Sea ice modeling in the Sea of Azov for a study of long-term variability

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Abstract. This study deals with an attempt to use the NEMO modeling framework to investigate the long-term variability of the sea-ice fields in the Sea of Azov. A coupled ocean-ice model is used to perform a simulation by using an earlier developed configuration of cascading sea basins (Azov, Black, and Marmara). Various features of geographical location cause the formation of sea ice in the waters of the Sea of Azov and in the coastal area of the north-western Black Sea shelf. For a preliminary accuracy assessment, the simulation results are compared with the data based on satellite observations. The restricted amount of the data for the rather small area under study, as well as the features of the regional weather conditions, produce rather low accuracy of the available data products based on the satellite data. At the same time, the available data from coastal weather stations, as well as archived observations, produce a fairly adequate pattern of the simulated variability of the sea-ice conditions in the basin.

1. Introduction
The Sea of Azov is a semi-enclosed inland basin located rather far from the ocean. Therefore, the variability of its physical parameters is highly dominated by the atmospheric conditions formed over the continent. Despite the very small area and depth (with a maximum as large as 14.5 m), the basin can be considered as an important transport hub. In addition, a large amount of river runoff affects its high fish productivity.

The Sea of Azov is characterized by significant spatial inhomogeneity of physical parameters. Interannual, seasonal, and storm-surge induced variations in the thermohaline regime are well pronounced [1]. A significant number of abnormal phenomena have been observed here recently under the stable anthropogenic impact, e.g. [2]. An important role both for the basin itself and for the neighboring Black Sea is played by the water exchange through the Kerch Strait. The inflow of more saline water masses and circulation features significantly affect the salinity of the basin. At the same time, the outflow and further propagation of nutrient-enriched Azov Sea waters can be manifested in the Black Sea from satellite observations [3]. Therefore, to produce forecasts of the thermohaline and circulation properties in the region, one should consider the cascading basins of the adjacent seas.

This problem is rather important within the framework of establishing regional marine nowcasting/forecasting systems, incorporating available observations and general circulation models to detail information about the sea state, e.g. the Black Sea Marine Forecasting Centre (BSMFC, http://mis.bsmfc.net), which is still operating and open to end users. Note that there are no systems at
the moment able to provide similar information for the Sea of Azov with sufficient resolution. In the global ocean forecasting centers, e.g. Copernicus Marine Environment Monitoring Service, CMEMS (http://marine.copernicus.eu/) or HYCOM (https://www.hycom.org), the spatial resolution of the provided products is rather low for studying regional circulation features and variability of thermohaline parameters of the Sea of Azov. Note that the operational forecast of the basin produced by the Hydrometeorological Centre of Russia (HMC) (http://hmc.meteorf.ru) is based on a model from [5]. However, it reproduces only circulation and storm surges not taking into account the temperature, salinity, and exchange with the Black Sea.

One of the difficulties for the solution of such problems is the need for sea ice modeling that is formed in the basin and characterized by significant interannual and seasonal variability. This results from the geographical position of the basin, its shallowness, and rather low sea water salinity [6]. Prediction of the sea ice conditions is complicated by continuous freezing of the new ice cover, together with its melting in certain areas of the basin in conjunction with a constant ice regime, as well as the atmospheric conditions. For example, a difficult navigation situation occurred in the winter of 2011 – 2012 [7]. The whole basin of the Sea of Azov was completely covered with ice and, due to the stable impact on the formed sea ice, its concentration and layering increased, leading to the formation of hummocks.

The need to implement a coupled model for sea and ice thermodynamics complicates the solution of the problem. A number of important results on numerical modeling of the ice conditions in the basin were obtained earlier in Russian works. For example, in [8], for the region of the Kerch Strait for 5 months, the period of 2011-2012, a locally one-dimensional model of the thermodynamics of ice formation and melting was used. The results obtained were compared only with data from coastal stations. The paper [8] is devoted to a study of the dependence of the evolution of the ice drift velocity field in the Sea of Azov on the direction and time of the wind exposure. A more sophisticated two-dimensional numerical model was used here considering, however, the idealized cases of uniform stable wind forcing.

Improving the quality of numerical modeling is usually achieved through the observational data assimilation. Regular measurements are available from coastal weather stations (CWSs). However, directly over the sea surface such information can be obtained from satellite images. An example of monitoring the emerging sea-ice extent situation and vessel positioning according to the COSMO-SkyMed radar satellites (E-GEOS, Italy) is presented in [10]. In [11], a set of visible and infrared NOAA satellite images made at the Japan station “Furuno Su-8” installed at “YugNIRO” (Kerch) for the winter of 2015–2016 was used as initial data. The main objective of these studies was to construct maps describing the main phases of the ice formation regime, and a description of the main ice characteristics. In [12], a series of optical images was investigated obtained from different satellites by using the satellite service “See The Sea” and the community sharing center “IKI-Monitoring”. Based on such observations, the ice drift was analyzed in the Kerch Strait before and after the construction of the Crimean Bridge.

