autumn and winter the situation was very similar, indicating that the model was functioning properly. Certain features of the seasonal variability in salinity were conspicuous. One is the consistency of the observed and calculated vertical distributions in the surface isohaline layer. A second feature is the underestimated salinity below the halocline in the Gdańsk Deep. On the other hand, the salinity decreased in the surface layer both in the observations and simulations at stations ZN2 and K (influenced by the Vistula), but increased in the near-bottom layer. In spring and summer 1996 the salinity was lower by c. 0.3 PSU. The correlation coefficients

Table 1. Statistical measures between modelled (MOD) and observed (OBS) water temperature T_w and salinity S at the monitoring stations in the Gulf of Gdańsk and Gdańsk Basin in 1994–96. (R – correlation coefficient, SD – standard deviation). Standard deviations refer to differences between observed and modelled temperatures and salinities

Station	T_w		S		Number of observations
	R	SD	R	SD	
P101	0.51	0.06	0.38	0.02	52
P104	0.65	0.04	0.05	0.02	81
P110	0.42	0.06	0.31	0.01	121
P116	0.83	0.03	0.18	0.01	111
ZN4	0.43	0.02	0.84	0.01	127
ZN2	0.82	0.26	0.69	0.07	71
NP	0.35	0.07	0.65	0.02	40
K	0.84	0.08	0.61	0.02	55
R4	0.58	0.04	0.45	0.01	50
P63	0.68	0.03	0.52	0.08	50

of the vertical salinity distributions in the Gulf of Gdańsk were similar to those of temperature, from 0.31 to 0.84 (Table 1). The variability of the parameter was low, so the standard deviations were smaller.

Another comparison was made between temperatures measured and simulated at various depths at station P1. The correlation coefficients decreased with increasing water depth from 0.97 at the surface through 0.9 in the thermocline to 0.59 in the halocline, and at the bottom the coefficient was negative (Fig. 9). The modelled surface salinity, as opposed to the modelled distributions, displayed a much lower correlation with observations. Only in the surface and near-bottom layers was the correlation somewhat better, but in the thermocline and halocline it was almost absent.

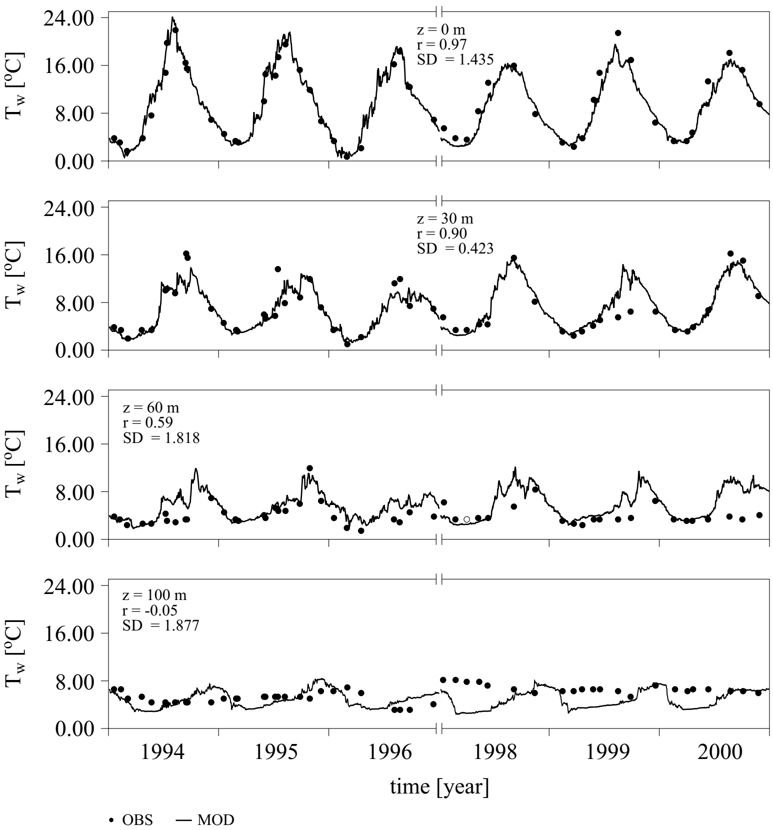

Fig. 9. Observed (OBS) and modelled (MOD) variability of water temperature T_w in 1994–2000 (station P1, Gdańsk Deep: z = 0 m, 30 m, 60 m, 100 m)

