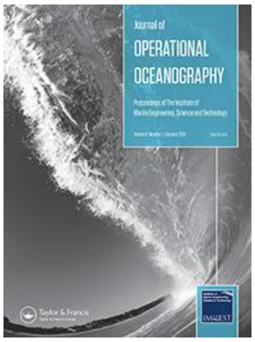

Journal of Operational Oceanography

ISSN: 1755-876X (Print) 1755-8778 (Online) Journal homepage: http://www.tandfonline.com/loi/tjoo20

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JOURNAL OF OPERATIONAL OCEANOGRAPHY, 2016
VOL. 9, NO. 1, 67–73
http://dx.doi.org/10.1080/1755876X.2016.1209368

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ABSTRACT
This paper presents a Coupled Ecosystem Model of the Baltic Sea – 3D CEMBS. The model was developed for the Baltic Sea region and forced by atmospheric data from the UM model (by the Interdisciplinary Centre for Mathematical and Computational Modelling, Warsaw University). The model was compared with hydrological data collected during cruises of r/v 'Oceania'. The analysis covers period from 2010 to 2013 for the main inflow axis on Southern Baltic domain. The evaluation results show a temperature and salinity correlation between the data ca 0.8 and 0.92, respectively. Simulated temperatures and salinity are generally well maintained. However, differences between model and *in situ* data depend on time and space, and arise with higher gradients.

ARTICLE HISTORY
Received 5 November 2015
Accepted 1 July 2016

KEYWORDS
Baltic Sea; hydrological data; temperature; salinity; modelling

Introduction

Numerical modelling of the Baltic Sea region is a very complex problem. Many factors such as fresh water inflow from rivers, proper atmospheric forcing and proper open boundary conditions have a great impact on model's performance. Due to strong stratification of the Baltic Sea, vertical mixing parameterisation must be very accurate. It is necessary to produce an accurate vertical profile with a proper thermocline and halocline. Proper consideration of water inflow from the North Sea is a crucial factor to achieve proper salinity values, as it is main source of the saline water in the Baltic Sea. It is therefore necessary to introduce open boundary conditions. To assess model's performance in the Southern Baltic region, a test run of the 3D Coupled Ecosystem Model of the Baltic Sea (3D CEMBS) was performed on historical data covering years 2011–2013. Results of this run were compared with *in situ* measurements of both temperature and salinity. The results of this comparison together with the operational system configuration are presented in this paper.

Hydrological data

Hydrological data analysed in this paper were collected during regular cruises of r/v 'Oceania' in the Southern Baltic between 2011 and 2013 (Rak & Wieczorek 2012). Due to ship activities, the data are devoid of summer cruises. High-resolution hydrographical sections were performed using a profiling Conductivity, Temperature, Depth probe (CTD) towed behind the vessel. The main section (Figure 1) was located along the axis of deep basins starting from the Bornholm Deep (BD) through the Slupsk Furrow (SF) to the Gdansk Deep (GD).

During measurements with the towed profiling system, IOPAS used Seabird 49 CTD sensor. The accuracies of the probe were $C = 0.0003$ mS/cm, $T = 0.002$°C, $P = 0.1\%$ of the full range. Temperature and conductivity sensors of CTD system were calibrated annually, post-cruise, by the manufacturers. The profiling system consisted of the CTD probe suspended in a steel frame towed on a cable behind the vessel. The suspension system ensured a horizontal position of the probe during profiling. The steel frame protected it from mechanical damage, while a metal chain fixed below the frame reduced the risk of contact with the seabed. To obtain a profile, the CTD system was lowered or raised between the surface and the bottom by releasing or hauling the towing cable. At a constant ship speed of ca 4 knots, a spatial resolution of ca 200–500 m was obtained for a basin with a typical depth of 60–120 m. With the CTD probe operating at frequency of 10Hz, vertical resolution of measurements was ca 3 cm (30 measurements per metre).

