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NUMERICAL SIMULATIONS OF SEA ICE CONDITIONS IN THE BALTIC SEA FOR 2010–2016 WINTERS USING THE 3D CEMBS MODEL

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ABSTRACT

Sea ice conditions in the Baltic Sea during six latest winters – 2010/2011 to 2015/2016 are analysed using coupled ice–ocean numerical model 3D CEMBS (3D Coupled Ecosystem Model of the Baltic Sea). Simulation results are compared with observations from monitoring stations, ice charts and satellite data. High correlation between model results and observations has been confirmed both in terms of spatial and temporal approach. The analysed period has a high interannual variability of ice extent, the number of ice days and ice thickness. Increasing number of relatively mild winters in the Northern Europe directly associated with climate change results in reduced ice concentration in the Baltic Sea. In this perspective, the implementation and development of the sea ice modelling approach (in addition to standard monitoring techniques) is critical to assess current state of the Baltic Sea environment and predict possible climate related changes in the ecosystem and their influence for human marine–related activities, such as fishery or transportation.

Keywords: Baltic Sea, sea ice, numerical modelling, remote sensing, climate change

INTRODUCTION

The Baltic Sea is a unique water area surrounded on all sides by land surface, connected with the ocean only by narrow straits. Including the Kattegat, Baltic Sea covers an area of approximately 420 000 km^2. As a result of abundant freshwater runoff from the surrounding land, Baltic Sea has very low salinity of 6 to 8 on the central basin's surface waters that drops below 3 in the northernmost regions. Apart from a few deeps, the sea is very shallow with an average depth of about 52 m. The Baltic Sea freezes at least partially in winter, which can directly affect navigability and maritime infrastructure. Usually, most of the regular marine transport routes are unaffected. However, a solid ice sheet forms during the most severe winters, making ports along the Polish and German coasts closed by ice for several days a year. Despite the negative effect of freezing for maritime traffic, the Baltic Sea ice is a very important factor regulating North European climate system [1, 2]. While open waters reflect only 3% to 10%, sea can reflect from 50% to even 70% of the incoming radiation [3]. Thus, ice cover affects not only optical, but also chemical and hydrographical properties of the ecosystem, as well as its biological part. Sea ice conditions in the Baltic Sea are dynamic with large interannual ice extent variability. Water freezing in the Baltic Sea usually starts at the end of October or at the beginning of November in the northern parts of the Bothnian Bay and in the inner regions of the Gulf of Finland. Thereafter, ice formation expands toward the central part of the Bothnian Bay and the coastal areas of the Bothnian Sea. During severe winters both the Bothnian Sea and the Gulf of Finland can freeze completely up to the northern part of the Baltic Proper. In years of relatively mild winters a compact ice cover hardly exists on Bothnian Sea and occurs only locally in the Gulf of Finland. The melting season begins in April in the southern parts of the Baltic Sea progressing towards the north. In early May ice covers only the northern part of the Bothnian Bay and disappears completely in the first half of June at the latest. The annual maximum ice extent of the Baltic Sea (MIB) occurs roughly between January and March, usually in late February or early March. In average at this time, ice covers ~40% of the total area of the Baltic Sea, which is about 165 000 km^2 [4, 5]. Due to specific interannual variability of ice conditions in the Baltic there are periods of time when significant anomalies occur in this pattern. The lowest MIB of 49 000 km^2 was recorded in 2008, while the winter of 1986/1987 was the most severe in the history of observations with MIB of over 420 000 km^2 [4]. Taking into account that thermal memory of the Baltic Sea is only 2 to 3 months [6] and there is no correlation between consecutive ice seasons, a situation when a mild winter occurs directly after extremely severe one (or vice versa) is quite common.

Observations of ice covered area and ice volume are essential for understanding changes in sea ice mass balance, interactions between the ice, ocean and atmosphere. Reliable projections of sea ice response in a warming climate is important also due to the fact that ice extent and mean winter air temperature in Northern and Central Europe are highly correlated [2] which in terms of a mass–related severity index varies with the North Atlantic Oscillation (NAO) [1]. Multiple analysis of the long–term Baltic Sea ice observations report a significant decreasing trend of MIB for the past 100 years of ~2% per 10 years making mild ice seasons more common [4,7-8]. The MIB decrease appears to have accelerated since the 1980s but the large interannual variability prohibits a clear assessment as to whether this increase is statistically significant [4].