The quality of the validated parameters was expressed in the form of correlation coefficients and standard deviations of differences between observed and modelled values (Table 1). The correlation coefficients for temperature were between 0.35 (station NP) and 0.84 (station K). The expected regularity, i.e. higher correlation coefficients accompanied by lower standard deviations of differences between the modelled and observed values, did not occur (Table 1). The simulations were over- or underestimated, which was indicated by the bias affecting simulation quality.

3.3. Vertical distributions of temperature and salinity in the Gdańsk and Bornholm Basins

The observed and modelled water temperature and salinity in 1994–96 and 1998–2000 were compared at stations P1, P140 and P5 (Fig. 10). Correlation coefficients for temperature were higher than those for salinity. Regression lines for salinity also diverged from the diagonal line on the diagram. This suggests the possibility of simulation bias.

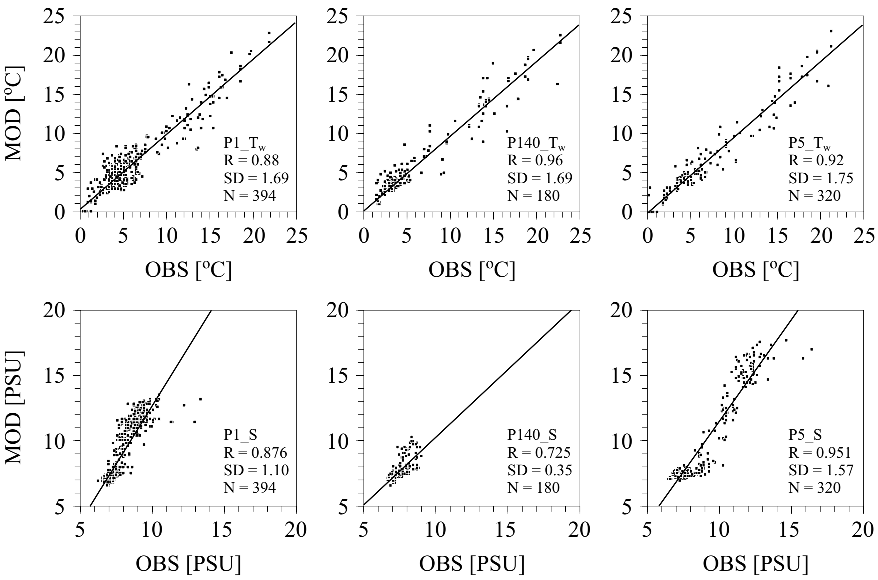

Fig. 10. Relationship between observed (OBS) and modelled (MOD) water temperatures T_w and salinities S in the southern Baltic (stations: P1, P140 and P5) between 1994 and 2000. (R – correlation coefficient, SD – standard deviation, N – number of observations)

Summer profiles corresponding to the measurements and calculations in August represent summer stratification. Vertical temperature distributions, except the one from the coastal station R4 (not shown), were very similar. This means that diffusion and heat advection were described correctly in the modelled region (Fig. 11). In the isohaline upper layer

