Papers

Activation of the operational ecohydrodynamic model (3D CEMBS) – the hydrodynamic part*

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Abstract

The paper describes the hydrodynamic part of the coupled ice-ocean model that also includes the ecosystem predictive model. The Baltic Sea model is based on the Community Earth System Model (CESM from NCAR – National Centre for Atmospheric Research). CESM was adopted for the Baltic Sea as a coupled

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

sea-ice model. It consists of the Community Ice CodE (CICE, model version 4.0) and the Parallel Ocean Program (POP, version 2.1). The models are linked through a coupler (CPL7), which is based on the Model Coupling Toolkit (MCT) library. The current horizontal resolution is about 2 km (1/48 degrees). The ocean model has 21 vertical levels and is forced by atmospheric fields from the European Centre for Medium Weather Forecast (ECMWF). A preliminary validation of the hydrodynamic module with in situ measurements and reanalysis from My Ocean (http://www.myocean.eu) has also been done. In the operational mode, 48-hour atmospheric forecasts provided by the UM model from the Interdisciplinary Centre for Mathematical and Computational Modelling of Warsaw University (ICM) are used. The variables presented on the website in real time for a 48-hour forecast are temperature, salinity, currents, sea surface height, ice thickness and ice coverage (http://deep.iopan.gda.pl/CEMBaltic/new_lay/index.php). The embedded model of the marine ecosystem, like ice, is not taken into account in this paper.

1. Introduction

The Baltic Sea is a very difficult basin where numerical modelling is concerned. On the one hand, mesoscale phenomena require the whole basin to be included; on the other hand, quite small spatial bathymetric structures are of major significance to the Baltic's hydrology. There is very strong vertical density stratification in the benthic zone, which is very important for the transport of inflowing waters. The overall water balance has to include rivers and precipitation. The proper spatial scale and long-term simulation are thus required to obtain a satisfactory projection of the real state of the Baltic Sea. Changes in hydrological parameters and velocity fields are important at large temporal scales – from days and months to decades and even longer. These changes depend on short- and long-term changes in the atmosphere and in the ocean worldwide. The model calculations take into account changes in the time scale from days to decades. This is the direction being taken by research defined by BALTEX phase II (Analysis of changes and climate variability (BALTEX 2006a, 2006b)). At present, the most modern supercomputers make it possible to undertake such a difficult task, although certain simplifications are still necessary (Osiński 2007).

Dzierzbicka-Głowacka and her co-workers have published several papers on the modelling of hydrodynamic and biological processes, for instance: Dzierzbicka-Głowacka (2000, 2005, 2006), Dzierzbicka-Głowacka et al. (2006, 2010, 2011a,b). In 2012, the operational ecohydrodynamic model (3D CEMBS) was launched at the Institute of Oceanology PAS with a ca 2 km horizontal grid; this also included rivers and a closed lateral boundary for the hydrodynamic module. The hydrodynamic variables presented on the website in real time for a 48-hour forecast are temperature, salinity, currents, sea surface height, ice thickness and ice coverage (http://deep.iopan.gda.pl/CEMBaltic/new_lay/index.php). A preliminary validation of the hydrodynamic module with in situ measurements and reanalysis from My Ocean (http://www.myocean.eu) has also been done.

2. 3D-CEMBS Model description

The Community Climate System Model/Community Earth System Model (CCSM4.0/CESM1.0) is a set of models consisting of five separate components with an additional coupler (CPL7), controlling time, exciting forces, domains, grids and information exchange between the models. The best descriptions of all the components (including updates) are on the CCSM4 website: http://www.cesm.ucar.edu/models/ccsm4.0/. For our purposes, CESM was adapted to the Baltic Sea – we call it the Coupled Ecosystem Model Baltic Sea (3D CEMBS). However, it is not an entirely active configuration. The ocean model (Parallel Ocean Program, POP, version 2.1) and the ice model (Community Ice CodE – CICE, version 4.0) work in the active mode, and they are impacted by the atmospheric data model (this part is called the atmospheric data model with the acronym datm7, see Figure 1). Other models are excluded from this configuration (also referred to as the stub mode). The main task of datm7 is to interpolate atmospheric data into the model domain. 3D-CEMBS also includes an ecosystem module (see Figure 1).

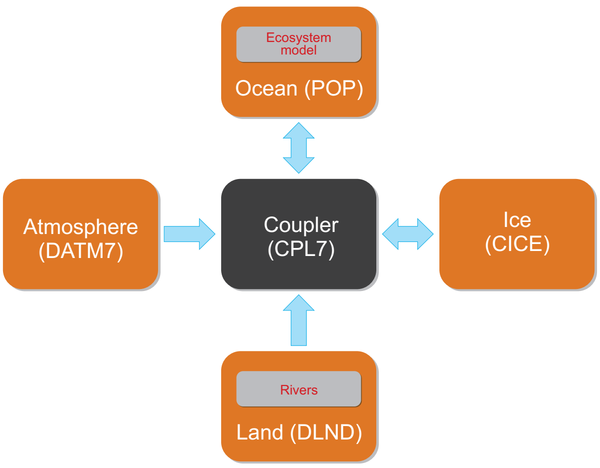

Figure 1. Schematic presentation of the Baltic model

The 3D-CEMBS model is configured at two horizontal resolutions – ca 9 and 2 km (1/12° and 1/48° respectively). The model bathymetry is represented by 21 vertical levels and the thickness of the first four

Table 1. Vertical resolution

Model level	Thickness	Lower depth	Mid-depth
1	5.0	5.0	2.5
2	5.0	10.0	7.5
3	5.0	15.0	12.5
4	5.0	20.0	17.5
5	6.0	26.0	23.0
6	7.3	33.3	29.7
7	8.8	42.1	37.7
8	10.6	52.7	47.4
9	12.8	65.4	59.1
10	15.4	80.8	73.2
11	18.6	99.4	90.1
12	22.4	121.8	110.6
13	27.0	148.9	135.4
14	32.6	181.5	165.2
15	39.3	220.8	201.2
16	47.5	268.3	244.6
17	57.3	325.5	296.9
18	69.1	394.6	360.1
19	83.3	477.9	436.3
20	100.5	578.4	528.2
21	121.6	700.0	639.2

surface layers is equal to five metres (Table 1). The bottom topography was based on ETOPO1-1, the arc-minute global relief model (http://www.ngdc.noaa.gov/mgg/global/global.html, National Geophysical Data Center). The bathymetric data were interpolated into the model grid by kriging. Initialization fields for temperature and salinity were interpolated from climatological data (Jansen et al. 1999) on the grid of the 3D CEMBS model. Other variables were obtained after cold-starting and running the model for several years to produce a spinup.