There is a great number of numerical models that have been used for the Baltic Sea over recent years to clarify different interactions between sea, sea ice and atmosphere [9-13]. Results from several models were also used to provide a regular sea-ice forecast to support the intense ship traffic on the Baltic Sea [14] and understand winter marine traffic and analyze winter ship navigation accidents [15]. Sea ice constitutes a natural barrier influencing the exchange of heat and nutrients as well as energy transfer between the ocean and the atmosphere. Therefore, numerical ocean-ice models have also been used to study and understand how changes in the climate system would impact the state of the Baltic Sea [16, 17], how ice cover dynamics affect biogeochemistry [18], or impact Baltic habitants such as ringed seals [19]. As the need to model sea-ice processes have been highlighted above, the aim of this article is to present and validate the coupled ocean-ice component of the 3D Coupled Ecosystem Model of The Baltic Sea (3D CEMBS) that has been implemented and developed in the Institute of Oceanology at the Polish Academy of Sciences. This is done by evaluating model results from the six winter seasons 2010/2011 to 2015/2016 compared with observations from monitoring stations, ice charts and satellite data.

MATERIALS AND METHODS

3D CEMBS MODEL

A coupled ice–ocean model has been used to calculate hydrodynamic conditions of the Baltic Sea area for the 2010–2016 period. This model origins from Community Climate System Model/Community Earth System Model (CCSM/CESM) coupled global climate model but has been downscaled and adapted for the Baltic Sea domain and further developed at the Institute of Oceanology, Polish Academy of Sciences and called the 3D Coupled Ecosystem Model of the Baltic Sea (3D CEMBS). It is a z–level coordinates, general circulation ocean model that solves the 3–dimensional primitive equations for stratified fluid using the hydrostatic and Boussinesq approximations. The model domain covers the whole area of the Baltic Sea including Kattegat and Skagerrak extended by a part of the North Sea in order to provide a buffer area for open boundary. However, for the purpose of this research, data outside of Kattegat border has been filtered out (Fig. 1a). There are four main source code blocks in 3D CEMBS (called modules or submodels):

- Ocean with Ecosystem – based on Parallel Ocean Program (POP) [20, 21];
- Sea Ice – based on Community Ice CodE (CICE) [22];
- Atmosphere – atmosphere forcing and deposition of nutrients (DATM);
- Land – freshwater inflow and nutrient loads from rivers and large coastal cities (DLND).

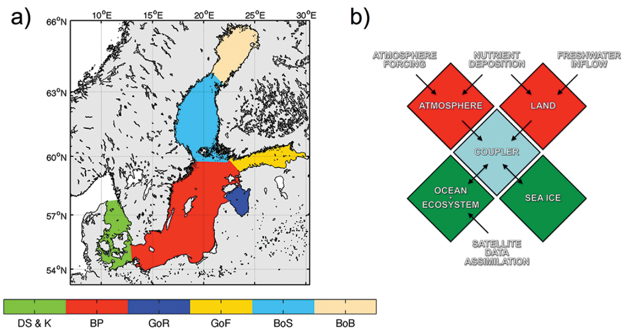

Fig. 1. 3D CEMBS model domain (a) and configuration (b). Sub–regional division: Danish Straits and Kattegat (DS & K), Baltic Proper (BP), Gulf of Riga (GoR), Gulf of Finland (GoF), Bothnian Sea (BoS), Bothnian Bay (BoB)