A more complex approach was implemented in [13]. Here MODIS sensor data from Terra and Aqua for 2006 – 2016 as well as in-situ measurements from coastal stations were used. They allowed one to obtain quality estimates of the proposed multi-component balance hydrological model, based on which long-term variability of sea-ice cover, sea-ice thickness, and seawater temperature of the Sea of Azov were obtained.

In addition to CWS data, regular observations of sea-ice characteristics in the delta of the Don River are carried out by the South Scientific Center, RAS [14]. Note that other available sources of sea-ice observations (ship and aircraft surveys) collected by the State Oceanographic Institute (SOI) are not open. Nevertheless, the results of a comprehensive analysis of these data taking into account satellite images and CWS data are usually published as an atlas, e.g. [15]. It allows one to obtain a representation of the long-term and spatial variability of the sea-ice characteristics in the basin.

The present paper demonstrates the results of using the NEMO ocean modeling framework [16] to reproduce the long-term variability of sea-ice cover in the basin of the Sea of Azov for further
development of the nowcasting/forecasting system for the cascading basins of the Azov, Black, and Marmara Seas. To assess the quality of the simulation results, we used various types of products obtained from satellite observations, the available CWS data, as well as sea-ice modeling results obtained in other works. The paper is organized as follows. A brief description of the LIM3 sea-ice model being used is presented in Section 2. The parameters of the cascading basins configuration developed for the NEMO are given together with a description of the numerical experiments and surface boundary conditions. In addition, the observational data used for preliminary validation and their brief characteristics are presented. Section 3 presents some results of variability analysis of simulated sea-ice fields in 2007–2016 and their comparison with CWS observations and satellite data products. Conclusions and discussion of the results are presented in Section 4. Inaccuracy of the used satellite data reprocessing is discussed.

2. Materials and methods

2.1. Brief description of used configuration

In this study, numerical simulation of sea-ice evolution was performed using the NEMO modeling framework [16], i.e. the ocean general circulation model OPA coupled with the LIM3 sea-ice model, whose detailed description can be found in [18]. The model simulates the thermodynamics of snow and ice on the sea surface taking into account ice-drift. In the LIM3 model, global (extensive) thermodynamic state variables are considered: sea-ice concentration, sea-ice volume, snow volume, ice enthalpy, snow enthalpy, sea-ice salt content, and sea-ice age.

In our simulations we use an eddy-resolving (1/24° in the meridional direction ≈ 4.6 km) configuration for the cascading basins of the Azov, Black, and Marmara Seas developed earlier. The domain bottom topography was prepared using an EMODNet bathymetry array [19] (Fig. 1(a), only the area of the Sea of Azov is presented). Atmospheric fields were obtained using the CORE bulk formula from the ERA5 reanalysis product provided by the European Centre for Medium-Range Weather Forecasts (ECMWF) [20] with a spatial resolution of 1/4°. The time resolution of 1 hour can be important for the reproduction of short-period processes and the diurnal cycle.

The climatic river runoff is prescribed in the Black Sea basin. The monthly data on the volume discharge for the largest rivers in the Azov Sea (Kuban and Don) [21] were used for the simulations. It was shown that this allows better reproduction of an unusual positive tendency of the Azov Sea water salinity observed in recent years. Initial conditions for the Sea of Azov were prepared using objective analysis of in-situ observations provided by CMEMS and the oceanographic database of the SeaDataNet project (https://www.seadatanet.org/).

Using the presented configuration, we perform two free run simulations of the cascade general circulation for the period from August 2007 to December 2016. The first one was carried out not taking into account the sea-ice model (exp. 1) using a special correction of the surface boundary conditions for the heat flux. This approach allows only obtaining information about the expected area of the sea-ice cover based on simple criteria for the sea water temperature on the first model level: it should be below the freezing point for the Azov waters (near -0.06 °C).

The second numerical experiment (exp. 2) was carried out in the coupling mode. Simulation allows one to reveal a large number of parameters of the sea state in the basins of the cascade and the sea-ice cover with an output frequency of 1 day⁻¹. Here we analyze only the characteristics related directly to the sea-ice fields. A comparison of the simulation results showed that the correction boundary conditions approach allowed reproducing the position of the boundaries and the size of the sea-ice cover area quite close to the results of exp. 2. Thus, our analysis will be focused more on the latter.