The ocean surface level (5 m depth) is restored on the basis of mean monthly T and S from climatological data, as a correction term to the explicitly calculated fluxes and overlying atmosphere or sea ice. The 3D-CEMBS domain is based on stereographic coordinates, but the equator of these coordinates is in the centre of the Baltic Sea (so we actually use rotated stereographic coordinates); we can assume that cells are square and that they are identical in area.

The current calculations are being performed on an IBM cluster type called Galera, which is located at the Academic Computer Centre in Gdańsk (CI TASK).

The driver time step is 1440 s; this also couples the time step. The time needed to compute a one-year integration of the ecohydrodynamic model is 30 hours on 16 processors for the 9 km resolution and 120 hours on 256 processors for the 2 km resolution.

2.1. The POP model

The ocean model is based on the Parallel Ocean Program (POP, Smith & Gent 2004) from the National Laboratory in Los Alamos (LANL), which is derived from the global ocean model (Semtner 1974) with additional conditions for a free surface (Killworth et al. 1991). This is a 'z' type model (identical thickness of layers for every cell); the three-dimensional equations describing the behaviour of the stratified ocean are solved by the model. Numerically, the model defines spatial derivatives in the spherical coordinates using the method of finite elements. The physical quantities of the model are embedded in the spherical grid of Arakaw B (Arakawa & Lamb 1977). It is a three-dimensional hydrodynamic model derived from the ocean model created in the late 1960s by Kirk Bryan (1969) and Michael Cox from the NOAA Geophysical Fluid Dynamics Laboratory in Princeton. The model was later modified and adapted by Semtner (1974) for vector processors. The whole class of models consisting of POP is called a Bryan-Cox-Semtner type model (B-C-S). The code of the model is adapted for supercomputers, but is also entirely suitable for machines of different architecture, for example, cluster types. The model is characterized by good numerical performance and is readily scalable on a large number of cores (Jones et al. 2003).

Models derived from the B-C-S type family are most commonly used for modelling the ocean. At present, B-C-S models are used in many research centres worldwide. These include both regional models, e.g. for the Baltic Sea (Meier 2005, Lehmann et al. 2004, Lass & Mohrholz 2003, Rudolph & Lehmann 2006), the North Atlantic (Brachet et al. 2004) and the Arctic (Masłowski et al. 2004) and global models (Lee & Coward 2003, Maltrud & McClean 2005), which analyse processes in coastal waters (Lass et al. 2001) and in the open ocean, over short periods of time and at small climatic scales (Nadiga et al. 2006; Bryan et al. 2006). In 2001, POP was adapted in the USA for the CCSM (Community Climate System Model) model as an oceanic component.

The list of primitive equations that the model solves is as follows:

– momentum equations,

– continuity equation,

– hydrostatic equation,

– equation of state,

– tracer transport.

These equations are typical and can be found in academic textbooks or POP reference manuals.

The barotropic solver is used in our configuration as a preconditioned conjugate gradient solver (PCG). Advection is represented by the central difference scheme. Horizontal mixing is parameterized by a biharmonic operator, and vertical turbulence is determined by k-profile parameterization (KPP – Large et al. 1994). The equation of state, introduced by McDougall et al. (2003), is also used. We have compared two schemes of horizontal mixing: Richardson vertical mixing and KPP. Like natural parameterization, KPP is diapycnal. The two schemes were compared with turbulence measurements by Li et al. (2001), who showed that the PP scheme underestimates turbulent mixing at low Richardson numbers (Ri) but overestimates turbulence mixing at high Ri (Peters et al. 1988). As a result, the thermocline simulated by the PP scheme is much too diffuse compared to observations. The KPP scheme does not assume a priori that the boundary layer is well mixed and explicitly predicts an ocean boundary layer depth. Within this boundary layer, turbulent mixing is parameterized using a nonlocal bulk Richardson number and the similarity theory of turbulence. Below the boundary layer, vertical mixing is parameterized through the local gradient Richardson number and a background mixing similar to the PP scheme. The results of a comparison of two independent runs with the same initial conditions and external forcing are presented in Figure 3 (see p. 528). This shows the same section from both runs with PP and KPP turbulence representations. The parameters used for both mixing schemes are presented in the descriptions of the images.

2.2. The CICE model

The ice model is based on elastic-visco-plastic (EVP) rheology (Hunke & Dukowicz 1997). Designed to work in accordance with the POP ocean model using parallel computing machines, it consists of several interactive elements: the thermodynamic model, which computes local growth rates of snow and ice from the vertical conduction of energy and momentum fluxes. It also defines the velocity of each ice cell based on wind and ocean velocity. It has a few vertical categories, so that the stress distribution is much closer to the real one. A detailed description of the ice model CICE (version 4.0) and its validation will be presented in a separate paper.

2.3. The atmosphere – external forces

The atmosphere contains exciting forces for the ocean and ice models. The atmospheric data come from ERA-40 reanalysis – daily average values for a period of 40 years.

The ERA-40 (ECMWF 40-year Reanalysis; Uppala et al. 2005) from the European Centre for Medium-Range Weather Forecasts (ECMWF) is a reanalysis of meteorological observations for the period September 1957–August 2002. The ERA-40 project incorporated all available observations, including satellite measurements, as well as the latest computing systems to create a consistent database (i.e. without implementation of changes for the entire computing period) for the past 40 years using one of the most modern models of the atmosphere. Omstedt et al. (2005) compared ERA-40 forces with data from the Swedish Meteorological and Hydrological Institute (SMHI), and concluded that only the low horizontal resolution ($2.5^\circ \times 2.5^\circ$) caused winds over the sea area to be weaker than they are in fact.