Those modules are responsible for the block–related processes simulation or data transfer with prior interpolation onto a domain grid. There is also an additional central block (coupler) responsible for synchronous exchange of information in the model and data stream control (Fig. 1b). 3D CEMBS is configured at approximately 2.3 km horizontal resolution (1/48°). The model grid has 21 irregular layers vertically. The thickness of the first four layers is 5 m and it grows with depth. Detailed model configuration (including equations appendix) has been presented in separate papers [23, 24]. When water temperature within the grid cell drops below the freezing point (salinity dependency equation) POP calls for CICE, which is responsible for numerical calculations of processes, related with sea ice variables. CICE active configuration within the 3D CEMBS model can be found in [23]. Atmospheric forcing data used in this simulation run origins from Unified Weather Prediction Model (UM) run at the Interdisciplinary Centre for Mathematical and Computational Modelling, University of Warsaw, Poland (www.meteo.pl). 3D CEMBS simulation run has been performed for the period from 1 January 2010 to 31 May 2016 with 2 years of spin–up stage. The reason for such a short simulation is the lack of a reliable long-term in-situ dataset that could be used to make a comparison with 3D CEMBS. In addition, the IMGW database was available only as images. Therefore, it is difficult to compare it quantity-wise with model results. Since ice disappears completely on the Baltic Sea each summer, a longer spin-up period is not mandatory. The output files were recorded with daily frequency. The Cressman data assimilation scheme has been used within this configuration in order to improve overall model accuracy [25, 26]. Satellite–measured sea surface temperature (SST) values from the Moderate Resolution Imaging Spectroradiometer (MODIS, Aqua satellite) taken from SatBałtyk Database [27–29] were used for this process. To analyse the differences in ice formation on a spatial scale, model domain has been divided onto six regions shown on Fig. 1.

FMI DATA

Baltic Sea ice concentration database from Finnish Meteorological Institute (FMI) [30] has been used in this paper for comparison with 3D CEMBS model results. Files were downloaded from Copernicus Marine Environment Monitoring Service. Available FMI ice concentration data is based on ice charts produced on a daily basis during the Baltic Sea ice season and show the ice concentration in a 1 km grid. Sea ice service at FMI produces sea ice parameters based on a manual interpretation of satellite data and ground truth. The satellite data used are Synthetic Aperture Radar data from RADARSAT–2 and visual and infrared data from MODIS and National Oceanic and Atmospheric Administration (NOAA). Ground truth origin from Finnish and Swedish icebreakers, ice observation stations of the Baltic ice services and ports. The RADARSAT–2 data are in ScanSAR Wide mode dual polarization and each scene covers an area of about 500 km^2 and is resampled to a spatial resolution of 100 m. The scenes are mainly focused to the Baltic Sea, Kattegat and Skagerrak east of 9°E. The Envisat data were in WideSwath mode with a swath width of 450 km and were resampled to a spatial resolution of 150 m. The data covered the same area as RADARSAT–2 data. The MODIS and NOAA data covers the charting area several times each day and are resampled to 500 m^2.

OSTIA DATA

The Operational Sea Surface Temperature and Ice Analysis (OSTIA) system runs operationally at the UK Met Office since November 2006 [31]. Output is a daily global coverage combined SST and sea ice concentration product based on measurements from several satellite and in–situ SST data sets. OSTIA uses SST data in the common format developed by GHRSST and makes use of the uncertainty estimates and auxiliary fields as part of the quality control and analysis procedure. Satellite derived sea ice products from the EUMETSAT provide sea ice concentration data to the analysis system. After quality control of the SST observations, a bias correction is performed. To provide the final SST analysis, a multi–scale optimal interpolation is performed using the previous analysis with a slight relaxation to climatology as the basis for a first guess field. Global daily analyses of foundation SST together with sea ice concentration and analysis error estimates are produced on a 1/20° horizontal resolution grid.

IMGW DATA

The Office of Hydrological Forecast is the Maritime Branch of the Institute of Meteorology and Water Management (IMGW) in Gdynia, Poland. The ice charts of the Baltic Sea ice conditions are produced within the office in the forms of graphic illustrations of information provided in the Ice Bulletin. The chart is issued twice a week in regular or mild winters and on daily basis in severe winters. The type of ice, its distribution and concentration as well as the processes of ice decay are presented by the international codes and symbols, according to the terminology and ice symbol system of the WMO (hummocks, crevices, ice ridges and packs). The chart provides additional information on ice thickness, distribution and operating icebreakers. For the purposes of this paper, all of the released ice charts from the investigated years have been shared on the basis of a science agreement.

