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SIMULATIONS OF SHELF CIRCULATION DYNAMICS IN THE LAPTEV SEA

Abstract

The article describes the modeling processes of the shelf circulation dynamics in the Laptev Sea with focus on the Lena Delta region. We try to estimate the role of different factors such as heat exchange with atmosphere, Lena runoff and tidal forcing on the dynamics in the region. An unstructured-grid Finite Volume Coastal Ocean Model (FVCOM) is used as a modeling tool.

Key words

Laptev Sea, Lena Delta, shelf circulation dynamics, FVCOM

Introduction

The polar shelf zones are highly dynamic and diverse systems. They form a border between warm and fresh water of continental drain and the cold currents of the northern seas. In the Arctic shelf region, multiple river deltas accumulate organic carbon. They host a unique and very diverse northern fauna and flora.

Over recent years, the Lena delta region of Laptev Sea acquired a special focus since it can serve as an indicator of climate change. A large number of observations in this region suggest a strong climate and biological changes for the last fifty years (Bauch et al., 2009; Hölemann et al., 2011). Organized as a part of the International Polar Year (2007 – 2008), joint study by the National Research Center of France, University of Alaska (USA) and Melnikov Permafrost Institute (Siberian Branch of Russian Academy of Sciences) has found that the Lena water temperature at the middle reach in the flood period had increased by 2 ° C compared to the values of 1950 (Costard et al., 2007).

Based on the results of observations in the Lena Delta region (Russian-German expeditions «Lena-2007», «Lena-2008») and Laptev Sea (Russian-German expedition «BARKALAV-2007/TRANSDRIFT-XII», «POLYNIA-2008/TRANSDRIFT-XIII», «BARKALAV-2008/TRANSDRIFT-XIV») it was found that in summer 2007 a positive anomaly of temperature and negative anomaly of salinity were present in the central and eastern part of the Laptev Sea in the mixed layer. The same structure of temperature and salinity was observed in summer 2008, but the magnitudes of anomalies were smaller. A continuous temperature increase was also found for Atlantic water. Such a powerful inflow of warm Atlantic waters into the Arctic Basin was not observed for the entire period of instrumental observations since 1897.

The long-term analysis by Polyakov et al. (2008) of the surface salinity change in the Arctic Basin and Arctic Seas, including the Laptev Sea, showed that ice-related processes, freshwater runoff and the way it spreads under the influence of atmospheric processes play a key role in salinity changes (freshening) of the upper layer over the past decades.

Johnson (2001) modeling studies showed that atmospheric forcing greatly determines the direction of freshwater transport in the Laptev Sea. The observations have confirmed that the variability of summer surface salinity in the Laptev Sea is mainly governed by local wind patterns associated with positive and negative phases of atmospheric vorticity over the adjacent Arctic Ocean (Dmitrenko et al., 2005). It should be emphasized that the winter water dynamics has very small impact on riverine water pathways in the summer (Dmitrenko et al., 2010a). In the end of the winter season (March-April) the surface hydrography pattern is nearly the same as in September modified by thermodynamic ice formation.

Driven by the need to explain and understand the processes in the Lena Delta, the main goal of this work is modeling of the shelf circulation dynamics in the Laptev Sea with focus on the Lena Delta region. Our more distant goal is the ecosystem modeling in the region, for which a model with consistent dynamics is a necessary step.

This note describes our results obtained while tuning the model so that it is able to simulate the climatic changes in the region, and studying with its help the variability of circulation under the action of atmospheric, tidal and run-off forcing. We examine the role of topography structure and temperature of freshwater runoff, characteristics of heat fluxes in determining the features of the temperature and salinity distributions in the region and the role of local wind pattern and tidal dynamics. Additionally, we estimate the impact of improved bathymetry representation on the shelf in the vicinity of Lena Delta on tidal dynamics and local temperature and salinity local. Numerical simulations were based on Finite Volume Coastal/Community Ocean Model (FVCOM; Chen et al., 2006).

Model description

We use FVCOM to carry out our simulations. It is developed for simulations of flooding/drying processes in estuaries and tidal-, buoyancy- and wind-driven circulation in the coastal region featuring complex irregular geometry and steep bottom topography. FVCOM is unstructured- grid, finite-volume, free-surface, prognostic, 3-D primitive equation coastal ocean circulation model (Chen et al., 2003; Chen et al., 2006).