To be able to use the ERA-40 data available on a numerical grid other than the grid of the Baltic model, it was necessary to interpolate the data. This was done by applying two-dimensional spline functions of the third order (Press et al. 2001).

The operational system uses 48-hour meteorological forecasts updated every 6 hours from the UM model used by the Interdisciplinary Centre for Mathematical and Computational Modelling of Warsaw University (ICM UW).

The model uses the following external fields:

- 2 metre air temperature and specific humidity,
- sea level pressure,
- precipitation (rain and snow),
- short and long wave radiation downwards,
- wind speed at 10 m height,
- air density.

2.4. River discharge

Volume data on river discharge come from the Balt-HYPE model of SMHI. Balt-HYPE is a hydrological model for simulating the flows of water and substances from precipitation, through the earth into streams and lakes, as far as river mouths. River basins are divided into subregions, and each subregion is further divided into classes according to land cover, soil type and altitude. Seventy-one rivers were included in the model. The catchment areas of most of the rivers lie in Sweden (34 rivers) and Finland (25 rivers).

Rivers in Estonia (4), Latvia (3), Poland (2), Lithuania (1), Russia (1) and Norway (1) were also included.

River discharge data has daily means. However, since we have no data with river discharge forecasts but only the database of the daily values from the years 1971–2008 (Balt-HypeWeb model, http://balt-hypeweb.smhi.se) the data for the operational model had to be approximated for the years after 2008. The approximation was carried out in two steps. First, we calculated the annual discharge for 2009–2013. The second step was to estimate the percentage input of each day to the total annual discharge.

2.5. Lateral boundary conditions

The model domain used in the 3D CEMBS is closed for computing reasons at the boundary between the Baltic and the North Sea, i.e. near the Skagerrak. In order to obtain the correct flows (including inflows into the Baltic Sea), it was necessary to create a flow in the Skagerrak, which would depend on the model time. In practice, each method has advantages and disadvantages, so it is good to use more than one method simultaneously. Basically, one method has been used – spectral nudging in the Skagerrak (restoring to climatological data).

At the ocean model surface the total heat budget is calculated from equation (1):

$$Q_T = Q_{SW} + Q_{LW\mathrm{in}} - Q_{LW\mathrm{out}} + Q_S + Q_l \,, \tag{1}$$

where Q_T – total heat flux at the ocean surface, Q_{SW} – net short-wave radiation, $Q_{LW\mathrm{in}}$ – incoming long-wave radiation, $Q_{LW\mathrm{out}}$ – outgoing long-wave radiation, Q_s – sensible heat flux, Q_l – latent heat flux.

Short- and long-wave radiation are taken from the UM weather model (ICM UW) (both are downward). At the sea surface the budget is presented in the paper (equation 1). The ocean model needs the net long-wave radiation, not the downward radiation. This means that outgoing waves are calculated in the model (at the coupler level) on the basis of simple black-body radiation (Stefan-Boltzmann law). Outgoing long waves are proportional to the fourth power of the surface temperature and emissivity of the sea surface (which is ca 0.9). Sensible heat flux is proportional to shear velocity and the difference between sea surface temperature and air temperature. Latent heat flux is calculated from the specific humidity difference.

Precipitation is treated as a freshwater flux (from the ocean's point of view, snow and rain are the same).

Wind stress at the topmost cell surface is proportional to the square of the wind speed and the wind direction. It is also proportional to the drag coefficient.

The bottom stress uses the quadratic drag coefficient (2):

$$\tau_u = (\gamma_1 + \gamma_2 \sqrt{u^2 + v^2}) \rho_o u \,, \tag{2}$$

where τ_u – bottom stress in u direction (zonal), ρ_o - water density, u, v – velocities in the u and v directions, γ_1 – linear drag coefficient (equal to zero when using the quadratic drag coefficient), γ_2 – quadratic drag coefficient.

This formula is more general than typical. It combines the linear and quadratic drag formulas. If γ_1 is equal to zero, we have the quadratic formula, but if γ_2 is zero, we have the linear one. The quadratic drag coefficient is dimensionless and has a value of the order of 10^{-3}; γ_1 was estimated to be 10^{-4}.

2.6. The operational system

To guarantee the systematic operation of this model, it was necessary to prepare a fully automatic system to support it. The system's operation is divided into a number of stages. The first one involves collecting and preparing the atmospheric data used by this model. These data are retrieved from the servers of ICM UW. They include 48-hour meteorological forecasts updated every 6 hours. After the data have been downloaded, a series of processes follows, which aim to adapt them to the model's requirements. In addition, the data are archived and backed up on local disks. Next, the model restart parameters are defined. Then the model starts and monitors the performance of the model, which is followed by retrieval of the results and their storage in the archive and on the website (http://deep.iopan.gda.pl/CEMBaltic/new_lay/index.php). A detailed description of the system will be presented in a separate paper.

3. Results

In the first half of 2011, the new CESM model was adapted to the Baltic domain.

The models have been adapted and work properly (see the website of this model). The results of 48-hour forecast simulations for areas and points are presented for the two model configurations described above. At present, the following parameters are available: temperature, salinity, water currents, sea level and ice coverage.

Model results are presented below showing the correct pre-validation operation describing KPP-parameterization, long-term surface temperature distributions and the initial model validation of the main hydrodynamic parameters for the year 2000.