3D CEMBS model

The 3D CEMBS model is based on the Community Earth System Model (CESM). It is a coupled climate model that consists of four components responsible for the ocean

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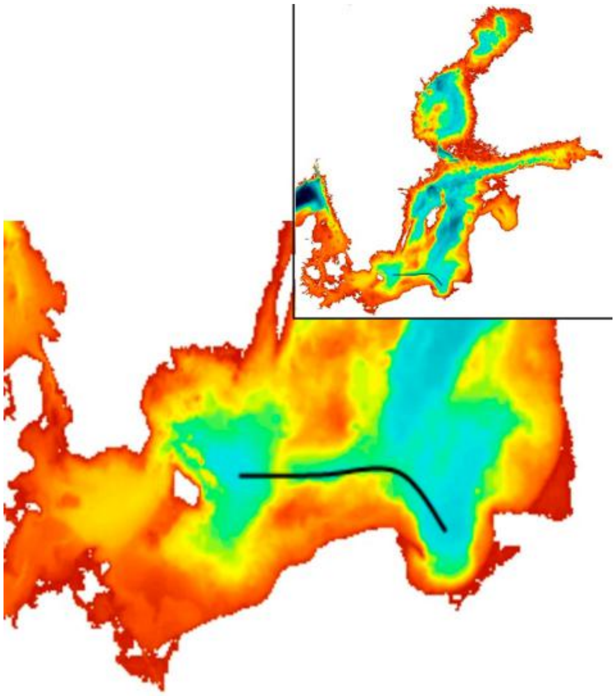

Figure 1. S/Y Oceania research cruises route.

(hydrodynamics and an ecosystem), ice, atmosphere and the land. Model's domain is based on stereographic coordinates, but the equator of these coordinates is in the centre of the Baltic Sea (rotated stereographic coordinates) and one can assume that the shape of cells is square and they are identical. Horizontal resolution of the model is 1/48°. Placement of variables in the horizontal direction is based on the Arakawa B-grid (Arakawa & Lamb 1977).

The ocean model is based on the Parallel Ocean Program – POP, version 2.1 (Smith & Gent 2004). It is a three-dimensional z-type model with 21 vertical levels that solves three-dimensional primitive equations for stratified fluids using hydrostatic and Boussinesq approximations. Vertical thickness of cells is 5 m for four first cells and increases with depth (Dzierzbicka-Glowacka et al. 2013). Main hydrodynamic variables produced by the model are temperature, salinity, currents velocity, sea surface level, ice cover area and thickness and many others. However, for the purposes of this paper only temperature and salinity are taken into analysis.

Main objective of this model is to simulate biogeochemical parameters such as: zooplankton, small phytoplankton, large phytoplankton (mainly diatoms), summer species (mainly cyanobacteria), one detrital class, dissolved oxygen and the nutrients nitrate, ammonium, phosphate and silicate. However, to fulfil this main task of the model, physical parameters of the water have to meet certain requirements. Atmosphere and land modules are inactive. Instead, data are provided from external sources. Atmospheric forcing is fed from the ICM-UM model developed at the University of Warsaw. The land module provides daily river inflow of freshwater from SMHI Balt-Hype Web and nutrient deposition as monthly mean values, based on historical data from Baltic Nest Institute. The initial state of the ocean model was prepared using temperature and salinity climatological data (Janssen et al. 1999).

Results

Results achieved from a test run of the model were compared with *in situ* data from different cruises of the S/Y Oceania. Cruises took place in the Southern Baltic region between 2011 and 2013. During these cruises temperature and salinity values were measured on all depths, among many other parameters. Section from which measurements were used to compare with model results is marked in Figure 1. Results of *in situ* measurements and model computations are presented in this part. Figures 2–6 show cross-sections for temperature and Figure 7 for salinity. Statistical comparison is presented in form of Taylor diagrams (2001) in Figures 8 and 9 for temperature and salinity, respectively. To present results from different cruises on one diagram all the statistics were normalised with standard deviation of reference measurement. Non-normalised values are presented in Tables 1 and 2.

The correlation coefficient R for temperature varies from 0.68 in December 2013 to 0.91 in February 2013.

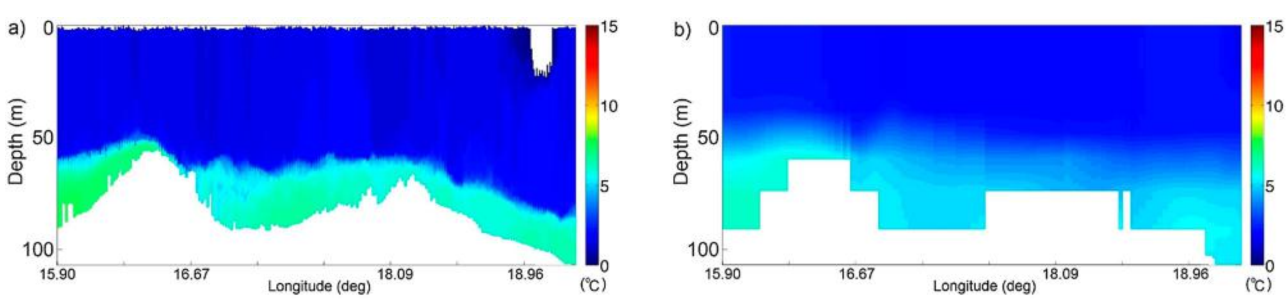

Figure 2. Temperature cross-section 19.02.2011. (a) *In situ*, (b) model.