Our model domain covers water depths down to 65 m (Fig.1). The minimum water depth in the model is 0.5 m. We use high quality unstructured grid, which allows us to take into account complexity of coastline, characteristics of the bathymetry and other peculiarities of the problem. The grid was constructed using algorithm described in Persson and Strang (2004). Elements sizes are vary from 400 m near the cost to 5 km at the open boundary. The mesh contains six vertical sigma-layers with 250000 nodes on each of them. FVCOM was run using spherical coordinates, with nudging temperature and salinity at open boundaries to external data. For vertical mixing and horizontal viscosity simulation we used the modified Mellor and Yamada level 2.5 and Smagorinsky turbulent closure schemes respectively. As advection scheme we used the second order upwind scheme. The FVCOM version employed in this study is time stepped by a mode splitting method (Chen et al., 2009). The time step for the external mode is 4.6 sec for the barotropic case and 2.5 sec for the baroclinic case, the ratio of internal mode time step to external mode time step is 10.

Input data

The bathymetry data were taken from GEBCO (The General Bathymetric Chart of the Oceans; http://www.gebco.net/data_and_products/gridded_bathymetry_data/). For coastline construction we compared GEBCO bathymetry data and NOAA (The National Oceanic and Atmospheric Administration) coastline data (http://www.ngdc.noaa.gov/mgg/shorelines/shorelines.html). To smooth the coastline we used cubic b-splines technique (Fig.1).

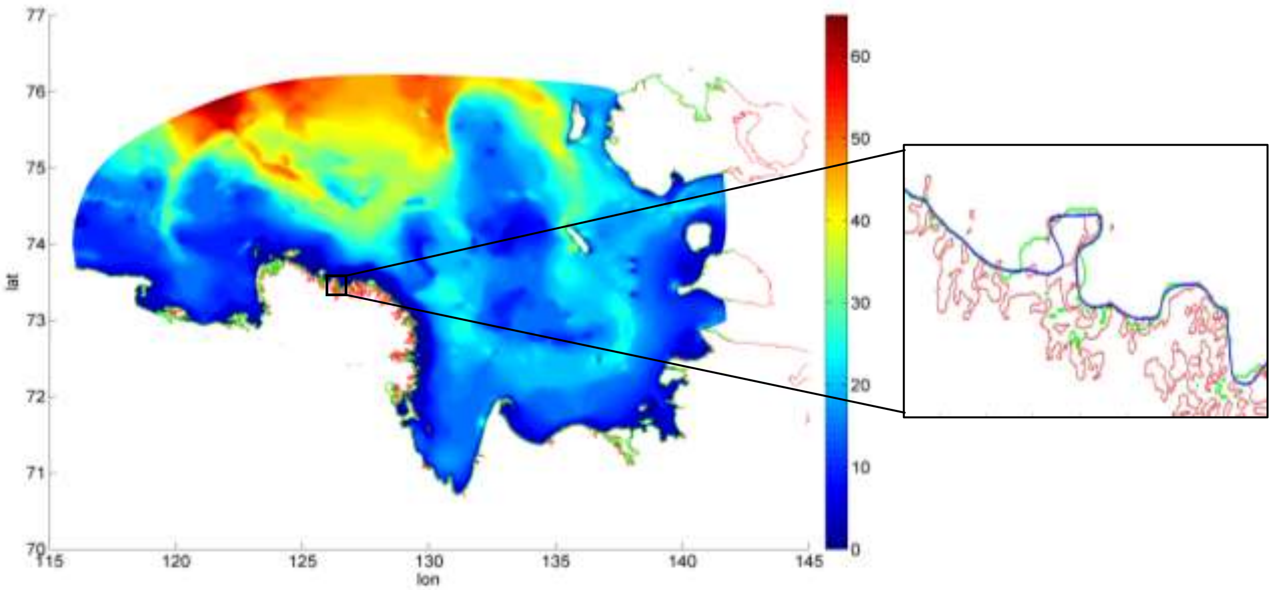


Fig. 1. The selected domain, bathymetry data from GEBCO (resolution of GEBCO grid is 30 arc-second), m. In red is shown coastline based on NOAA data, in green – coastline, which was obtained from GEBCO bathymetry data. On the right picture in blue is shown constructed coastline (smoothed using cubic b-splines technique).

The wind magnitudes and direction and radiation fluxes were taken from the regional, non-hydrostatic model provided by the consortium for Small-scale Modeling (COSMO). The time resolution of COSMO forcing is 1 hour. The COSMO model with included thermodynamic sea-ice module provides a high quality atmospheric forcing, which takes into account the presence of a thin layer of ice, and can be applied for short-range simulations (Steppeler et al., 2003; Schättler et al., 2008; Schröder et al., 2011). We used results from COSMO simulations with 5 km resolution performed for the Laptev Sea area with and without assumption that the Laptev Sea polynyas are ice-free.