3.1. KPP-parameterization

Preliminary tests were performed to validate the model on the 2 km grid. Figure 2 shows the vertical distribution of temperature measured at the end of summer 2000 in the Baltic Sea, performed using Richardson vertical mixing (Figure 3a) and k-profile parameterization (KPP) (Figure 3b). The coefficients used for PP vertical mixing were: background vertical viscosity bckgrnd_vvc = 0.2 cm^2 s^{-1}, diffusivity bckgrnd_vdc = 0.05 cm^2 s^{-1} and the coefficient of the Richardson-number function rich_mix = 50. The coefficients

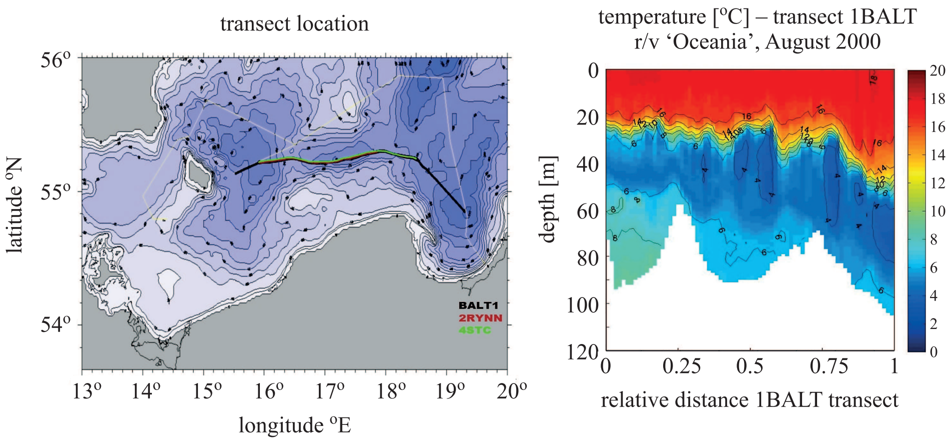

Figure 2. The temperature profile measured in the Baltic Sea in August (measurement taken at the Institute of Oceanology PAS)

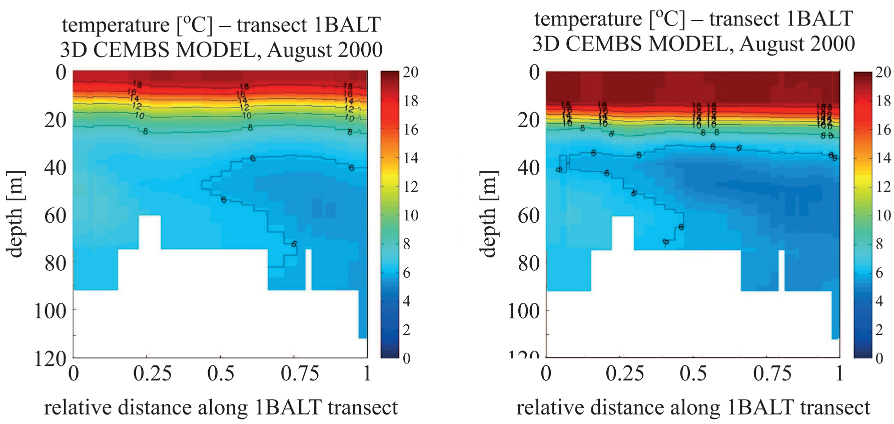

Figure 3. The temperature profile based on Richardson vertical mixing (left) and on KPP (right)

used in the KPP scheme were: base background vertical diffusivity bckgrnd_vdc1 = 0.02 cm^2 s^{-1}, depth at which background vertical diffusivity is vdc1 (0.02): bckgrnd_vdc_dpth = 25 × 10^6 cm, inverse of length scale over which diffusivity transition takes place bckgrnd_vdc_linv = 4.5 × 10^{-5} cm^{-1}, ratio of background vertical diffusivity to viscosity Prandtl = 10, coefficient for Richardson-number function rich_mix = 50 (Large et al. 1994).

In situ data (Figures 2 and 4) were collected during regular cruises of r/v 'Oceania' in the southern Baltic Sea using a profiling CTD probe towed behind the vessel. The main section (transect 1BALT, Figure 2a) was located along the axis of deep basins starting from the Arkona Basin and continuing over the Bornholm Deep and Słupsk Furrow as far as the Gdańsk Deep.

The results show that KPP yields a much better temperature distribution in the Baltic Sea, both in August and in other months (see Figure 4). Comparisons of other years yield similar results.

Comparison of model results with in situ data indicates that the model accurately reflects vertical mixing, reflected by temperature distributions in the water column (Figure 4).

3.2. Long-term temperature distributions

In addition, simulations were performed with historical data, which were compared with the model data (results from the 3D CEMBS and SMHI models (see Figure 5 in Meier 2002)) and the experimental data (on four measuring buoys deployed in the Baltic Sea, Figure 5) from HELCOM http://ocean.ices.dk/helcom/Helcom.aspx?Mode=1 and SMHI http://www.smhi.se/oceanografi/oce_info_data/SODC/download_en.htm.

The simulations and measurements from 1963 to 2007 were compared. The correlations of all the parameters recorded decrease from surface to bottom. The consistency of the calculated values with the measured distributions was particularly good with regard to temperature. These results also testified to the fact that the environmental conditions did not radically change and the simulated processes behaved as expected.

Figure 6 shows the modelled sea-surface temperature. The modelled values of this temperature (T_{mod} – the value from the first layer – 5 m) were compared with values measured in situ (T_{exp} – the sea-surface temperature) at particular measurement stations; the estimated errors are set out in Table 2.

The calculated mean errors (systematic and statistical) in the investigated region of the Baltic Sea are -0.05025 and ± 1.33 respectively. Also,