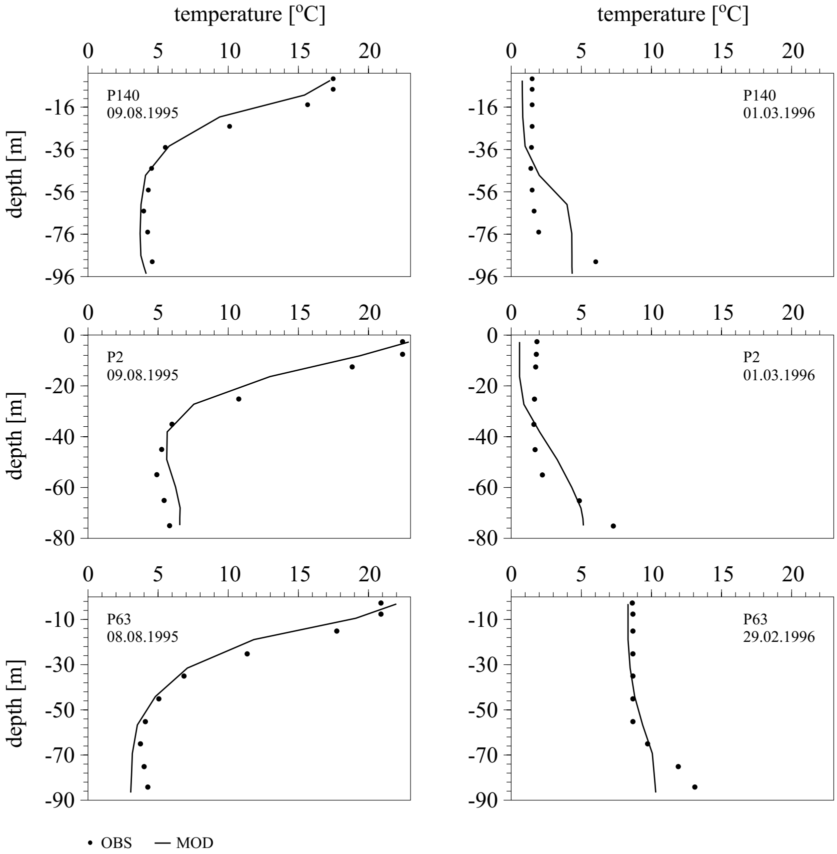

Fig. 11. Vertical distributions of water temperature (stations P140, P2 and P63; Gdańsk Basin; summer 1995, winter 1996)

the modelled distributions were almost the same as the observations; only below the halocline were they underestimated (Fig. 12).

The comparison of observations and simulations in 1994–2000 showed a high correlation at the stations in the open water bodies of the southern Baltic (Table 2). The correlation coefficients for water temperature were higher than those for salinity. Better simulations of distributions were obtained at the open sea stations than at the coastal ones (see P1 and P5 and P140) (Table 2). The correlation of temperature and salinity decreased at deeper levels. Near the bottom, the values obtained differed from the expected ones.

The modelled water temperatures were overestimated at the stations in the Gulf of Gdańsk and underestimated at the open water stations in the Gdańsk Basin. All the modelled salinities were underestimated by 5–10% in relation to the observed ones. The greatest underestimation was noted at

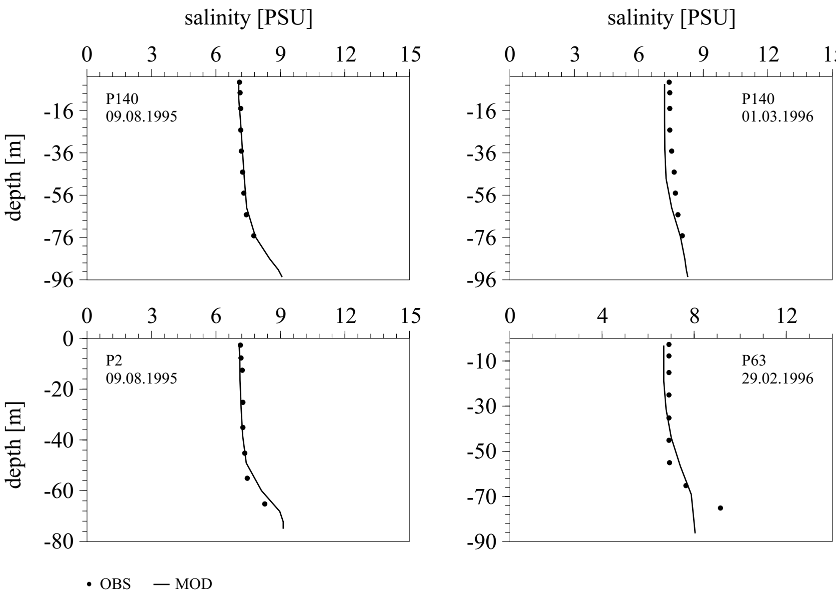

Fig. 12. Vertical distributions of water salinity (stations P140, P2 and P63; Gdańsk Basin; summer 1995, winter 1996)