RESULTS

ICE CONCENTRATION

Ice concentration snapshots are compared in Figure 2 for all investigated winter seasons and available datasets. 3D CEMBS model results as well as FMI & OSTIA charts are shown as a percentage while IMGW Ice Charts are presented without making any changes, using World Meteorological Organisation Concentration Colour Code standards.

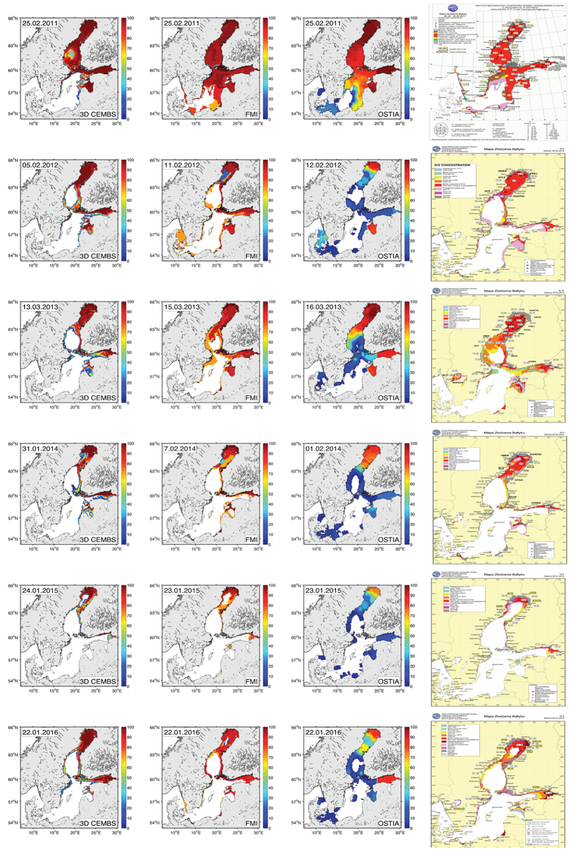

Fig. 2. Ice concentration snapshots on the day of the maximum extent. Rows denote winter seasons (from 2010/2011 – top to 2015/2016 – bottom) and columns denote datasets (from left to right: 3D CEMBS, FMI, OSTIA, IMGW respectively). Note the differences in snapshot dates

A snapshot is taken on the day of the maximum ice extent (MIB). Detailed values of observed and simulated MIB's with the dates of occurrence as well as model errors are presented in Table 1. 3D CEMBS model results tend to have lower ice extent values than observations. The biggest difference can be seen during the most severe winter of 2010/2011 when MIB of 343 000 km^2 recorded by OSTIA was almost two times higher than the 3D CEMBS with 183 000 km^2. However, the day of MIB occurrence was the same for all datasets and occurred exactly on February 25th.

On a daily scale, extent values can have fairly large variations, both due to real changes in ice cover from growth, melt, or from motion of the ice edge, and due to ephemeral weather and surface effects. Figure 3 shows the annual cycle for 3D CEMBS and OSTIA results of ice extent. Both plots show that ice on the Baltic Sea starts to form usually somewhere at the end of December while melting completely in the middle of May. This is common for both severe and mild winters differing only in the size of the ice cover. MIB usually occur somewhere between the middle of January and March.

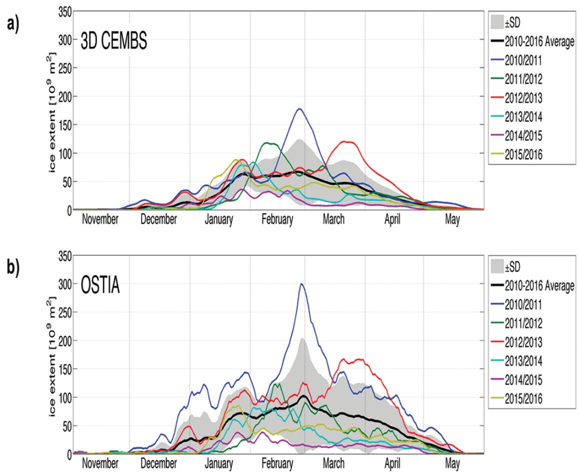

Fig. 3. Ice extent annual cycle for 3D CEMBS (a) and OSTIA (b). The black solid curve denotes the mean time evolution of ice extent area for the period 2010/2011–2015/2016 and the shaded area shows the range of variability defined by one added or subtracted standard deviation. 5–day trailing mean has been used

