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Development and validation of a high-resolution hydrodynamic model for Polish Marine Areas

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Abstract

This study presents the development and validation of a high-resolution 3D hydrodynamic model, CEMBS-PolSea, designed to resolve submesoscale features in Polish Marine Areas. The model, derived from the Community Earth System Model (CESM), employs a horizontal resolution of 575 m and 66 vertical layers. It incorporates advanced parameterizations for horizontal and vertical mixing processes, and integrates meteorological and river inflow data. A novel satellite data assimilation module was implemented to enhance model accuracy. The model was calibrated and validated using in situ measurements from the International Council for the Exploration of the Sea (ICES) database and satellite observations over the period 2019–2023. Results demonstrate strong agreement between model outputs and observational data, particularly for surface temperature (Pearson's $r = 0.95$) and salinity ($r = 0.89$). The model successfully captures temporal and spatial variations in temperature and salinity profiles, with some discrepancies noted in deeper layers. The integration of satellite data assimilation significantly improved model performance, particularly in surface temperature predictions. This high-resolution model represents a significant advancement in simulating complex coastal dynamics and submesoscale features in the Polish Marine Areas, offering a valuable tool for marine ecosystem management and climate change impact studies in the region.

Keywords

Numerical modelling; High-resolution model; Hydrodynamics; Southern Baltic

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1. Introduction

In recent years, the application of modelling studies has become a pivotal component in the monitoring and management of marine environments. This is particularly relevant for the Polish Marine Areas, where the complexity of ecological and hydrodynamic processes necessitates sophisticated and accurate modelling approaches. Current models employed for the Southern Baltic Sea environment include hydrodynamic models, biogeochemical models, and coupled physical-biological models. These models are instrumental in simulating various physical and biological processes, such as water circulation, temperature distribution, salinity, nutrient cycling, and plankton dynamics (Daewel and Schrum, 2013; Dzierzbicka-Głowacka et al., 2013a,b; Eilola et al., 2009; Gräwe et al., 2015; Hordoir et al., 2019; Markus Meier, 2007; Meier et al., 2014; Murawski et al., 2021). Hydrodynamic models, such as the Baltic Sea Ice-Ocean Model (BSIOM, Markus Meier, 2007), the HIROMB-BOOS Model (HBM, Murawski et al., 2021) and the General Estuarine Transport Model (GETM, Gräwe et al., 2015), are widely used to understand the physical dynamics of the Baltic Sea, including the Polish Marine Areas. These models simulate the movement and mixing of water masses, which is crucial for understanding currents, temperature distribution, and salinity gradients. Biogeochemical models, on the other hand, focus on the chemical and biological aspects of the marine environment, such as nutrient cycles, oxygen levels, and the dynamics of primary production. Coupled physical-biological models integrate these aspects to provide a holistic view of the marine ecosystem, facilitating the study of interactions between physical processes and biological responses (Eilola et al., 2009; Meier et al., 2014). One of the primary challenges in marine modelling is achieving a resolution that sufficiently captures the intricacies of these processes. Traditional models with lower resolution often fail to resolve small-scale phenomena, such as coastal currents, eddies, and localized nutrient upwelling. These small-scale processes are critical for understanding the marine ecosystems' overall health and dynamics. For instance, low-resolution mod-

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els might overlook the impact of small-scale eddies on nutrient distribution, which can affect primary productivity and, subsequently, the entire food web (Schrum et al., 2003). Recent advancements in computational power and modelling techniques have enabled the development of high-resolution models, which offer enhanced accuracy and detail. These improvements allow for better representation of complex interactions within the marine environment, including coastal dynamics, pollutant dispersion, and ecosystem responses to climatic and anthropogenic changes. For example, implementing high-resolution models has significantly improved the ability to simulate and predict hypoxic events in the Baltic Sea, which are crucial for managing fisheries and protecting marine biodiversity (Meier et al., 2014). Increased model resolution enhances our ability to predict and mitigate the impacts of various stressors on marine ecosystems. By resolving finer-scale processes, high-resolution models provide a more comprehensive and precise picture of the marine environment, facilitating informed decision-making and effective management strategies. This advancement is crucial for addressing contemporary environmental challenges, and ensuring the sustainability and health of the Polish Marine Areas. High-resolution models are also better equipped to simulate future scenarios under different climate change projections, helping policymakers and researchers develop adaptive strategies for marine conservation (Lehmann et al., 2011). The objective of this study is to utilize the high-resolution 3D hydrodynamic model CEMBS-PolSea (Coupled Ecosystem Model of the Baltic Sea — Polish Marine Areas) for a detailed analysis of submesoscale features in the Polish Marine Areas. We aim to present a model that has the potential to serve as a valuable tool for supporting ecosystem management and environmental protection by providing insights into how small-scale processes influence system dynamics. The paper also demonstrates the calibration and validation of the model by comparing its results with in-situ and satellite data, as well as other models, to assess its accuracy and practical applicability.