Table 2. Statistical measures between modelled (MOD) and observed (OBS) water temperature T_w and salinity S at the monitoring stations in the Gdańsk and Bornholm Basins in 1994–2000. (R – correlation coefficient, SD – standard deviation). Standard deviations refer to differences between observed and modelled temperatures and salinities

Station	T_w		S		Number of observations
	R	SD	R	SD	
P1	0.888	1.69	0.876	1.10	394
P140	0.964	1.44	0.725	0.35	180
P5	0.925	1.75	0.951	1.57	320

station P1 (100 m depth), where simulations were c. 25% lower as compared to the observed values.

At the stations along the Polish coast (10–40 m depth) the vertical distributions of temperature and salinity were homogeneous. The observed and simulated profiles were almost the same, and the differences were insignificant: 0.3°C or 0.3 PSU.

3.4. Sea surface temperature validation using satellite imagery

The analysis of sea surface temperature measured from satellite images and modelled in the same spatial and temperature scale were significantly similar (Fig. 13). Both the remotely-sensed and modelled SSTs were higher in the lagoons than in the Gulf of Gdańsk. However, the latter was higher than in the Gdańsk and Bornholm Basins. SSTs determined from the sea heat balance and water body dynamics were correctly described by the model. Direct correlations of satellite and modelled pictures (c. 20 thousand km^2) ranged from 0.222 to 0.665, with 0.4 being the dominant value (Table 3). These coefficients are statistically significant since 40 thousand pixels were taken into account. The correlation coefficient (0.665) between the observed and modelled SST, obtained as a result of almost one and a half years' model simulation, is a very good result. The values of such coefficients are more important as regards justifying the model's quality than the correlation relationships at individual stations. In the present model validation 15 pairs of fields in the southern Baltic were compared.

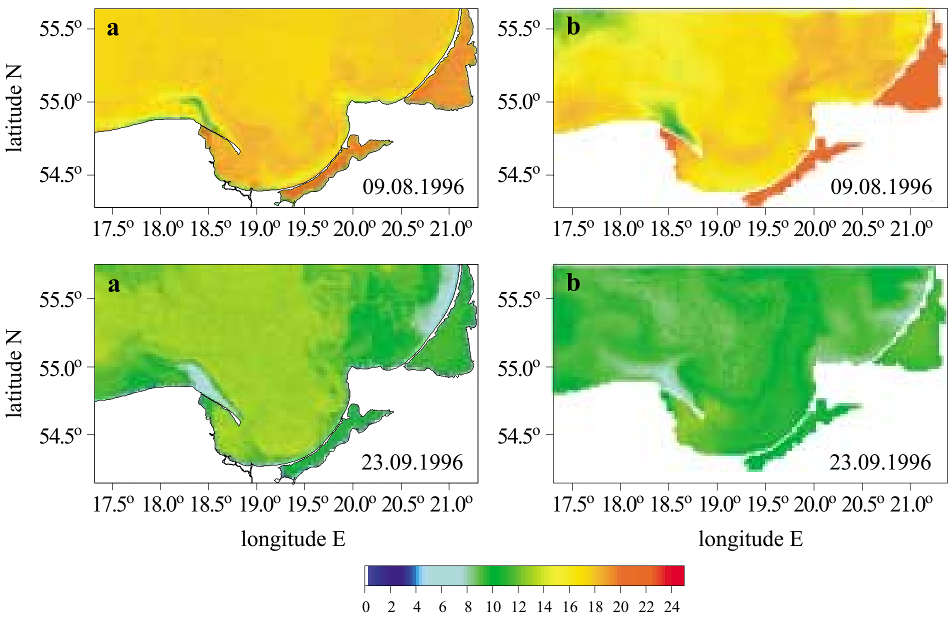

Fig. 13. Sea surface temperature SST fields 09.08.1996: observed (a), modelled (b) and 23.09.1996: observed (a), modelled (b)