So far, focus was put mostly on the temporal scale of ice formation by showing either the conditions during the most extreme day in terms of extent per season (Fig. 2) or total ice extent area evolution without exploring its spatial distribution (Fig. 3). To get the full picture and distinguish potential high–risk zones for human activity (for example marine transportation or development) it is important to include the regional character of ice formation and see which areas are commonly ice–covered for the longest period, in what parts of the region as well as where and when the freezing/melting processes starts. To help achieve that goal, 3D CEMBS model simulated maps of ice days (Fig. 4) are presented. Each grid cell has a corresponding number of days when ice concentration was above 15%.

Tab. 1. Observed and simulated maximum ice extent (MIB) with the date of occurrence (Δ = model error)

Winter season	Maximum ice extent (10^9 m^2)					Date				
	3D CEMBS	FMI	OSTIA	Δ_{FMI}	Δ_{OSTIA}	3D CEMBS	FMI	OSTIA	Δ_{FMI}	Δ_{OSTIA}
2010/2011	183	309	343	–126	–160	25 Feb	25 Feb	25 Feb	0	0
2011/2012	126	179	145	–53	–19	05 Feb	11 Feb	12 Feb	–6	–7
2012/2013	124	177	173	–53	–49	13 Mar	15 Mar	16 Mar	–2	–3
2013/2014	90	100	97	–10	–7	31 Jan	07 Feb	01 Feb	–7	–1
2014/2015	40	51	46	–11	–6	24 Jan	23 Jan	23 Jan	1	1
2015/2016	94	110	106	–16	–12	22 Jan	22 Jan	22 Jan	0	0

In order to connect both spatial and temporal aspects of ice evolution, the percentage of region covered by ice (Fig. 5) was calculated for six Baltic Sea regions according to the division in Fig. 1.

It is worth noticing, that even during mild winters northernmost areas of Bothnian Bay are covered by ice at least for a hundred days and ice covers eastern part of Gulf of Finland around the mouth of Neva River for at least a month or two. Also, Danish Straits & Kattegat as well as Baltic Proper are pretty much ice free most of the time with the exception of the coastal area.

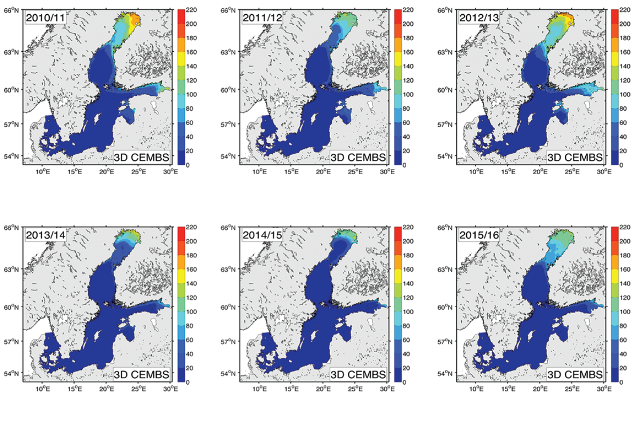

Fig. 4. Number of ice days (ice conc. > 15%) simulated by 3D CEMBS model. From left: 2010/2011, 2011/2012, 2012/2013 (top) and 2013/2014, 2014/2015, 2015/2016 (bottom)