2. Material and methods

2.1 Preparation and configuration of the 3D physical model CEMBS-PolSea

The developed 3D model CEMBS-PolSea is derived from the Community Earth System Model (CESM) with a G-type configuration, which is a coupled global climate model developed by NCAR (National Center for Atmospheric Research). CESM consists of five separate components (modules) with an additional coupling element responsible for controlling the time step, forcing, domain, and information exchange between modules. For the CSI-POM project (Digital Information System for Polish Marine Areas), CESM was downscaled and adapted for the region of Polish Marine Areas and further developed at the Institute of Oceanology of the Polish Academy of Sciences. The horizontal resolution of the 3D CEMBS-PolSea model is about 575 m. Vertically, the model has 66 layers (levels) with thicknesses ranging from 5 to 83 meters.

The 3D CEMBS-PolSea model consists of active and passive components. The active element is the Parallel Ocean Program (POP). The passive modules are responsible for providing atmospheric and riverine freshwater forcing. The main part of the 3D CEMBS-PolSea model is the ocean model, in which horizontal mixing processes are represented by diffusion and advection. Energy dissipation is handled by a biharmonic operator. The vertical mixing applied in the model is known as “K-Profile-Parameterization” (KPP). Shear instability processes are parameterized using the Richardson number gradient, while diffusion and viscosity (regarding temperature and salinity) are implemented perpendicularly to the density isolines.

The domain of the 3D CEMBS-PolSea model covers the open Baltic Sea to the west and north, necessitating the provision of boundary conditions. For the hydrodynamic part of the model, in addition to temperature and salinity, it is necessary to prepare sea surface height data and barotropic current components. Boundary data for the model are provided by the 3D CEMBS model with a horizontal resolution of 2 km. It should be noted that using the results of the 3D CEMBS model as a source of boundary conditions means that, under operational conditions, the 3D CEMBS must complete its calculations before the 3D CEMBS-PolSea model can be run.

The ocean model (POP) used to develop the 3D CEMBS-PolSea model required significant modifications, which are presented in the Supplement along with the names of the modules that were modified (due to the numerous changes, they are described in a very general manner, and all detailed information can be obtained from the author).

2.2 Development of the numerical grid and bathymetry for the 3D CEMBS-PolSea model

The creation of a correct orthogonal numerical grid and the associated bathymetry is the most crucial element in developing the Southern Baltic model. An analysis of the requirements was conducted, and it was decided that a grid with a resolution of 575 m would be the optimal solution, balancing accuracy and computational efficiency. Advanced interpolation methods were applied to maintain the appropriate variability in the seabed topography. Subsequently, the obtained bathymetry was manually refined by overlaying it with high-resolution shoreline data. Corrections were made where necessary to ensure proper fluid (seawater) movement.

The bathymetric data come from the EMODnet Bathymetry database, which provides a service for viewing and downloading the most accurate available, consistent digital terrain models (DTM) for European marine regions, along with various bathymetric data, products, and ser-

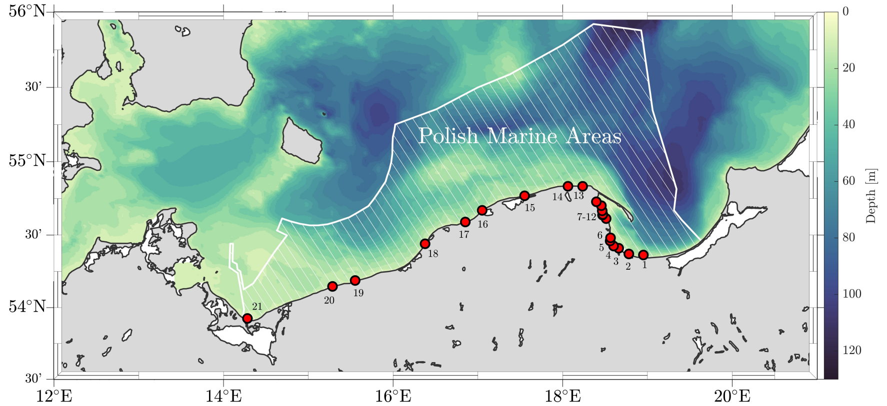

Figure 1. Bathymetry of the "effective domain" of the 3D CEMBS-PolSea model with marked river mouth locations for the 21 rivers implemented in the model and hatched Polish Marine Areas.

vices. The DTM is generated and regularly updated by the EMODnet Bathymetry team using an increasing number of bathymetric data sets.

By combining these data, a bathymetry with a horizontal resolution approximately 575 m, was created. Vertically, the grid is divided into 66 levels with thicknesses ranging from 5 to 83 meters. From the surface to 255 meters (255 meters correspond to 51 layers), the levels are 5 meters thick, and then their thickness increases up to 83 meters for level 66. The bathymetry covers not only the limits of Polish Marine Areas (Figure 1) but is larger, reaching also part of the North Sea, to ensure that the boundary conditions and related effects at the boundary do not affect the correctness of the results in the so-called "effective domain".