2.2. Products of reprocessing of satellite measurements

To validate the simulation results, daily data on the sea-ice concentration from OSTIA [22] with a spatial resolution of 0.05° were used. The product is based on sea surface radiation brightness data
from a passive microwave radiometer Special Sensor Microwave Imager Sounder (SSMIS). It uses a combination of modern algorithms and atmospheric correction. The spatial resolution of the data is 0.05°. The data are provided by CMEMS (http://marine.copernicus.eu).

![Figure 1](image-url)

**Figure 1.** Initial and boundary conditions for numerical simulation: (a) bathymetry (in color) [m] for the Azov Sea basin and a simplified scheme for areas (TB – Taganrog bay, CA – Central Azov, WA – Western Azov, KS – Kerch Strait); (b) - minimum value of 2 m air temperature (°C) over the Azov Sea in winter (blue) and the number of freezing days (i.e. with an air temperature below 0°C) (orange) according to ERA5 reanalysis product.

On the other hand, the sea surface temperature (SST) and the sea-ice temperature (SIT) data from MODIS / Aqua (https://modis.gsfc.nasa.gov) were obtained using a technique from [23] (the spatial resolution is 0.05°). For certain dates we use a subjective (visual) classification of the area covered by sea-ice from visual imagery with a resolution of 250 m obtained by the same sensor.

3. **Results**

A simple classification of winters by atmospheric conditions was proposed in [15]. The simulation results showed a rather close classification. As noted above, according to [15] 2007/2008, 2010/2011, and 2011/2012 were classified as mild winters; and 2008/2009, 2009/2010, 2012/2013 and 2013/2014, as warm ones. Figure 1(b) shows the agreement of the reanalysis data from ERA5 with the proposed
classification, i.e. one can identify mild winters with a greater number of freezing days than for the warm one. For the latter, rather low air temperatures can be observed, but with a smaller number of such days.

The analysis of the sea-ice cover area (not presented here) and sea-ice concentration according to the results of numerical modeling (Figure 2) allows us to distinguish mild and warm winters presented in Table 1. During mild winters the sea-ice cover is general for the entire Azov Sea basin, while during warm ones sea ice covers about 60% of the basin. The mild winter of 2013/2014 according to [15] can be mentioned here particularly. According to NEMO simulations, the period of sea-ice covering the area of the Azov Sea is quite lasting, over 2 months. This fact is in better agreement with the MODIS / Aqua observations. The same can be revealed from OSTIA reprocessing and MODIS / Aqua images.

![Figure 2. Interannual variability of the basin-averaged sea-ice concentration according to the results of numerical modeling (blue) and to OSTIA (orange); gray indicates periods of sea-ice cover according to the results of MODIS / Aqua treatment.](image)

| Years     | Winter type | Ice creation | Ice vanishing | Lasting, days |
|-----------|-------------|--------------|---------------|---------------|
| 2007/2008 | mild        | 2007-12-17   | 2008-03-09    | 83            |
| 2008/2009 | warm        | 2008-12-20   | 2009-02-28    | 66            |
| 2009/2010 | warm        | 2009-12-18   | 2010-03-05    | 78            |
| 2010/2011 | mild        | 2011-01-13   | 2011-03-30    | 77            |
| 2011/2012 | mild        | 2012-01-20   | 2012-04-11    | 82            |
| 2012/2013 | warm        | 2012-12-17   | 2013-02-16    | 61            |
| 2013/2014 | mild        | 2013-12-15   | 2014-03-06    | 74            |
| 2014/2015 | warm        | 2014-12-02   | 2015-03-03    | 91            |
| 2015/2016 | warm        | 2016-01-01   | 2016-02-22    | 53            |

When comparing the numerical simulation results and observed data OSTIA, a fairly good agreement is found between the average sea-ice concentrations during the ice formation. In addition,
the phase of the local maxima winter matches sufficiently exactly. It is important to note here that according to OSTIA sea ice is observed in December and March. Visual analysis of MODIS / Aqua RGB images is more consistent with exp. 2 throughout the period under study. Moreover, the analysis procedure implemented in OSTIA introduces noticeable artifacts for the coastal areas of the Sea of Azov. This leads to the fact that sea ice in some parts of the water area is observed throughout the year, which, obviously, is not true. In addition, this significantly spoils the representation of the array data in 2016. Therefore, for this year the results of the comparison are not presented.