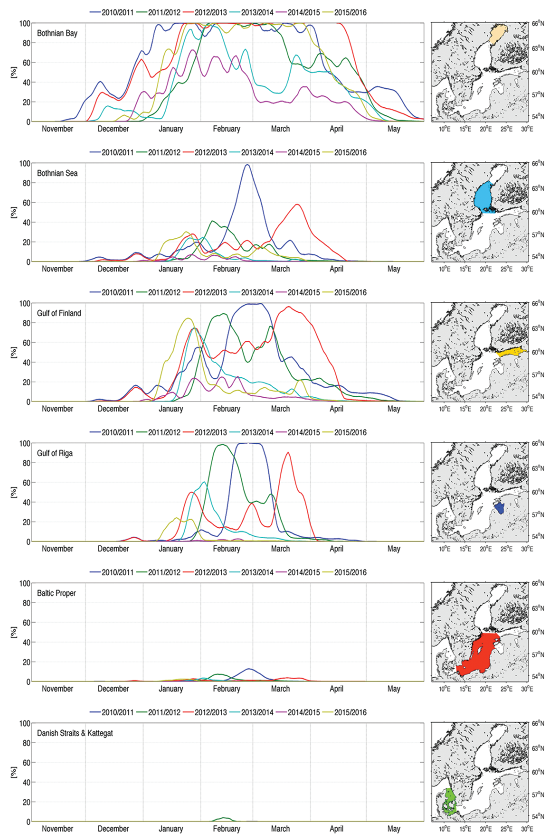

Fig. 5. Ice covered region percentage for all winters in Bothnian Bay (a), Bothnian Sea (b), Gulf of Finland (c), Gulf of Riga (d), Baltic Proper (e), Danish Straits and Kattegat (f). 5–day trailing mean has been used

DETAILED ICE EVOLUTION

Winter 2010/2011

Winter 2010/2011 was severe with the highest values for ice area covered since the extremely severe winter of 1986/1987. The end of November and December were exceptionally cold and the amount of sea ice began to increase. As mid–December approached, there was ice in all Finnish coastal areas. Frosty weather continued at the beginning of 2011 and the ice–covered area expanded to more than 100 000 km^2 (Fig. 3) at the beginning of January. At that time, ice covered the entire Bothnian Bay and the Quark as well as the Archipelago Sea. The latter half of February turned out to be exceptionally cold causing the amount of sea ice to increase rapidly, and the peak of the ice winter was reached on February 25th (Tab. 1).

Winter 2011/2012

In statistics based on MIB, the winter of 2011/2012 was average and shorter than usually, as it started exceptionally late, and the last pieces of ice disappeared earlier than average. Wintery weather had set in late January, and the cold conditions continued in February which caused the sea ice cover to expand, and the ice extent reached its peak somewhere between 5th and 12th February (depending on data source – see Table 1).

Winter 2012/2013

The Baltic Sea ice season 2012/2013 was average but the turning point of the winter was late. Ice formation in the innermost bays of the northern part of the Bothnian Bay began with the end of November. At the beginning of March cold arctic air started to flow to Scandinavia and the extent of ice began to grow reaching its maximum somewhere between 13th and 16th March (Tab. 1). From then on, the cold nights formed new ice but sunny days melted them and the extent of ice did not enlarge any more. The last ice melted from the southern Bothnian Bay and Gulf of Finland at the beginning of May. The Bothnian Bay was ice–free on the first days of June (Fig. 5 – Bothnian Bay section) .

Winter 2013/2014

Season 2013/2014 was mild. The ice formation in the innermost bays of the northern part of the Bothnian Bay began with the end of November. Since January was exceptionally cold, the extent of ice reached its maximum at the beginning of February. After this, the weather became milder, and the southern winds pushed the ice fields together. The rest of February was unusually mild. In the beginning of March the ice extent was below 50 000 km^2. April was warmer than average and at the end of the month ice appeared only in the Bothnian Bay. Finally, The Baltic Sea became ice–free nearly two weeks earlier than usual having the last ice melted in the Bothnian Bay around May 15.

Winter 2014/2015

This ice season was exceptionally mild. The ice formation in this mild season began in the middle of November in the northern part of the Bothnian Bay. December and the beginning of January were milder than usual with only a short cold period till the last days of January resulting in the culmination ice extent around January 24th. March and April were warm which left the remaining ice formation only in the Bothnian Bay. The last ice melted in the first half of May. The Baltic Sea was ice–free two weeks earlier than usual.