2.2.1 Preparation of input fields – meteorological data

At the interface between the water and the atmosphere, the 3D CEMBS-PolSea model is supplied with the meteorological data derived from the Unified Model (UM) developed at the Interdisciplinary Centre for Mathematical and Computational Modelling of the University of Warsaw. Certain parameters interpolated onto the model's grid serve directly as forcing data. These include wind components at a height of 10 m, air temperature at a height of 2 m, specific humidity, atmospheric pressure at sea level, convective and large-scale precipitation, and shortwave and longwave components of top-down radiation. Any absent parameters are computed through an additional atmospheric data module seamlessly integrated into the 3D CEMBS-PolSea model. This includes the determination of air density and the portion of scattered and direct radiation within the visible and near infrared spectrum.

2.2.2 Preparation of input fields – river inflows

In the 3D CEMBS-PolSea model, data on river flows were utilized from three sources, i.e.:

- The SWAT hydrological model, developed as part of the 'Integrated Information and Prediction Service WaterPUCK' project (Dybowski et al., 2020, 2019; Dybowski and Dzierzbicka-Głowacka, 2023; Dzierzbicka-Glowacka et al., 2022).
- The HYPE hydrological model, which provides publicly available historical data on river flows.
- Operational river flow data from the Institute of Meteorology and Water Management (IMGW), acquired through the CSI-POM project funding.

In the 3D CEMBS-PolSea model, 21 rivers flowing into the Baltic Sea from the territory of Poland were implemented (Table 1). The locations of these rivers within the domain of the 3D CEMBS-PolSea model are marked with red points in Figure 1.

2.3 Satellite data assimilation module

Leveraging the source code of the Parallel Ocean Program modules (POP), the 3D CEMBS-PolSea is equipped with a new integrated satellite data assimilation module. Implementation of the assimilation module was performed in two phases. Firstly, the module that is responsible for obtaining and processing the satellite-derived sea surface temperature data from the SatBałtyk system was developed. Subsequently, a novel method was devised for assimilating satellite data, and was then integrated into the framework of the 3D CEMBS-PolSea model. The aim of this addition was to improve the overall accuracy of model results, both in the case of short-term forecasts as well as retrospective long-term analyses utilising historical datasets. Although temperature assimilation may potentially improve the accuracy of other modeled variables, in this study we will focus solely on presenting the improvements in temperature.

2.3.1 Satellite data processing module

Satellite data used in CSI-POM come from the SatBałtyk project database and are sea surface temperature (SST) results based on measurements from the Moderate Resolution Imaging Spectroradiometer (MODIS AQUA) and

Table 1. List of rivers implemented in the 3D CEMBS-PolSea model along with the indication of data sources and average flow from 2019–2023.

No.	Data source	River Name	River mouth		
			Longitude	Latitude	Average flow [$m^3\ s^{-1}$]
1	IMGW	Vistula	18.952222	54.363333	840.91
2	IMGW	Bold Vistula	18.780833	54.370556	4.25
3	IMGW	Still Vistula	18.660833	54.41	4.25
4	HYPE	Oliwski Stream	18.600586	54.424954	0.31
5	HYPE	Kamienny Stream	18.56	54.46	0.45
6	HYPE	Kacza	18.564578	54.480982	0.29
7	HYPE	Ściekowy Canal	18.512801	54.612853	0.21
8	SWAT	Zagórska Stream	18.470111	54.637337	0.11
9	IMGW	Reda	18.473611	54.641111	3.83
10	SWAT	Gizdepka	18.466508	54.665896	0.3
11	SWAT	Żelistrzewo Canal	18.456478	54.701147	0.17
12	SWAT	Płutnica	18.397408	54.727827	0.91
13	HYPE	Czarna Woda	18.235621	54.833114	2.13
14	HYPE	Piaśnica	18.0625	54.833333	3.88
15	IMGW	Łeba	17.550913	54.768489	5.46
16	IMGW	Łupawa	17.050754	54.669476	7.00
17	IMGW	Słupia	16.851781	54.589827	14.94
18	IMGW	Wieprza	16.377235	54.440368	14.00
19	IMGW	Parsęta	15.552121	54.187679	21.24
20	IMGW	Rega	15.285449	54.146726	14.3
21	HYPE	Oder	14.281895	53.924596	652

the Advanced Very High Resolution Radiometer (AVHRR). Prior to being used by the model, these results undergo a calibration process to local Baltic Sea conditions, alongside atmospheric correction and filtration procedures. Raw maps are linked in space, corrected geometrically for changes in the satellite's position and radiometrically in case of numerical errors during data transmission. Data in the SatBałtyk system have a horizontal resolution of 1 km and cover the entire area of the Baltic Sea. Therefore, after reception, the system narrows the area down to the CSI-POM model domain and interpolates it onto the 575 m resolution grid used in the project. Daily average values obtained by combining all satellite images available on a given day are used for assimilation. The middle of the assimilation window is every day at noon. This is taken into account during the process of combining the data by applying appropriate weights dependent on the time difference between noon and each measurement. The data acquisition module is fully automated. It detects the presence of new files, transforms the data into the required form, and saves results together with files containing metadata. These metadata files play a crucial role in enabling continuous monitoring of satellite data status, enabling the module that manages the entire system to trigger assimilation when needed.