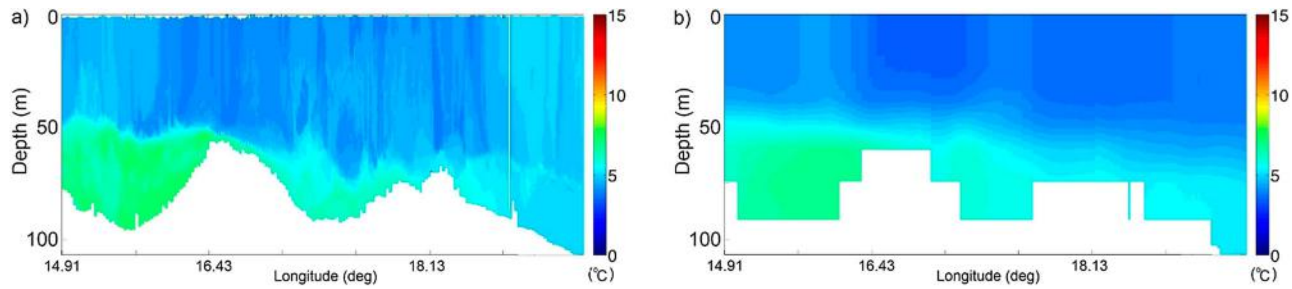

Figure 3. Temperature cross-section 18.01.2012. (a) *In situ*, (b) model.

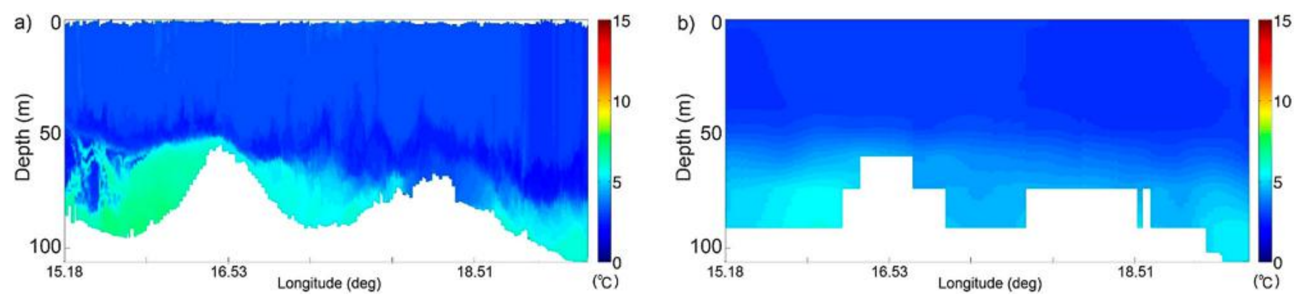

Figure 4. Temperature cross-section 03.04.2012. (a) *In situ*, (b) model.

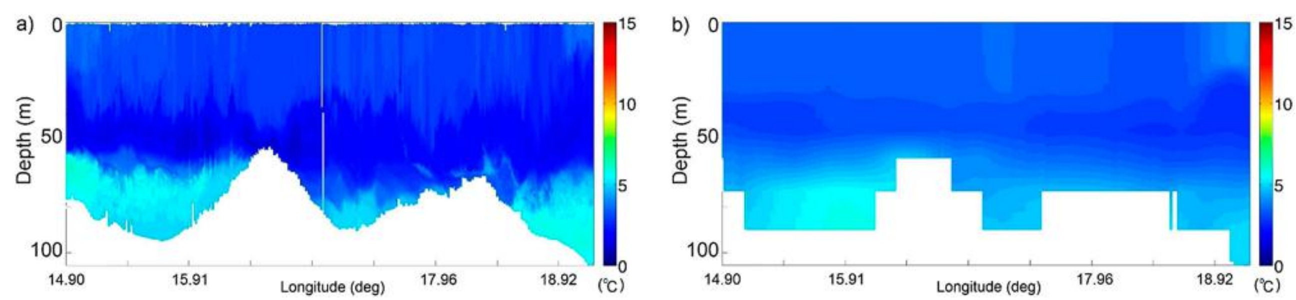

Figure 5. Temperature cross-section 23.04.2013. (a) *In situ*, (b) model.