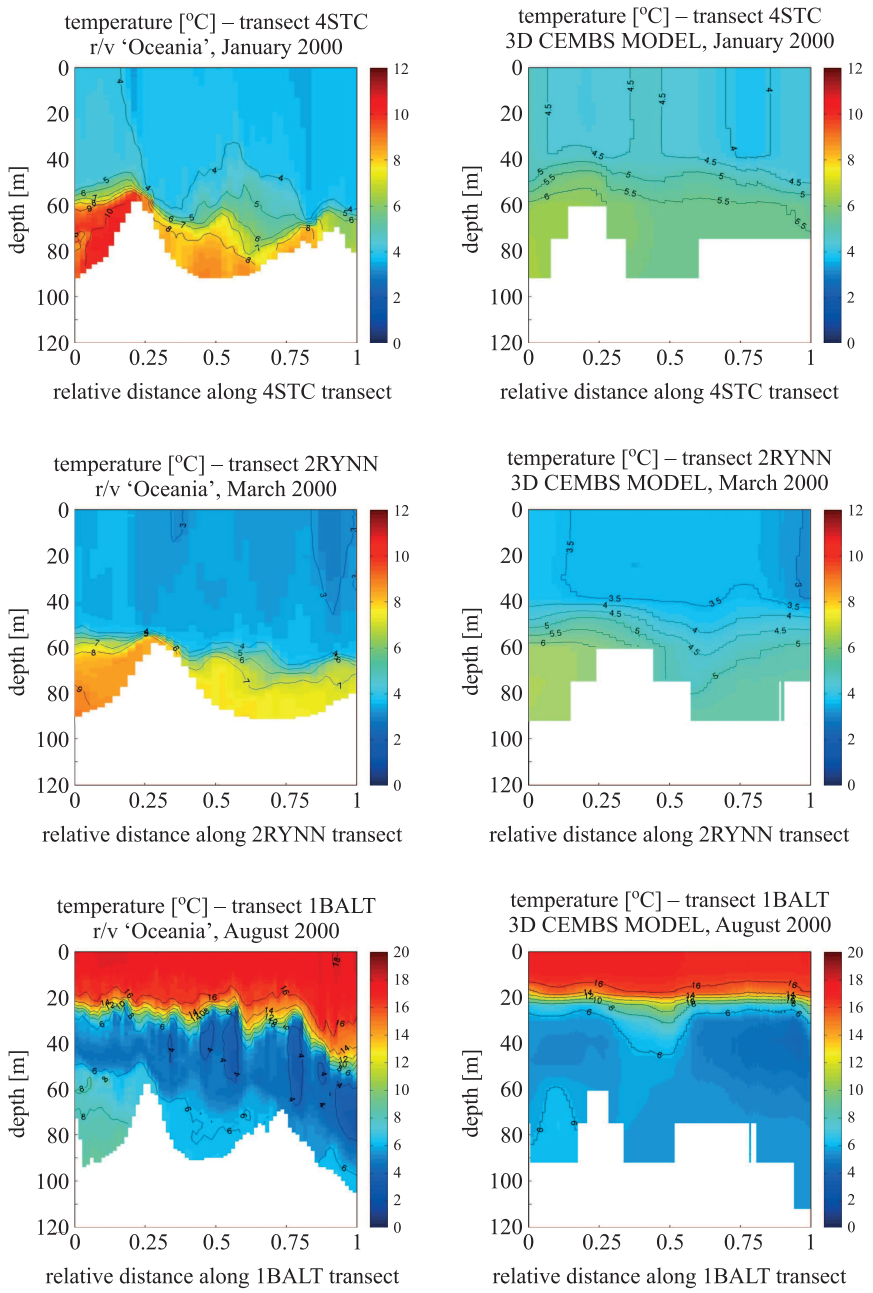

Figure 4. The temperature profile based on in situ data (left) and on model results (right)

the Pearson product-moment correlation coefficient was used to compare the model results of the sea surface temperature with the measurements (see

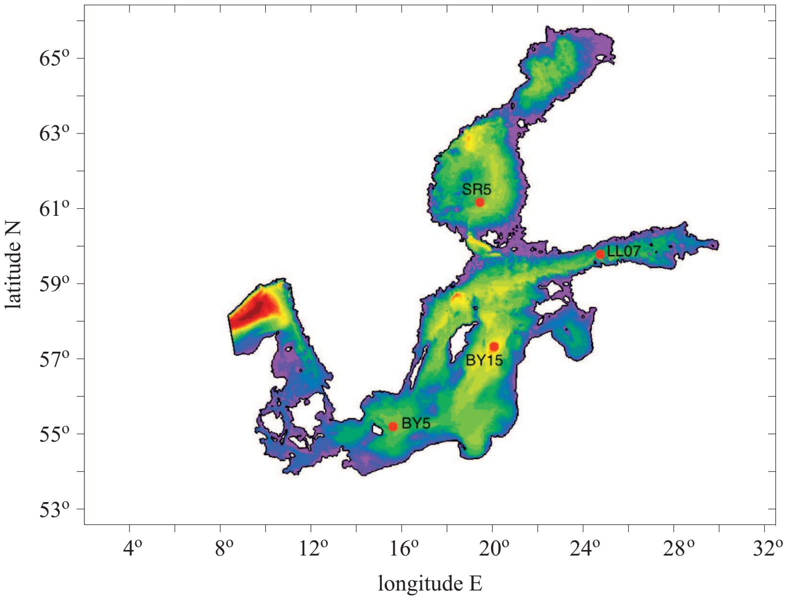

Figure 5. Distribution of measuring buoys for which the comparison was performed (see Figure 1 in Meier 2002)

Table 2, last column). The mean correlation coefficient for four points was 0.97035 for 1963–2007.

This level of accuracy is satisfactory for diagnosing the state of the Baltic ecosystem, because the model state parameters are calculated for the whole cell (an area of ~ 4 km^2), not for particular points at sea where the in situ measurements were performed.

Moreover, the results from Meier's (2002, Figure 5) and our model for the period 1980–1994 are very similar. They were presented at the 8th Baltic Sea Science Congress (Janecki et al. 2011).

3.3. Initial validation

Data from the MyOcean model (http://www.myocean.eu/web/38-modelling.php) were also compared in two regions for the year 2000. This reanalysis is based on the Baltic community physical ocean model code Hiromb-BOOS-Model (HBM-V1). The main hydrodynamic results from two models (MyOcean and 3D CEMBS) are presented in Figures 7 and 8. Figure 7 shows the surface distributions of temperature, salinity, currents and sea level from the model that are compared to MyOcean data. Salinity and temperature were also presented with experimental temperature from SMHI, and Figure 8 shows the vertical profiles. It is evident that the