The quality of the model is demonstrated by the generation of up- and downwelling in this region (Fig. 13): the modelled temperatures and durations of these events are consistent with the values recorded by satellite. Upwellings are locally created by easterly winds in the vicinity of the Hel Peninsula and Vistula Lagoon and are areas of lower temperatures resulting from the raising of deep water. Downwellings, generated by

Table 3. Correlation of the water temperature fields R: modelled and observed by means of satellite imagery

Date	12.04.95	23.05.95	30.05.95	19.03.96	16.04.96	03.08.96	04.08.96	05.08.96	06.08.96	07.08.96	08.08.96	09.08.96	19.08.96	20.08.96	23.09.96
R	0.52	0.67	0.14	0.06	0.36	0.37	0.42	0.34	0.23	0.45	0.43	0.43	0.52	0.36	0.22

westerly winds, are characterised by the accumulation of warm water off the eastern coast of the southern Baltic.

4. Model validation

The bias of the model was expressed as the relation between all observations and simulations (Fig. 14). The lack of decreasing standard deviations and high correlation coefficients between the observed and modelled sea level fluctuations indicated the model's good quality and its shortcomings. Simulations were either higher or lower as compared to the measured values (Figs 3 and 4).

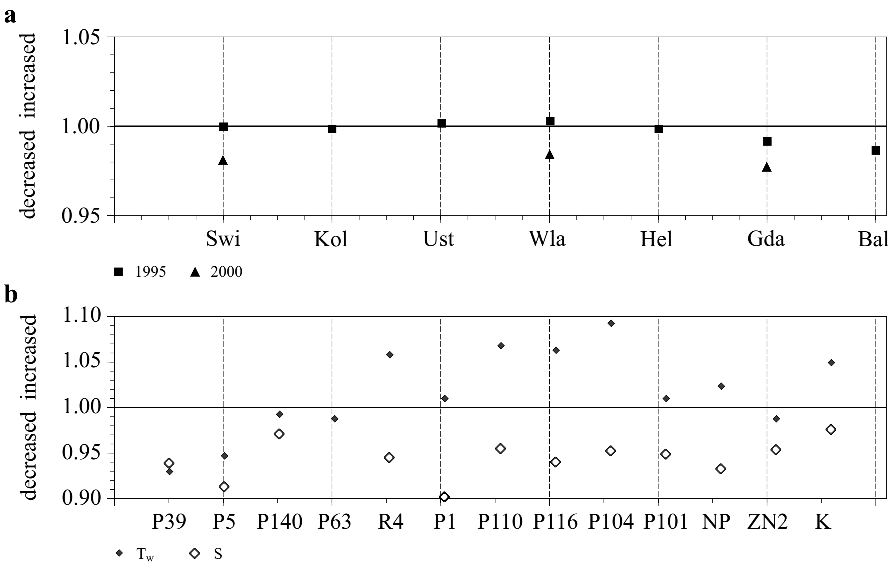

Fig. 14. Bias of simulations of sea level fluctuations in 1995 and 2000 (Swi – Świnoujście, Kol – Kołobrzeg, Ust – Ustka, Wla – Władysławowo, Hel – Hel, Gda – Gdańsk, Bal – Baltiysk) (a) and water temperature and salinity in 1994–2000 at monitoring stations P39–K (b)

The modelled sea level fluctuations were closest to the observed ones at Świnoujście, Kołobrzeg, Ustka and Hel stations. However, they were