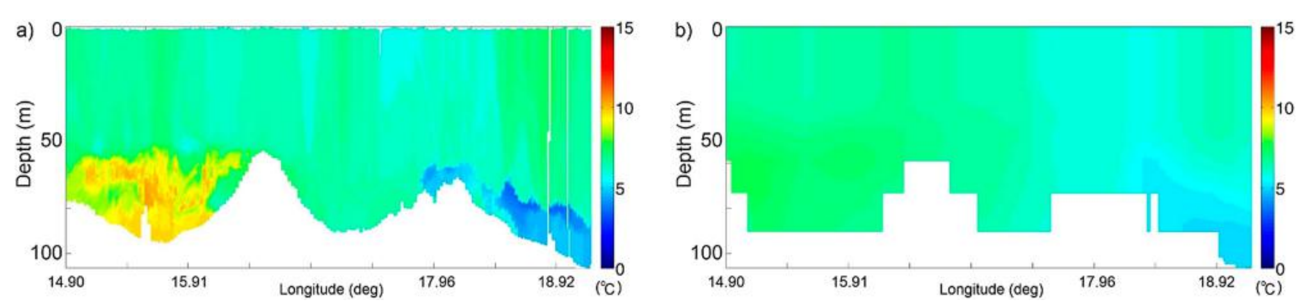

Figure 6. Temperature cross-section 11.12.2013. (a) *In situ*, (b) model.

In general the correlation tends to be higher at the beginning of each year. Systematic error $\langle \varepsilon \rangle$ is much lower than 1°C and its sign changes with different measurements, meaning that model calculations are not biased. RMSE values are also lower than 1°C except for results from January 2011 where RMSE is 1.03°C. There is no clear correlation between the time of year and model errors.

The correlation coefficient for salinity is higher than 0.9 in most cases. Systematic and statistical errors are less than 1 psu for all cases. Unlike in the case of temperature, the correlation coefficient of salinity does not

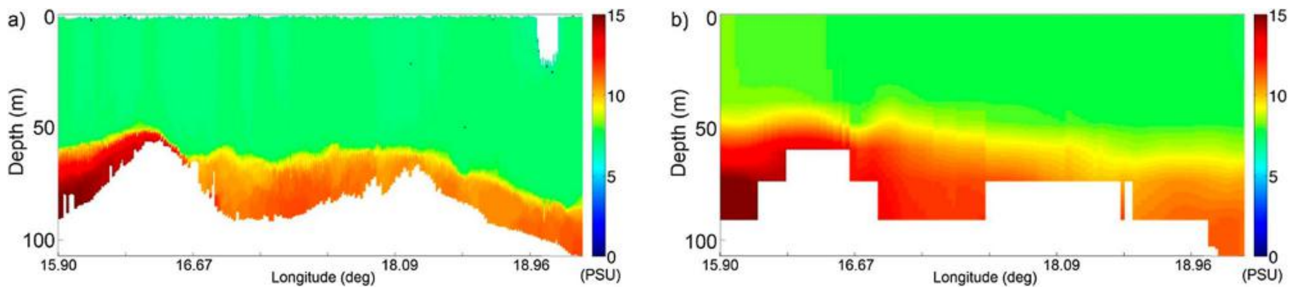

Figure 7. Salinity cross-section 19.02.2011. (a) *In situ*, (b) model.