2.3.2 Satellite data assimilation module

The assimilation module is based on modified and extended components derived from the CESM model and then integrated into the 3D CEMBS-PolSea model. This facilitates the seamless incorporation of satellite-derived measurements into model computation results at every timestep but also allows utilizing a multitude of pre-existing settings and features within the model framework. These include technical parameterization such as usage of parallel high performance computing capabilities of the system and the modules governing data ingestion and processing within the model. They also allow for analytical parametrization including but not limited to set up of the assimilation window duration, assimilation frequency, etc. The assimilation method selected for the CSI-POM system (Nowicki et al., 2015) takes as input values of a given variable obtained from the calculations of the model V_{mod} and from satellite measurements V_{sat} and produces assimilated values V_{assim} using numerical equations parametrized by a set of modifiable parameters. The most important of these parameters are:

- data_type – the frequency of new assimilation data appearance simply means the frequency at which new data suitable for assimilation becomes available. It could be yearly, monthly, or even every N hours,
- data_inc – in the case of data_type being every N hours, this parameter specifies the N number,

- interp_freq – determines how often information from assimilated data is introduced into the model results, e.g. every N hours, every time step, etc.,
- interp_type – defines the type of temporal data interpolation between the time scale defined by the first two parameters and the timescale defined by the third one. Possible options include nearest neighbour, linear interpolation and 3rd order polynomial fitting using four nearest neighbours,
- interp_inc – determines how often the difference between model and satellite data is recalculated,
- restore_tau – specifies the time after which model results should reach values consistent with the satellite measurements.

At each computational iteration, using parameters data_type and data_inc, the assimilation module evaluates whether new assimilation data should be introduced. If the conditions are met, the module proceeds to load new V_sat data. To ensure the model's stability, the assimilated data cannot be directly incorporated all at once within a single time step. Instead, the interp_freq parameter allows for a gradual introduction of the data, for instance, at intervals such as every 0.5 hours. The restore_tau parameter offers a mechanism to specify the duration over which the model should converge towards assimilated values. Using these parameters, the module effectively divides the current difference between satellite and model values so that they correspond to the number of interp_freq periods that will fit into the restore_tau timeframe. This ensures a smooth introduction of assimilated data while preserving the integrity of the model's equations and system equilibrium.

$$\mathrm{dV_{step}} = (\mathrm{V_{sat}} - \mathrm{V_{mod}})/(\mathrm{restore\_tau}/\mathrm{interp\_freq})$$

$$= \mathrm{dV}/(\mathrm{restore\_tau}/\mathrm{interp\_freq})$$

$\mathrm{dV_{step}}$ is a partial increment that will be introduced into model results with a single assimilation step. The value of a given model variable depends on numerous influencing factors, e.g. transport, radiation, etc. Consequently, the initial difference between the model results and measurements denoted as dV and the $\mathrm{dV_{step}}$ resulting from it, must be periodically adjusted so that the model converges towards the anticipated value. This ongoing correction process occurs at intervals specified by the interp_inc parameter. The resulting value of the assimilated variable is calculated as follows:

$$\mathrm{V_{assim}} = \mathrm{V_{mod}} + \mathrm{dV_{step}}$$

Verification of the satellite data assimilation module within the 3D CEMBS-PolSea model is presented in the following section of the article.

3. Results

3.1 Calibration and Verification of the 3D CEMBS-PolSea Physical Model

Tables 2–5 provide a comprehensive statistical comparison of the 3D CEMBS-PolSea model against the ICES (International Council for the Exploration of the Sea) data over the years 2019 to 2023.

Table 2. Statistical comparison of the 3D CEMBS-PolSea model with ICES data for water temperature (time-dependence). ICES data averaged to model layers. ICES CEMBS-PolSea ICES vs CEMBS-PolSea.

	ICES			CEMBS-PolSea		ICES vs CEMBS-PolSea	
Year	N	Mean [°C]	STD [°C]	Mean [°C]	STD [°C]	cRMSD [°C]	Pearson's r
2019	3770	6.59	2.05	6.58	1.86	0.93	0.90
2020	2137	8.27	3.16	8.11	3.16	1.36	0.91
2021	2350	7.06	4.10	7.11	3.77	1.21	0.96
2022	2051	7.07	4.30	7.01	4.08	1.08	0.97
2023	721	9.39	4.75	9.32	4.58	1.37	0.96
2019–2023	**11029**	**7.29**	**3.54**	**7.25**	**3.35**	**1.14**	**0.95**

Table 3. Statistical comparison of the 3D CEMBS-PolSea model with ICES data for water temperature (depth-dependence). ICES data averaged to model layers. ICES CEMBS-PolSea ICES vs CEMBS-PolSea.