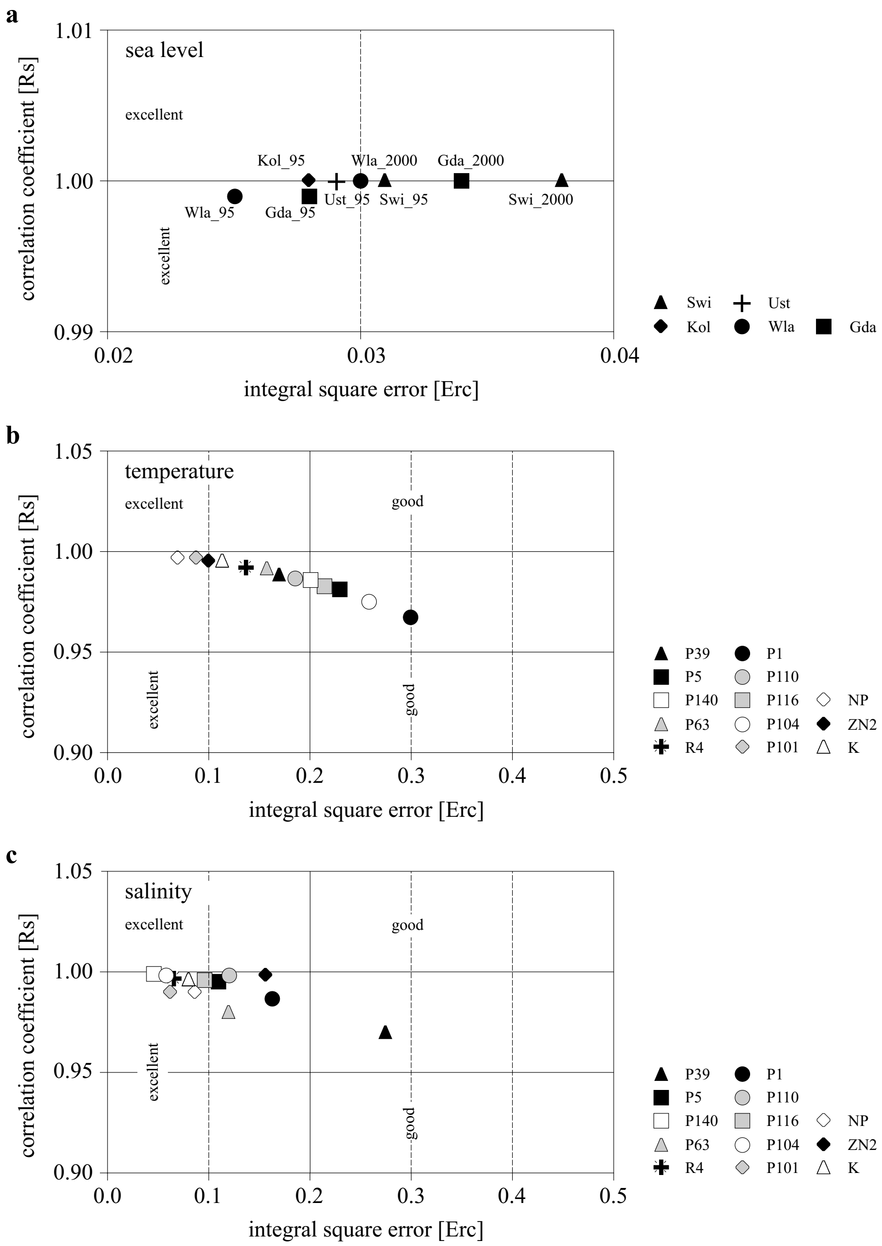

Fig. 15. Special correlation coefficients in the function of the integral square error for sea level fluctuations in 1994 and 2000 (a), water temperature (b) and salinity at monitoring stations P39–K (c) in 1994–2000

underestimated at Gdańsk and Baltiysk and slightly overestimated at Władysławowo. Simulations for the year 2000 showed a considerably higher correlation coefficient (c. 0.82) in relation to those obtained for 1995 (0.69 –0.77). However, they were characterised by a markedly higher bias, mean absolute deviation and mean square error. Despite these deficiencies, the special correlation coefficient R_s at all stations and dates lay within the bounds of the highest-class models (Ozga-Zielińska & Brzeziński 1994). The simulation quality of sea level fluctuations demonstrates the good validity of the model (Fig. 15).

The effectiveness coefficient E for water temperature, including correlation values reduced by the conditional bias (C^2 in (6)) and the unconditional bias (B^2 in (7)) of the model, was 20% higher than the coefficient for salinity. This makes a significant contribution to the quality of the hydrodynamic model with respect to the respective correlation coefficients of 0.927 and 0.928 for temperature and salinity. It is also confirmed by the absolute bias Q_m,which is 6% lower for temperature than for salinity. The special correlation coefficient for salinity was higher because both mean and total square errors were lower (Table 4). The model validation based on the special correlation coefficient for temperature in the function of total square error is better at the shallow-water stations (Fig. 15). The modelled temperature distributions were satisfactory at almost all the deep-water stations (P116, P1, P63, P140 and P5), and very good at the shallow offshore ones in the Gulf of Gdańsk and further along the coast (P39, R4, P110, P104, P101, K, NP and ZN2) (Fig. 15).