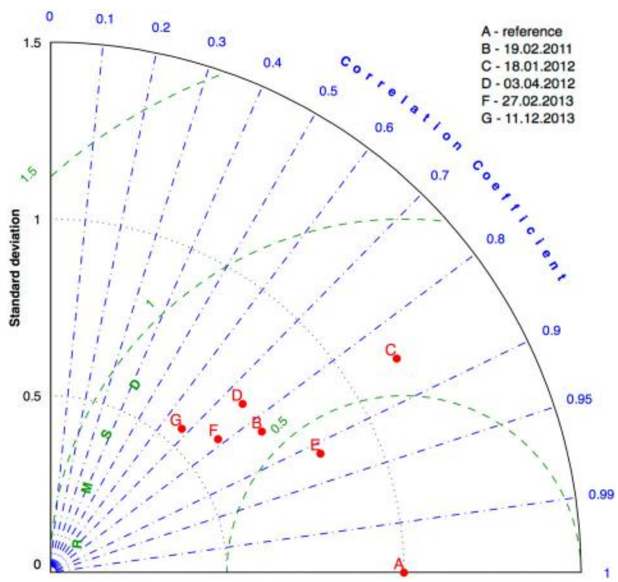

Figure 8. Taylor diagram for temperature.

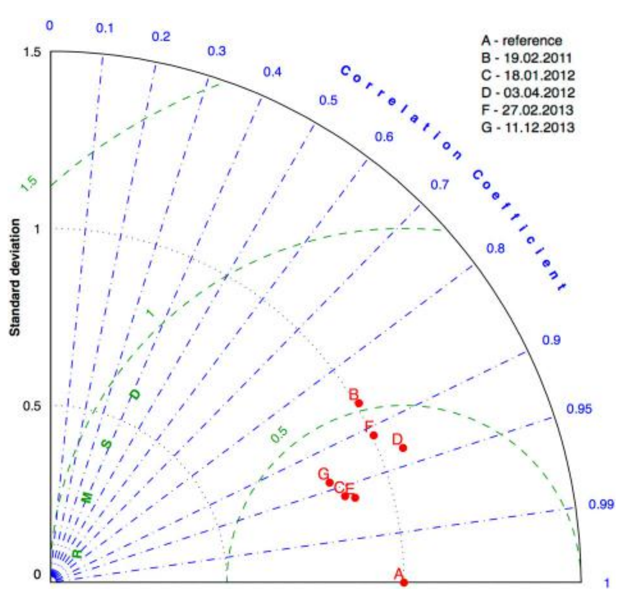

Figure 9. Taylor diagram for salinity.

Table 1. Statistical comparison of temperature results.

Date	R	σ (°C)	$<\varepsilon>$ (°C)	RMSE (°C)
19.02.2011	0.83	1.30	0.62	1.03
18.01.2012	0.85	0.99	−0.30	0.53
03.04.2012	0.75	0.81	−0.10	0.74
27.02.2013	0.91	1.24	0.10	0.61
23.04.2013	0.78	0.66	0.66	0.70
11.12.2013	0.68	0.56	−0.29	0.75

show any clear connection with seasons. Neither do systematic and statistical errors. In case of salinity the bias is always positive indicating that salinity calculated by the model is slightly higher than that measured *in situ*. However, this difference is relatively small.

Constantly forming thermocline and its migration during the year will find impact on the model's performance. The best reflection of the hydrological data is in the first quarter of the year (Figures 2 and 3) while the upper layer is well mixed after winter storms. Warming of the surface layer in April (Figure 5) forces winter water to remain at the depth of 50 m. However, in early April (Figure 4), a thin layer of winter water observed in measurements is not present in model results. Thick winter layer in late April (Figure 5) is visible although the difference in temperature between data is ca 1.5°C. Cooling of upper layers in December (Figure 6) leads to a nearly constant temperature in the mixed layer, which is well reflected by model results. However, beneath thermocline, where the advection is the most important forcing factor, differences between data are very high, ca 3°C. These differences are noticeable in both, vertical and horizontal directions.

The salinity changes are well maintained by the model. The maximum difference is ca 1.5 psu. Taking

Table 2. Statistical comparison of salinity results.

Date	R	σ (PSU)	$<\varepsilon>$ (PSU)	RMSE (PSU)
19.02.2011	0.86	1.64	0.99	0.85
18.01.2012	0.96	1.85	0.24	0.63
03.04.2012	0.93	2.27	0.63	0.81
27.02.2013	0.96	2.26	0.70	0.70
23.04.2013	0.91	2.25	0.93	0.95
11.12.2013	0.94	2.00	0.58	0.84