	ICES			CEMBS-PolSea		ICES vs CEMBS-PolSea	
Depth [m]	N [°C]	Mean [°C]	STD [°C]	Mean [°C]	STD [°C]	cRMSD	Pearson's r
0–5	1231	9.39	5.32	9.13	5.11	1.20	0.98
5–50	7171	6.93	3.51	7.01	3.32	1.02	0.96
> 50	2627	7.28	1.86	7.02	1.66	1.37	0.81

Table 4. Statistical comparison of the 3D CEMBS-PolSea model with ICES data for salinity (time-dependence). ICES data averaged to model layers. ICES CEMBS-PolSea ICES vs CEMBS-PolSea.

Year	ICES			CEMBS-PolSea		ICES vs CEMBS-PolSea	
	N	Mean [–]	STD [–]	Mean [–]	STD [–]	cRMSD [–]	Pearson's r
2019	3770	9.55	2.93	9.49	1.83	1.48	0.91
2020	2137	9.38	2.63	9.47	1.80	1.34	0.89
2021	2350	8.76	2.39	8.91	1.65	1.23	0.88
2022	2051	8.84	2.34	9.07	1.85	1.11	0.89
2023	721	8.00	1.78	8.41	1.40	1.01	0.83
2019–2023	**11029**	**9.05**	**2.58**	**9.17**	**1.79**	**1.29**	**0.89**

Table 5. Statistical comparison of the 3D CEMBS-PolSea model with ICES data for water salinity (depth-dependence). ICES data averaged to model layers. ICES CEMBS-PolSea ICES vs CEMBS-PolSea.

Depth [m]	ICES			CEMBS-PolSea		ICES vs CEMBS-PolSea	
	N [°C]	Mean [°C]	STD [°C]	Mean [°C]	STD [°C]	cRMSD	Pearson's r
0–5	1231	7.45	0.81	7.74	0.82	0.82	0.91
5–50	7171	8.00	0.99	8.56	0.99	0.92	0.85
> 50	2627	12.75	2.69	11.55	1.71	1.59	0.83

3.1.1 Temperature

The comparison between the model results and ICES data for water temperature (time-dependence) is illustrated in Table 2. The Pearson correlation coefficients (r) for each year range from 0.90 to 0.97, indicating a strong positive correlation between the ICES and 3D CEMBS-PolSea model data. The highest correlation occurred in 2022 (r = 0.97), suggesting excellent agreement between the model and observed data for that year.

The mean temperatures from the 3D CEMBS-PolSea model are generally lower than the ICES data across all years, with the smallest discrepancy in 2021. This indicates that while the model is consistently slightly cooler, it follows the observed trends closely. The standard deviations of the 3D CEMBS-PolSea model temperatures are slightly higher than those of the ICES data, implying more variability in the model. This could suggest that the model amplifies some of the natural variations found in the observational data. The centered root mean square deviation (cRMSD) values are relatively low, with the lowest in 2019 (0.93°C) and the highest in 2023 (1.37°C). These values indicate that the model errors are small and consistent over the years. Table 3 provides a statistical comparison of the 3D CEMBS-PolSea model with ICES data for water temperature, considering depth dependence. The ICES data has been averaged to align with the model layers. The correlation is very high at shallow depths (0.98 for 0–5 meters), slightly lower for intermediate depths (0.96 for 5–50 meters), and drops at greater depths (0.81 below 50 meters). The cRMSD is the lowest (1.02°C) for the 5–50 meters range and highest (1.37°C) for depths below 50 meters. A comprehensive analysis was performed to assess the influence of various factors on the model's accuracy, particularly in the deeper layers. Our findings suggest that the one-year spin-up period may have been insufficient, potentially allowing boundary conditions to propagate into portions of the effective domain. This issue, however, shows a diminishing effect with each subsequent year, indicating that the model gradually adjusts to the imposed boundary conditions over time. Future simulations may benefit from an extended spin-up period to mitigate this initial drift and enhance the overall accuracy in the deeper layers.

3.1.2 Salinity

In Table 4, statistics comparing salinity data from the 3D model CEMBS-PolSEA with ICES data in a temporal variability context for the years 2019–2023 are presented.

The correlation for the entire dataset is 0.89, varying between 0.83 and 0.91 across the years. The model data exhibits mean values similar to the ICES data and lower variability (the model has higher inertia).

In terms of depth dependency, the salinity from the 3D model CEMBS-PolSEA exhibits correlations ranging from 0.83 to 0.91 (Table 5). For depths from 0 to 50 meters, the model means are higher than the ICES data, whereas below 50 meters, the model mean is lower than the ICES data. This difference is likely due to inaccuracies in representing salinity near the bottom close to the Danish straits.