Figure 3 shows the spatial distribution of the sea-ice thickness. For a mild winter of 2007/2008 the characteristic sea-ice thickness does not exceed 30 cm, except for coastal regions where ice rafting is observed. The water area of the basin was completely covered with ice only two weeks in January. The average sea-ice concentration in this period reaches 95%. Then its area decreases, and by the end of February the sea-ice cover occupies about half of the basin. Complete cleansing of the sea-ice occurs in early March. In the mild winter of 2011/2012 the sea-ice cover begins to form somewhat later (at the end of December). By the end of January the sea-ice thickness reaches a large value (up to 120 cm, off the Crimean coast). A feature of this winter, together with long and cold atmospheric conditions, is a stable northeastern wind, which forms a layer of sea ice in the western part of the sea. The average sea-ice concentration in this period reaches almost 100% and is maintained for almost a month. Complete cleansing of the sea ice occurs in early April.

For a preliminary assessment of the adequacy, we compared the sea-ice thickness from the results of numerical modeling with field measurements taken from [13]. It presents data on the sea-ice thickness of the Azov Sea ice on the CWS (Taganrog, Genichesk, Yeisk) according to the simulation results and measurements from the HMC Russia (hmc.meteorf.ru). For Taganrog, maximum values of thickness were obtained in 2013, 2015, and 2016 and are equal to 50-60 cm. However, according to measurements the maximum thickness reaches 50 cm in 2011/2012. In other years the simulation results correspond to measurements. In Genichesk, differences are observed only for the winter of 2010/2011 where the sea-ice thickness by modeling is more than 50 cm and by measurements – 30 cm. In Yeisk, according to the calculation the maxima were observed in 2010/2011 and 2013/2014 and from measurements in 2011/2012. At station Mysovoye 2011/2012 stands out, where the maximum thickness is 75 cm, and according to HMC data it is only 30 cm. Qualitatively, the simulation results correspond to measurements, except for several events.

The location of the sea-ice edge is compared according to the results of the numerical simulation and satellite data. To do this, we found the areas of intersection and the difference between the areas covered with ice and normalized to the total area of the Sea of Azov. This characteristic allows one to get an idea of the spatial coordination of sea-ice fields. The analysis showed that most of the sea-ice coverage according to MODIS / Aqua data lies within the area occupied by ice obtained in exp. 2.

The results of a comparison of the numerical simulation and OSTIA data are shown in Figure 4. One can see that during the period of ice formation the areas of sea-ice coverage are more than 85% consistent. This is especially true for the mild type of winters: 2007/2008, 2010/2011, 2011/2012, and 2013/2014. In warm winters low values of intersection result from a small area of simulated sea-ice cover. For December and March the difference between the analyzed arrays is about 50%. It can be explained by the presence of false sea ice in OSTIA described above.

The position of the proposed ice coating region obtained from the numerical experiment, exp. 1, quite accurately corresponds to the calculation of exp. 2 (not shown in the Figure 4).
Figure 3. Average monthly sea-ice thickness (cm) according to the results of numerical modeling (exp 2) in January (left) and February (right) for warm (top) and mild (bottom) types of winters.

Figure 4. Areas of intersection and difference of sea-ice cover between the simulation results and OSTIA data normalized to the total sea area.

4. Conclusions and discussion
This study presented the results of an attempt to reproduce the spatial and temporal variability of the ice cover of the Sea of Azov obtained by using NEMO modeling framework. A regional configuration of cascading seas was adapted to achieve the objectives. The thermodynamics and dynamics of the sea ice were reproduced by the LIM3 NEMO component. The simulated sea-ice cover parameters from 2007 to 2016, the concentration and thickness, in particular, were verified with satellite observational data products and data from coastal weather stations. The model reproduces a typical pattern of formation of a sea-ice field which does not contradict the previously obtained results and observations. The features of this scheme for the period under study agrees with a classification of winter atmospheric conditions based on the available field data.

The sea-ice concentration averaged over the basin according to the simulation results is in good agreement with the OSTIA satellite measurements reprocessing, despite the fact that the time of presence of sea ice according to the modeling results is shorter. The phase and amplitude of the local maxima of sea-ice concentration during this period seem to be simulated quite well. The noted
disagreement with the OSTIA data may be caused by the inaccuracy of the mapping procedure used to obtain the gridded array, since an analysis of another data from the MODIS / Aqua showed better consistency with the numerical modeling results. The preliminary numerical experiment was performed only with an ocean circulation model but, nevertheless, it allows one to determine the expected areas of sea-ice formation. The size of the sea-ice coverage area in this case is rather close to the results of numerical simulations coupled with the LIM3.

The presented simulation, however, was performed by means of a model developed for the sea ice of Arctic regions, and it should be used after accurate tuning by taking into account the regional peculiarities of the basin. The thickness of the modeled sea ice does not agree well with the measurements from coastal weather stations. This can be explained by using a too coarse spatial resolution of the configuration, which was insufficient for reproducing the circulation and thermodynamics of the coastal zone. Nevertheless, the location of the sea-ice edge agrees rather well with the results of numerical modeling.

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