Winter 2015/2016

The ice winter 2015/2016 was mild and considerably shorter than average. Around the turn of the year, the weather cooled considerably and ice started to form. However, January began with cold temperatures and cold weather continued for about three weeks. This resulted in the maximum ice extent forming at January 22nd (Tab. 1). Even though February and March were warmer than the long–term average, the extent of the ice cover started to decrease in the last week of March. The Gulf of Finland became free of ice in the middle of April and the warm weather at the beginning of May melted the remaining ice fairly quick making The Baltic Sea completely ice free around the middle of May.

DISCUSSION

Economic growth within the Baltic Sea region corresponds directly with a 34% marine traffic increase in the last 10 years (the number of icebreakers however has not increased). Therefore, the lack of high–resolution ice condition daily information and forecast can lead to serious economic losses [32, 33]. Using numerical modelling in addition to standard monitoring techniques (remote sensing and direct observations) brings a lot of benefits giving the ability to provide complex information of sea ice conditions with very high spatial and temporal resolution, which has become of vital importance in human marine activity.

Changes in the sea ice can have multiple effects in sea level rise, ecosystem, etc. Some species that use sea ice cover as a natural breeding area, for example seals (*Halichoerus grypus*) may have to migrate to the northern region of Bothnian Bay to survive [19].

While some northern populations are declining or migrating to new areas, there are evidences of multiple species that extend their breeding habitats becoming invasive in some areas [34].

Also, the natural hazards and risk for marine infrastructure can occur. At the same time, one could see rising opportunities for new navigation routes and exploration of areas that are currently restricted or limited to only a few months a year.

Accuracy of the satellite observation techniques and methods is heavily constrained by many limiting factors like (among others) weather, attached instruments or even algorithms used to process data. Numerical models on the other hand, (while not forgetting about their limitations) enable simultaneous projection of many sea ice cover parameters (even at low values) with a great temporal and spatial resolution including ice thickness.

Winter of 2010/2011 was the most extreme since 1986/1987 and it is not very likely that these events will happen often in the upcoming years especially in the climate change perspective. Therefore, good simulation of less severe winters proves that 3D CEMBS is a viable tool for ice conditions simulations and can be used for IPCCs scenario induced long–term runs. Since climate changes induce ocean's temperature to rise, lots of the changes (including ice melting) happen in the water column and are invisible for instruments (e.g. satellites) that see and measure only the surface layer. Therefore, numerical simulations have an advantage in this field since they enable to predict the real volume changes and rate (speed) of investigated processes.

CONCLUSIONS

The analysed period 2010/2011 to 2016/2016 can be characterized as very dynamic in terms of interannual variability of ice parameters. The correspondence between 3D CEMBS model results and observations in terms of both temporal and spatial analysis is encouraging. The most severe winter season was 2010/2011 followed by mild winters 2013/2014–2015/2016. There are some differences between the model and FMI/OSTIA/IMGW data, especially during the severe winter 2010/2011. Even though the day of MIB in model (25th Feb 2011) was the same as the observation date, the simulated value of ice extent area was 39% lower in comparison with FMI (up to 45% lower for OSTIA). For other winters simulated values were usually only around 10–15% lower than observation.

The authors believe that the main reason for this underestimation is the 5 m surface layer thickness of the ocean model. To cool down such thick layer, so it's temperature drops below the freezing point requires more time. In reality, fast ice starts to form in a thin surface layer. This should be solved by a model assimilation. However, there are periods of time, especially during winter, when satellite images are not available due to high cloudiness.

It is uncertain what might be the other potential reason for this underestimation, since there are many factors influencing it. Ice concentrations from satellite imaging are also sensitive to the algorithm used, and the resulting numbers for extent depend not only on algorithms but on other processing steps as well. Also, it is important to note that the extent values have uncertain significance when taken individually [34]. It is clearly visible that even though the model tends to slightly underestimate ice conditions it reacts very well to atmosphere forcing what can be confirmed by only minor differences in the dates for maximum extent at each winter season.

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Calculations were carried out at the Academic Computer Centre in Gdańsk.

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