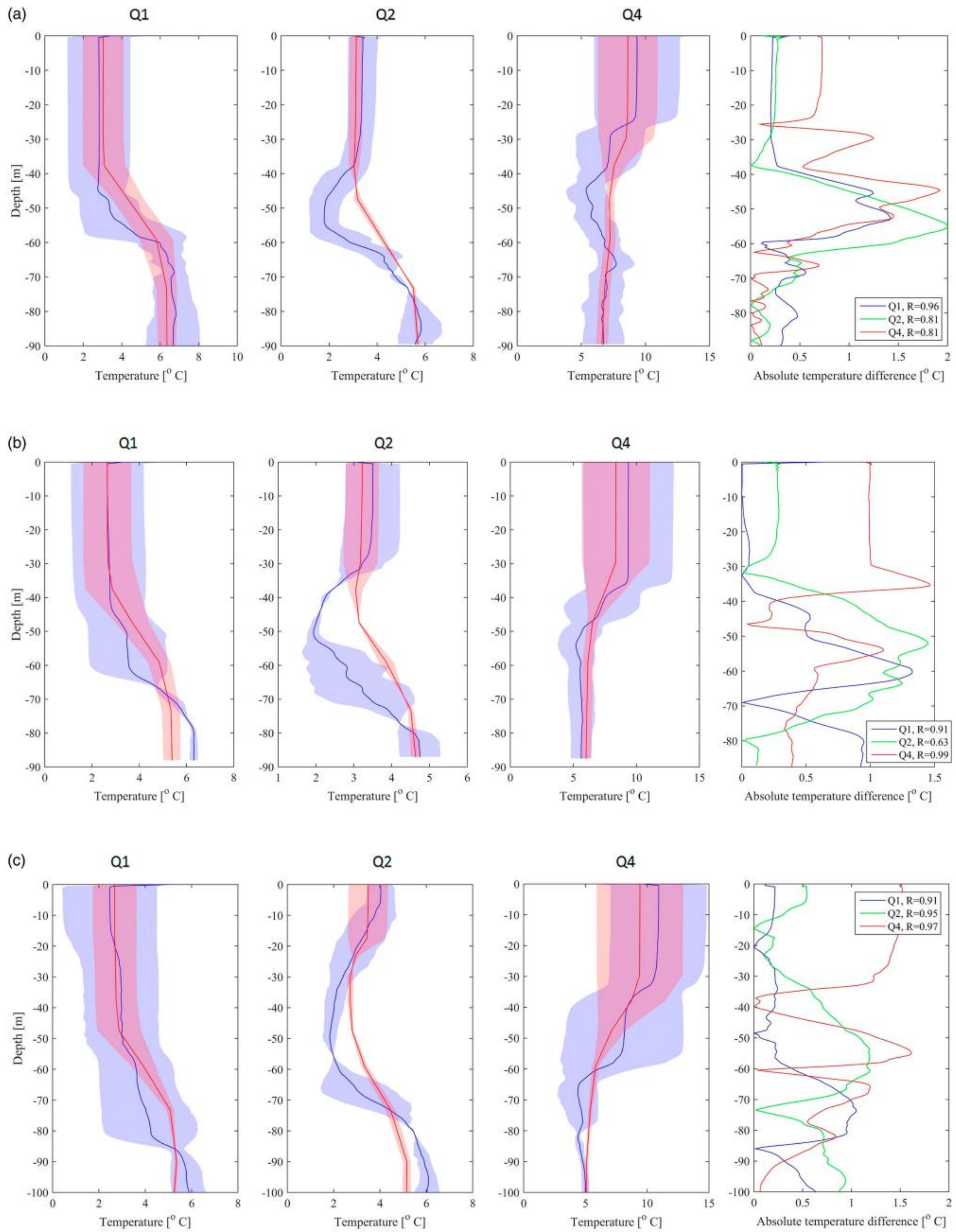

Figure 10. Mean temperature, standard deviation and difference between the model and *in situ* data for three quarters of the year. The upper plots represent BD, middle SF and bottom GD, where red is model, blue is *in situ*.