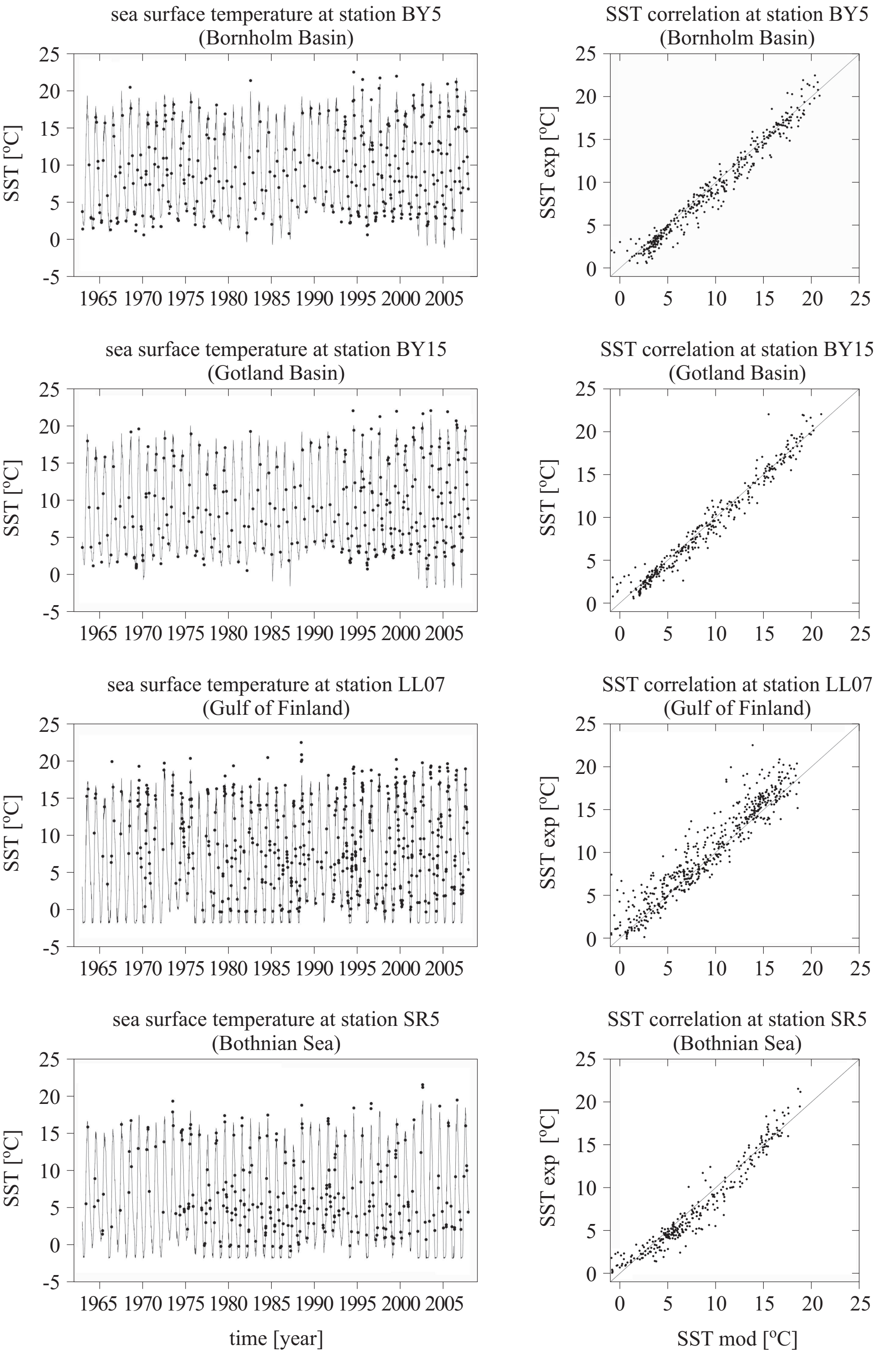

Figure 6. Comparison of the model results (*continued on next page*)

(**Figure 6.** *continued*) of the sea surface temperature with experimental data from HELCOM http://ocean.ices.dk/helcom/Helcom.aspx?Mode=1 and SMHI http://www.smhi.se/oceanografi/oce_info_data/SODC/download_en.htm

Table 2. Absolute errors and correlation coefficients in estimating the sea surface temperatures on the basis of modelled data from CEMBS model for four points: BY5 – Bornholm Deep, BY15 – Gotland Deep, LL07 – Gulf of Finland and SR5 – Bothnian Sea

Point	Arithmetic statistics		Correlation coefficient
	Systematic error $<\epsilon>$ [°C]	Statistical error σ_ϵ [°C]	
BY5	0.479	$\pm$ 1.05	0.9821
BY15	0.170	$\pm$ 1.10	0.9815
LL07	−1.070	$\pm$ 1.80	0.9518
SR5	0.220	$\pm$ 1.37	0.9660

correlation is best for temperature profiles. Salinity is also well correlated. While the distributions of currents and sea level are not incorrect, they are not as good as those of temperature and salinity. The correlation coefficients, statistical and systematic errors are given at the top of the images. It is difficult to say why there are differences between the data from MyOcean and CEMBS. MyOcean also provide modelled output, but after reanalysis. There is no trend in CEMBS output (this means that currents in the Gulf of Finland are slightly stronger than those yielded by reanalysis, but in the Baltic Proper these values are very similar). Moreover, the salinity and temperature profiles show rather good agreement between the two models. Obviously, a very important part of the model is the bottom topography. If the bathymetry is closer to reality, the currents should be more consistent. The representation of turbulence is also very important. But the salinity and temperature profiles show that our choice was no aberration. The model does not have any assimilation that could improve the results.