3.2 Seasonal and spatial variability

3.2.1 Temperature

The lowest average monthly temperatures occur in February, while the highest are in August, reaching maximum values in the Puck Bay of over 20°C. Figure 2 shows the

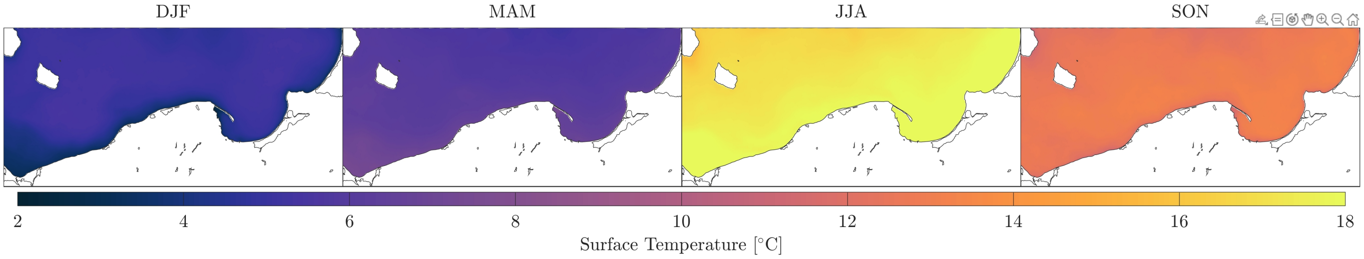

Figure 2. The average seasonal variability of surface temperature from January 2019 to December 2023, 3D CEMBS-PolSEA model data.

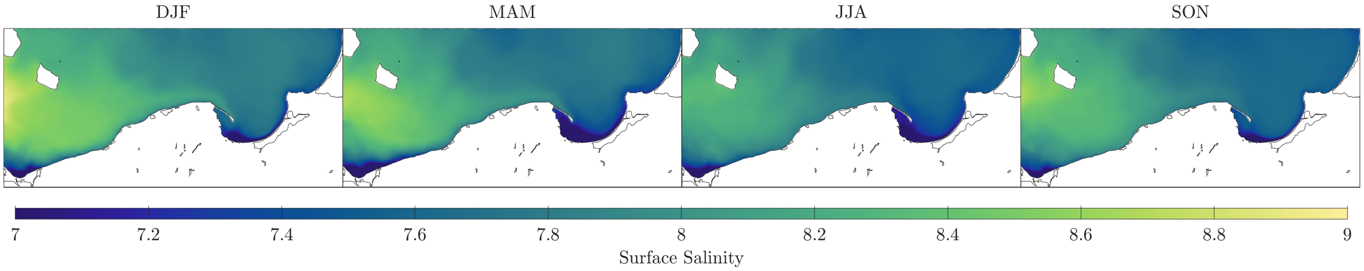

Figure 3. The average seasonal variability of surface salinity from January 2019 to December 2023, 3D CEMBS-PolSEA model data.

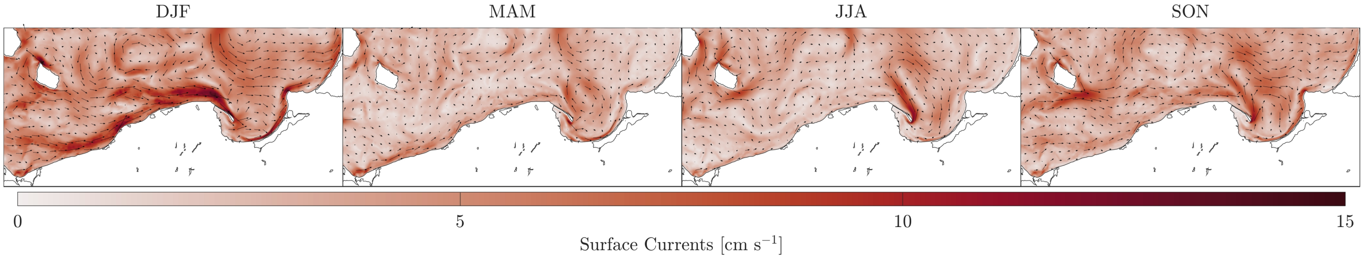

Figure 4. The average seasonal variability of surface currents from January 2019 to December 2023, 3D CEMBS-PolSEA model data.

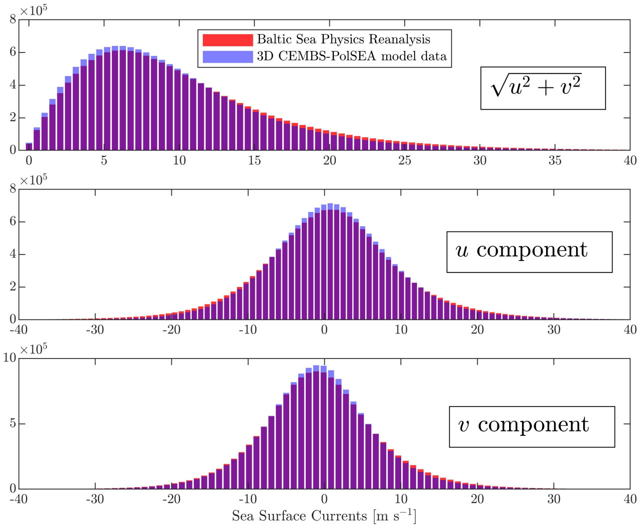

Figure 5. Histograms of sea surface currents from Baltic Sea Physics Reanalysis and 3D CEMBS-PolSEA model from January 2019 to December 2021.

seasonal variability of the average surface temperature for the period from January 2019 to December 2023.