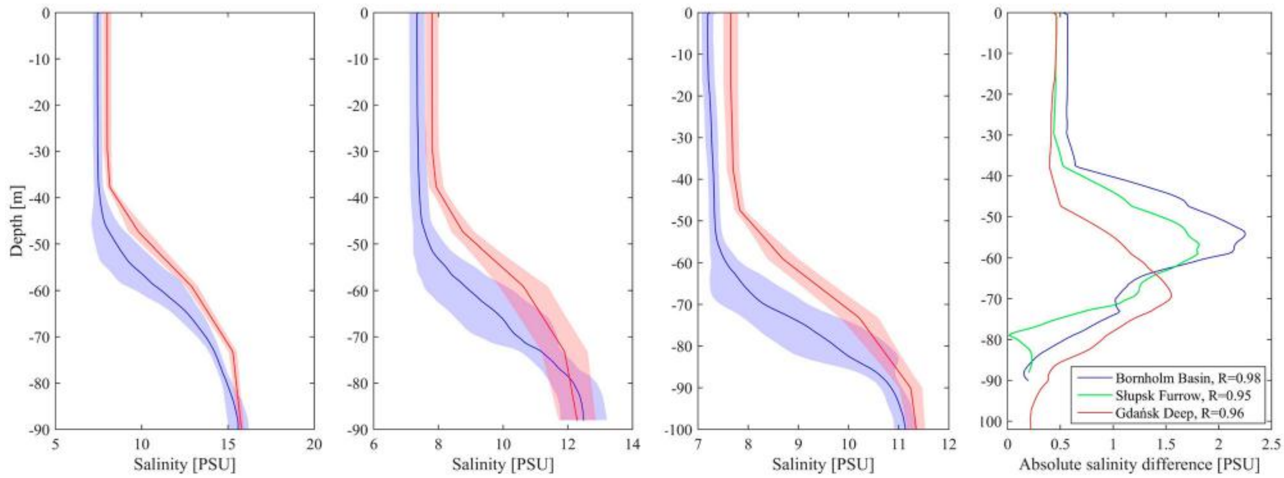

Figure 11. Mean salinity, standard deviation and difference between the model and *in situ* data. The plots represent BD, SF and GD, respectively. Red is model, blue is *in situ*.

into account advection of the saline water, there are inequalities (Figure 7). The difference between the depths of the halocline is bigger than the model's vertical resolution. The difference between haloclines depth reaches 15 m.

In situ and model data from three deep basins, BD, SF and GD were compared (Figure 10) taking into account temperature from three quarters of the year. Correlation coefficients are ca 0.81. General comparison between data is satisfactory. Lowest value of R can be observed in mixed layers, surface and near-bottom layer. However, differences in temperature rise from ca 0.5 up to 1.5°C for the first and fourth quarter of the year. Highest difference is mainly at the depth of thermocline and movement of the thermocline during the year causes maximum difference between the data sets. Salinity shows no seasonal variation and therefore Figure 11 shows only spatial differences between data for BD, SF and GD. The highest differences are at the depth of halocline and vary for each basin. Highest differences in BD, SF and GD are at the depth of 55, 60 and 70 m, respectively.

Conclusion

Simulated temperatures are generally well maintained. Differences arise with higher vertical gradients. Early thin layer of winter water is not present in the model results and late thick layer is slightly visible. Thus, differences between the data sets in the winter layer are up to 2°C. Vertical profiles of the temperature in the BD, SF and GD areas are well maintained by the model. The temperature difference between data sets is ca 0.71°C. Highest differences are visible in 23 April and 11 December 2013. The accuracy of the model is better in the first quarter of the year and slightly decreases with time. In case of salinity results show very good mean correlation ca 0.91. The depth of the halocline is similar as in the *in situ* data. However, highest differences can be observed mainly at the depth of thermocline and halocline. The lowest difference is at the surface and near-bottom layers. Therefore, it leads to conclusion that higher gradients of temperature and salinity cause bigger differences between model and *in situ* data. This means that model has some difficulties with reflecting the changes in the water's state. This can be caused by the thickness of vertical layers, which is increasing with depth. The thicker the layer, the harder it is to represent actual changes in temperature and salinity especially in the areas of high gradient values. Thus, the results suggest possibility, that higher model resolution may lower differences between the data and increase the accuracy of the model. Work on increasing the vertical model resolution is underway.

Combined simulations results and *in situ* data can be used to examine the mass, ocean currents and processes called inflows of saline water from the Danish Straits. Model data can be used to extend available data as well as to fill the gaps between hydrographical cruises. However, a comparison between 3D CEMBS model and cruises leads to the conclusion that further improvements of the model should be implemented. In particular the vertical resolution should be increased. However, to fulfil the basic purpose of this model such as simulate biogeochemical parameters, resolution is sufficient.

Acknowledgement

Calculations were carried out at the Academic Computer Centre TASK in Gdansk.

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

The partial support for this study was also provided by the project Satellite Monitoring of the Baltic Sea Environment – SatBaltyk founded by European Union through European Regional Development Fund [POIG 01.01.02-22-011/09].

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