Figure 4 shows a comparison between in situ measurements of temperature and our model for three transects done from r/v 'Oceania' in January, March and August 2000. The lines representing those transects are shown on the left-hand side of Figure 2. Subsurface layers have a very similar temperature and the profiles are not identical. The modelled bottom layers are underrepresented, and we think that the model requires a little work on horizontal and vertical parameterization, although salinity and temperature profiles are very similar (see Figure 8). The horizontal axis shown in the

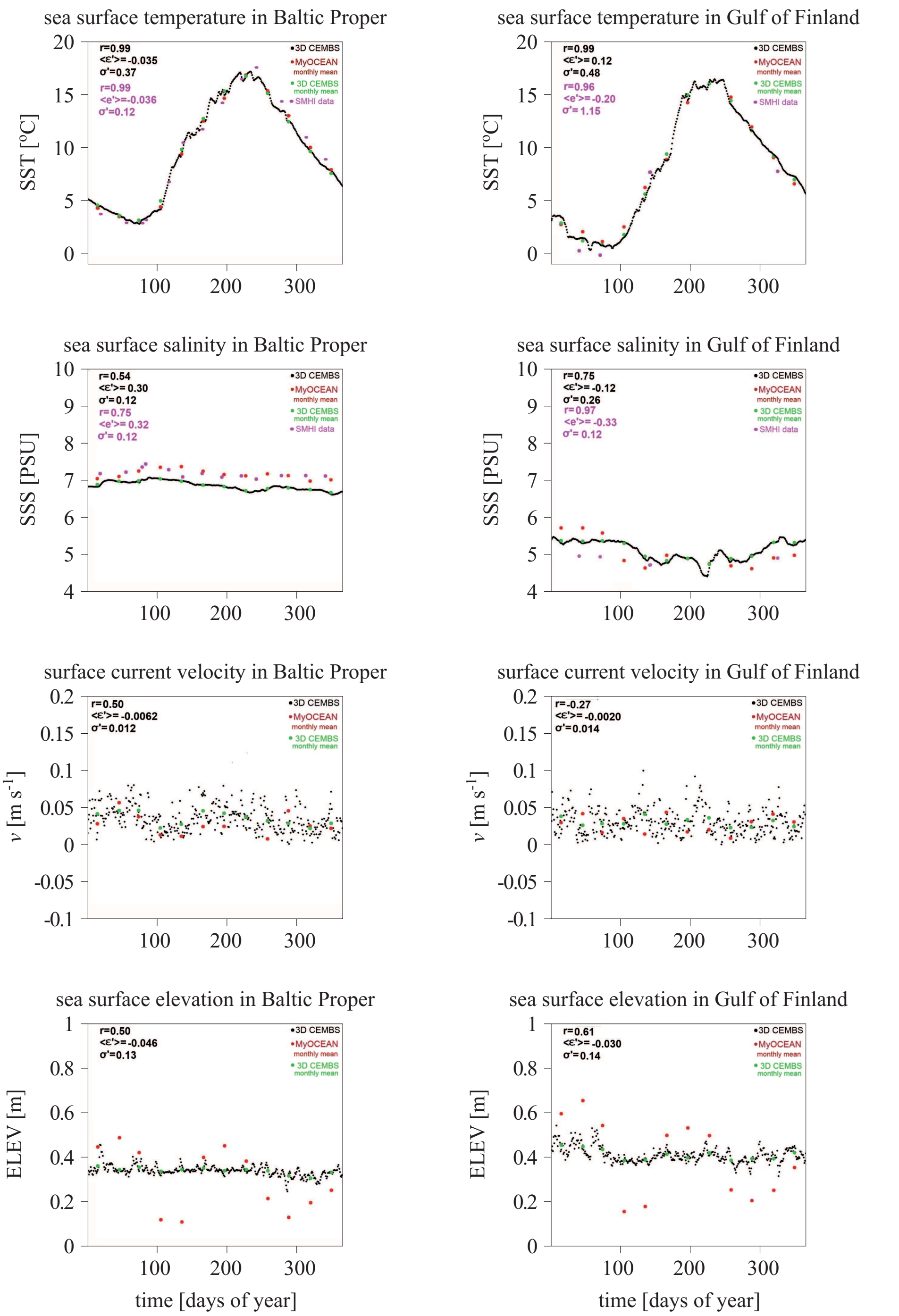

Figure 7. Comparison of surface distributions of the temperature, salinity, currents and sea level for two regions (Gdańsk Deep (*continued on next page*)

(**Figure 7.** *continued*) and Gulf of Finland). Data from MyOcean, 3D CEMBS model and SMHI (only temperature and salinity)