Table 4. Statistical parameters of temperature T and salinity distributions S at all stations between 1994 and 2000

Parameter	Q_m	C^2	B^2	E_{rs}	E_{rc}	r	r^2	E	R_s
T	0.980	0.0004	0.0004	2.816	0.256	0.927	0.859	0.858	0.977
S	0.921	0.100	0.073	0.891	0.109	0.928	0.861	0.687	0.994

where: Q_m – absolute bias of model; C^2 – conditional bias of model; B^2 – unconditional bias of model; E_{rs} – mean square error; E_{rc} – integral square error; r – correlation coefficient; r^2 – coefficient of determination, E – Nash-Sutcliffe effectiveness coefficient; R_s – special correlation coefficient.

5. Conclusions

The applied statistical measures enabled the model quality in relation to the spatial variability of sea level fluctuations to be validated. The modelled and observed vertical distributions of seasonal variability of temperature and salinity showed good conformity and indicate relatively good flow simulations.

In the present work the model validation was extended to stations in the Puck Bay, Vistula Lagoon and Bornholm Basin, and remotely-sensed SSTs in the Gulf of Gdańsk were compared to the modelled fields. This endorses the validation of model. An extended range of statistical measures were applied to the measurements and simulations at the stations in the Gulf of Gdańsk, i.e. bias, mean and total square error, and the effectiveness coefficient of simulations. High correlation coefficients do not show whether the simulation values are overestimated or underestimated in relation to the measured ones. The model bias enabled the effective coefficient of correlation relationship quality to be determined.

A high conformity of simulations and values measured during three-year periods (1994–96 and 1998–2000) was achieved. The model compactness allows hydrodynamic processes in shallow and deep water bodies of the southern Baltic to be forecast or hindcast irrespective of seasonal periodicity. The reconstruction of phenomena and processes described in the present hydrodynamic model indicates that it can be reliably applied for scientific purposes and even used in operational practice.

Comparison of measured and modelled sea level variations and SSTs shows that this part of the validation was positive. However, at the monitoring stations the vertical distributions of temperature were overestimated and those of salinity were underestimated (Fig. 14). The upper parts of the modelled profiles achieved better conformability with observed values than the lower ones (Figs 6–8, 11–12). Simulated near-bottom temperature fluctuations at station P1 differed from measured values. Reproduction of distributions, particularly of salinity below the halocline towards the bottom, was unsatisfactory.

To improve on such an unfavourable result it would seem sensible to make allowances for the observed sea level and water salinity and temperature at the boundary between the Baltic and North Seas. The lack of salt in the deeper layers of the Baltic was due to the insufficient information from this boundary area.

Another way of improving the model results is to alter the model. In the model validated here, mixing processes were described by the Mellor-Yamada turbulence closure scheme. In near-shore regions, where surface and bottom boundary effects strongly interact, the scheme used in the POM model for representing mixing in bottom boundary layer was incorrect (Durski et al. 2004). These authors achieved encouraging results when investigating two vertical mixing parameterisations – the Mellor-Yamada scheme, and the enhanced K profile parameterisation – to represent the bottom boundary layer (Durski et al. 2004). Before the next validation of our model is attempted, it would be desirable to perform some numerical experiments with reference to the new vertical mixing schemes.

Acknowledgements

For the model validation, sea level data at Baltiysk were supplied by the Institute of Oceanology, Kaliningrad, Russia. The temperature and salinity observations collected during southern Baltic monitoring were made available by the Institute of Meteorology and Water Management, Marine Department, Gdynia. Temperatures and salinities measured in the Vistula Lagoon were obtained from the Nature Conservation Inspectorate, Elbląg. The Landsat satellite imagery was obtained from Southampton University, England.

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