3.2.2 Salinity

The average surface salinity in this part of the Baltic Sea is 7.86 (see Figure 3). The lowest surface salinity values are found near river mouths, while the highest values are in the western part of the domain (closest to the Danish straits connecting the Baltic Sea with the North Sea).

3.2.3 Currents

The average value of the surface current speeds in the studied area is 10.3 cm s^{-1} with a standard deviation of 8.14 cm s^{-1} (see Figure 4). However, there are also currents with speeds exceeding 150 cm s^{-1} during winter storms between January and March. To compare the surface current values from the 3D CEMBS-PolSEA model with data from the Copernicus Baltic Sea Physics Reanalysis (https://doi.org/10.48670/moi-00013), it was necessary to properly prepare both the measurement data and the model data in advance, as the model grid and the Baltic

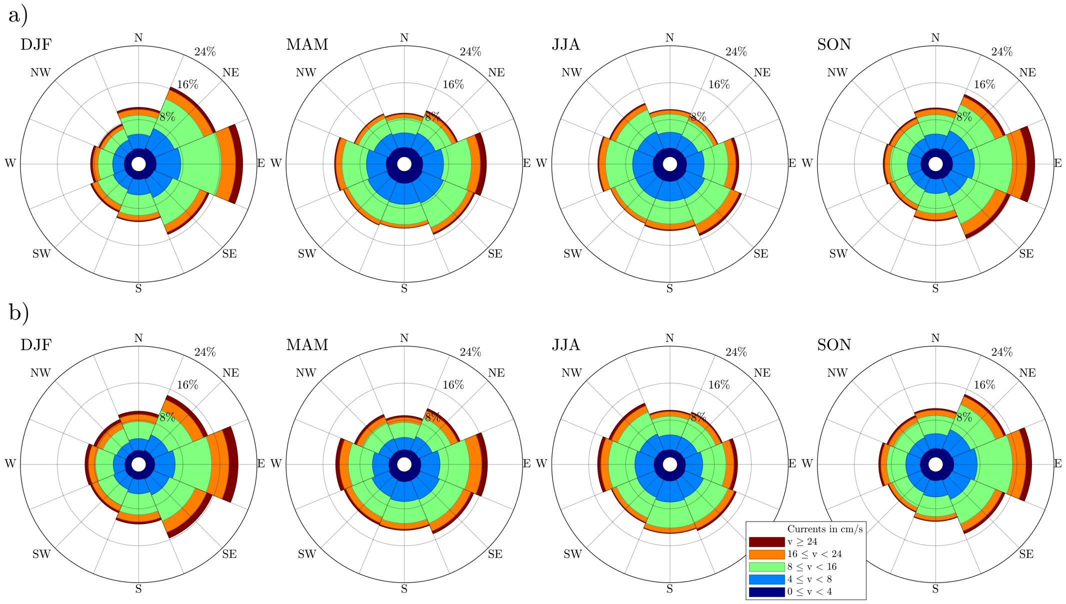

Figure 6. Diagrams showing the distribution of directions and magnitudes of surface current velocities in different months of the year (mean from 2019–2021) for a) the the 3D CEMBS-PolSEA model data and b) Baltic Sea Physics Reanalysis data from Copernicus Marine Service Information https://doi.org/10.48670/moi-00013.

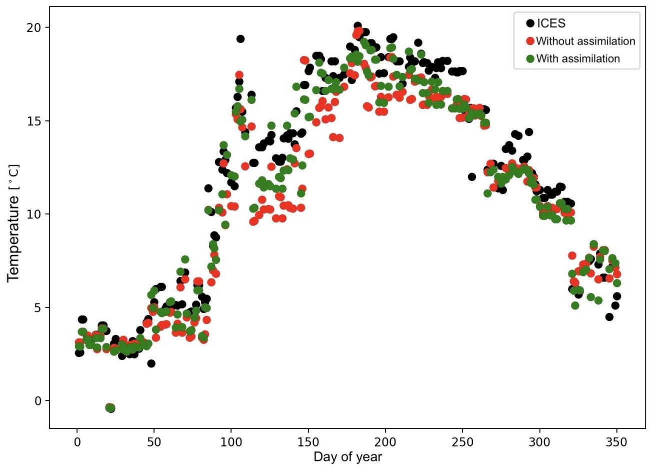

Figure 7. Time-dependent comparison of model surface temperature with and without assimilation module to ICES data.

Sea Physics Reanalysis grid did not overlap and had different resolutions. In the first step, we masked the Copernicus Baltic Sea Physics Reanalysis data to exclude areas directly adjacent to the coastline. Next, the 3D CEMBS-PolSEA model data were cropped to match the Reanalysis data coverage and spatially averaged, ensuring that each Reanalysis grid cell corresponded to a single model value, derived from averaging the values of 12 model grid cells. As a result of this procedure, we obtained two consistent datasets, which were then compared. Figure 5 shows the histograms of the surface current velocities from the 3D CEMBS-PolSEA model and the Baltic Sea Physics Reanalysis for the years 2019–2021. It can be observed that the overall characteristics of the datasets are similar (with a correlation of 0.99), but the model produces slightly more small velocities. This may be due to averaging from the model's higher resolution grid to the lower resolution of Baltic Sea Physics Reanalysis, described above. Next, we present diagrams (so-called wind roses) illustrating the distribution of directions and velocities for each season (average from 2019–2021) for the 3D CEMBS-PolSEA model data in Figure 6a and for the Baltic Sea Physics Reanalysis data in Figure 6b. The dominant current directions coincide for both datasets in each month. Additionally, the velocity distribution in each direction shows good agreement between the datasets.