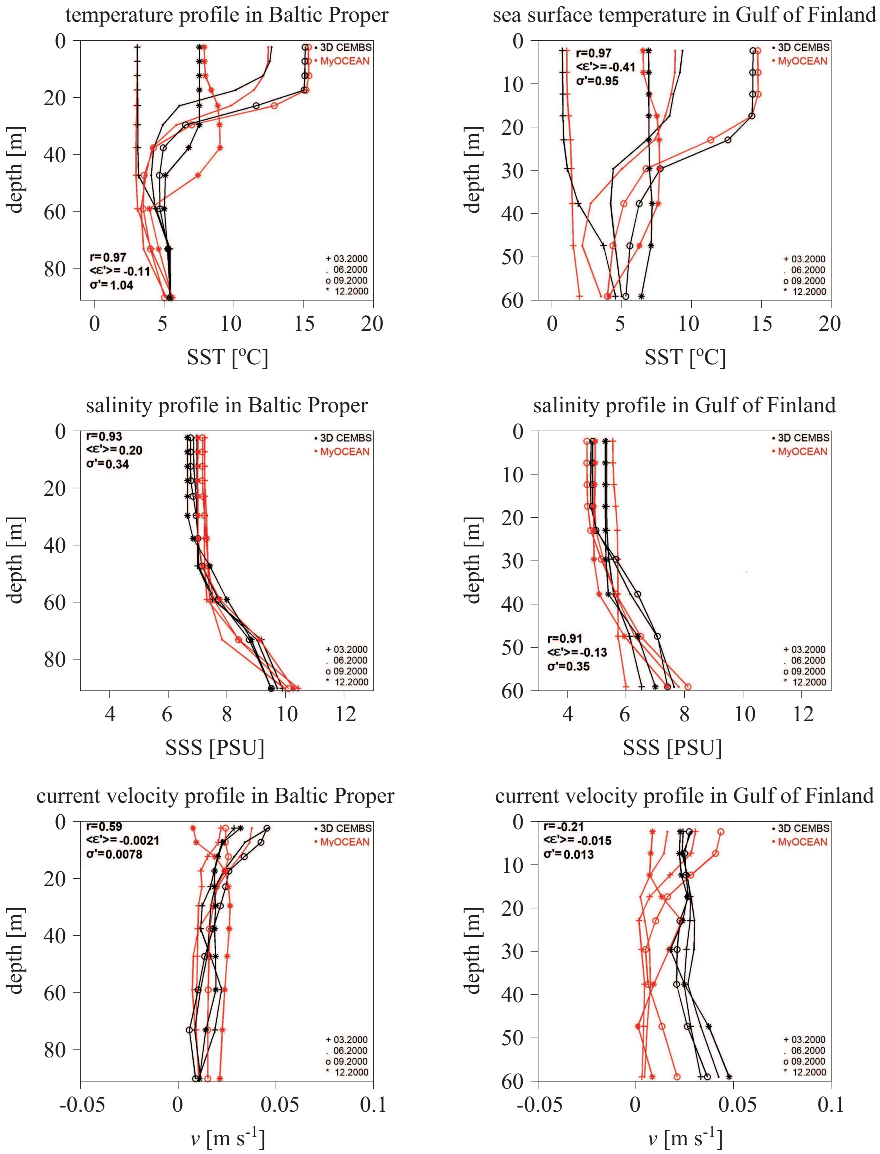

Figure 8. Data from MyOcean and 3D CEMBS model. Vertical profiles of the main hydrodynamic parameters, temperature, salinity and velocity (absolute value) for two regions (Baltic Proper and Gulf of Finland)

images of the transects shows relative distance along the transect. This means that 0 is the starting point of a transect and 1 is its end point (see Figure 2).

The results are typical of our model. With increasing distance from the Danish Straits, the salinity and temperature profiles become more consistent with the MyOcean model and measurements. This implies that the Danish Straits region requires more detailed bathymetry to ensure correct saline and dense water transport.

3.4. Ice component

Temporal ice cover is a significant element in the modelling of the Baltic Sea. Ice cover prevents the exchange of momentum and heat fluxes between the atmosphere and the sea. The northern Baltic (the Gulf of Bothnia, the Bothnian Sea, the Gulfs of Riga and Finland) is covered with ice every winter, whereas the southern Baltic is ice-covered only during severe winters. In winters of average severity, 45% of the Baltic Sea is covered with ice, which in the northern regions of the sea remains for half a year. As we have already indicated, this model contains the ice model (CICE) as an active component. But as the results from the ice model are not the main focus

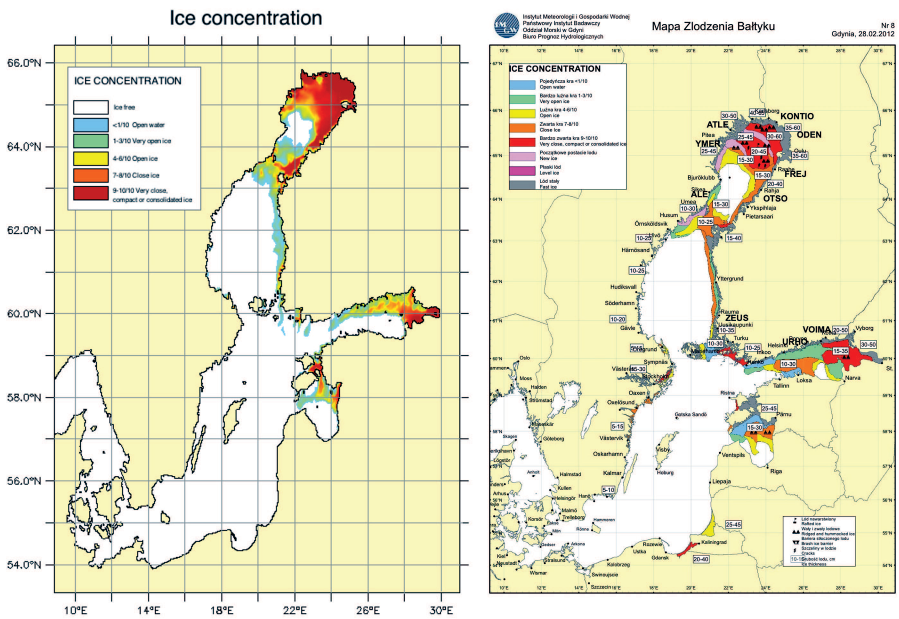

Figure 9. Ice concentration [%] – results obtained from the model (a) and experimental data from the Polish meteorological service (IMGW http://www.pogodynka.pl/baltyk) (b) for 28 February 2012

of this paper, we show only a comparison between the operational model and the observed Baltic Sea ice state from the Baltic Sea meteorological services. The ice concentration from both sources is presented in Figure 9. It is immediately evident that there is good agreement between real ice concentrations and model results.

4. Conclusions

At present, one of the most important aspects of oceanological studies is monitoring the state and bioproductivity of marine ecosystems. Bioproductivity plays a considerable role in local and global changes. These are difficult to assess as we need to understand not only the mechanisms affecting biological production and the functional relations between physiological processes in zooplankton species, but also the environmental parameters in the sea and how they influence the food chain.

To study the complexity of hydrophysical and biological processes in the marine environment, and the links between these processes, state-of-the-art mathematical modelling and computer simulations are required. Although fieldwork provides the most reliable information on these mechanisms and processes, it requires comprehensive and costly in situ observations conducted under a variety of hydrological conditions over long periods of time. They are nevertheless essential for the collection of sufficient statistical data for an adequate diagnosis of the state of the environment and for forecasts. The variables presented on the website in real time for a 48-hour forecast are temperature, salinity, currents, sea surface height and also ice thickness and ice cover.

The 3D CEMBS model (at present – the hydrodynamic module) is a suitable tool for studying the variability of environmental parameters in the southern Baltic Sea at time scales from days to many years. It can also be used to forecast ecological changes in the Baltic.

The next step in our modelling work will be to run the operational system for the biological module on the 2 km grid with the assimilation of satellite data (to be presented in a separate paper). We also intend to run the ecosystem model within the population model to study the impact of climate changes on the growth of the most important species of calanoid copepods in the Baltic Sea.

Because the amount of data on sea colour is limited by clouds in temperate latitudes, models assimilating satellite data are going to be an important part of the SatBałtyk project (Woźniak et al. 2011a,b) (within which the present model is to be applied).

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