3.3 Assimilation

To verify whether assimilation yields the expected results, a model verification was conducted by comparing the results of the model without assimilation to the model with assimilation against observational data from the ICES database. Figure 7 illustrates the variation in surface temperature over time. It can be observed that the assimilated data (green) are closer to the ICES results (black) with a correlation coefficient of 0.98, mean error of −0.59°C and RMSE 1.25°C than the non-assimilated results (red) with a correlation coefficient 0.97, mean error −0.93°C and RMSE 1.66°C. There is a clear improvement in terms of mean error, which has decreased by approximately 37%. RMSE has decreased by about 25%, which is also a significant improvement. This indicates that, in general, assimilation is functioning correctly as it brings the model results closer to the actual measurements. Overall, the CEMBS-PolSea model demonstrates strong performance and alignment with measurement and reanalysis data, making it a reliable tool for simulating and understanding the dynamics of the studied marine areas. The consistently high Pearson correlation coefficients reinforce the model's validity in capturing temporal variations.

4. Discussion and conclusions

The development of the high-resolution 3D hydrodynamic model, CEMBS-PolSea, represents a significant advancement in our ability to simulate and understand the complex dynamics of the Polish Marine Areas. This section discusses the implications of our results, placing them in the context of existing research, highlighting potential applications of the model, and identifying areas requiring further improvement. Our results show that the CEMBS-PolSea model accurately reproduces observed temperature and salinity profiles, with strong correlations between model results and in situ measurements ($r = 0.95$ for temperature and $r = 0.89$ for salinity). These findings are consistent with other high-resolution models used in marine environments, such as the Baltic Sea Ice-Ocean Model (BSIOM) and the HIROMB-BOOS Model (HBM), which also demonstrated improved accuracy in simulating physical dynamics at smaller scales (Eilola et al., 2009; Meier et al., 2014). The integration of satellite data assimilation, particularly for sea surface temperature, further enhances the model's precision, as evidenced by reduced root mean square deviation (RMSD) values. Similarly, Holt and Proctor (2008) demonstrated the importance of high-resolution models for accurate simulations of seasonal circulation and volume transport on the northwest European continental shelf. High-resolution models like CEMBS-PolSea are crucial for capturing submesoscale features such as eddies, coastal currents, and local nutrient upwellings. These features play a significant role in nutrient distribution, primary productivity, and overall ecosystem health (Schrum et al., 2003). For instance, low-resolution models may fail to capture these small-scale processes, leading to inaccurate predictions of biological responses and ecosystem dynamics. The ability of the CEMBS-PolSea model to resolve such features underscores its value for ecological and environmental studies in the southern Baltic Sea. Timmermann et al. (2002) highlighted the similar importance of high-resolution models in simulating ice-ocean dynamics in the Weddell Sea, demonstrating the versatility of such approaches in various marine regions. The capabilities of the CEMBS-PolSea model to accurately simulate water circulation, temperature distribution, and salinity gradients make it a valuable tool for marine ecosystem management. By providing high-resolution, detailed forecast data on hydrodynamic parameters, the model can support maritime planning, mitigate risks associated with extreme events, and deliver valuable information to stakeholders. Moreover, the model's ability to simulate future scenarios under different climate change projections can aid in developing adaptive management strategies, ensuring the sustainable development and resilience of the Polish Marine Areas. Future work could involve coupling the CEMBS-PolSea model with biogeochemical models to achieve a more comprehensive understanding of the marine environment. Such integrations have been shown to improve the simulation of nutrient cycles, oxygen levels, and primary production, providing insights into the interactions between physical processes and biological responses (Meier et al., 2014). For example, coupling with models that simulate plankton dynamics could enhance predictions of algal blooms and their impacts on water quality and marine life. Coupling of nitrogen cycling with hydrodynamic models can assist with the estimation of the N budget (Fennel et al., 2006). The inclusion of a satellite data assimilation module is a significant advancement, but further improvements are necessary to address discrepancies observed in deeper water layers. Enhancing the parameterization of vertical mixing and incorporating additional observational data sources, such as autonomous underwater vehicles and gliders, could improve the model's accuracy in these areas. Continuous validation against a broader range of observational datasets will also be crucial for maintaining and enhancing the model's reliability. The CEMBS-PolSea model represents a significant step forward in resolving submesoscale features and improving our understanding of physical dynamics in the Polish Marine Areas. Its high-resolution capabilities and integration of advanced data assimilation techniques make it a powerful tool for marine ecosystem management and climate change research.

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Conflict of interest

None declared.

Supplementary materials

Please follow this link to see the supplementary material associated with this article.

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