The temperature and salinity fields for initializing the model and for daily nudging on the open boundary were taken from Arctic simulations by R. Gerdes and P. Rozman with focus on the Laptev Sea region (Rozman et al., 2011). This model provides data, which are in a good agreement with long-term mean (1920-2008) surface salinity distribution for winter season (February-April) described in (Dmitrenko et al., 2010a) and salinity observation data for May, 2008 (provided by M. Janout). Also, the provided salinity/temperature patterns are close to the pattern of seasonal cycle from summer of 2007 to late winter/spring of 2008 shown in (Hölemann et al., 2011). This sea-ice model provides daily data for temperature and salinity field in the region for six vertical layers.

The input daily Lena runoff data, derived from observations, were provided by Hydrological Institute, St. Petersburg. The runoff temperature was set to either 0.5°C or 5°C, which present, according to Yang et al. (2002), Yang et al. (2005) and Costard et al. (2007), the approximately lower and upper bounds for mean temperature in the river mouth during May respectively. For assessment of the influence of local bathymetry on temperature and salinity patterns we used additionally bathymetry measurement data in Lena Delta region. The observation bathymetry data at 27686 locations (the average distance between points is about 800m) in close proximity to Lena Delta were provided by Paul Overduin (Alfred Wegener Institute, Potsdam).

The model is forced by tidal elevation prescribed at the open boundary from different models: TPX06.2, TPXO7.1 and AOTIM with Doodson correction. We paid special attention to tuning the conditions at open boundaries so as to obtain best agreement with the observational data. The model simulates the four most energetic tidal constituents: M_2, S_2, O_1, K_1 (Sofina, 2008; Lenn et al., 2011;Kowalik, 1993; Dmitrenko et al., 2012).

Tidal dynamics analysis

Observations of tidal currents over the Laptev Sea continental are rare and fragmentary. The starting point of the analysis was tide gauges data provided by Kowalik and Proshutinsky (KP) (can be downloaded from http://www.ims.uaf.edu/tide/). Based on observation data near the open boundary and features of different models we designed new open boundary conditions. To specify the correct open boundary conditions is one of the central problems of our modeling due to small depths in the area under consideration. We should emphasize that for the selected domain the amplitudes and phases on open boundary should be corrected near the cost (depth<10-15m) if they are taken from any of models. The horizontal resolution of TPX06.2 and TPXO7.1 and associated inaccuracies in bathymetry data limit their skill in presenting the tidal features in the coastal zone. As concerns AOTIM (The Arctic Ocean Tidal Inverse Model), in addition to its 2D character, the linear assumption used in it makes it incapable of simulating residual currents (Chen et al., 2009).

The AOTIM was created based on (Egbert et al., 1994) data assimilation scheme by computing the inverse solution with all available tidal gauge data (Padman and Erofeeva, 2004). As a ‘prior’ solution was used the Arctic Ocean Dynamics-based Tide Model (the numerical solution to the shallow water equations). This pan-Arctic 2-D linear model is highly resolved (5-km regular grid), simulates 4 most energetic tides constituents (M_2, S_2, O_1 and K_1). Assimilated data consist not only coastal and benthic tide gauges (between 250 and 310 gauges per tidal constituent) but also available satellite altimeters (Padman and Erofeeva, 2004). Model bathymetry is based on the International Bathymetric Chart of the Arctic Ocean (Jakobsson et al., 2008). AOTIM5 does not include the effects of sea ice presence.

The TPXO7.1 and TPXO6.2 is a global inverse tide model developed by Gary Egbert and Lana Erofeeva at Oregon State University. The resolution of these models are 1/4^o x 1/4^o. TPXO7.1 and TPXO6.2 assimilates ‘TOPEX/Poseidon (T/P) and TOPEX Tandem satellite radar altimetry (available for the ice-free ocean between +/-66^o latitude), and *in situ* tide gauge data in the Antarctic and the Arctic’. TPXO7.1 is one of the most accurate global tidal solutions.

Chen et al. (2009) presented high resolution unstructed grid finite volume Arctic Ocean model (AO-FVCOM) in application for tidal studies. A spherical coordinate version of the instructed grid 3-D FVCOM was applied to the Arctic Ocean for tides simulation. The size of elements varies from 1 km in the near coastal areas to 15 km in the deep ocean; model resolves accurately the irregular coastal geometry. However, the largest amplitude and phase differences between modeled and observed tides were caused by the model errors along the Russian coast (Chen et al., 2009).

The designed open boundary condition provides better agreement with observation data compared to the case when the condition directly derived from AOTIM, TPXO6.2 or TPXO7.1 is used. The results from the tidal simulations for East Siberian shelf provided by Sofina have been also included in the analysis. Table 1 shows the results of comparison for M_2 constituent.

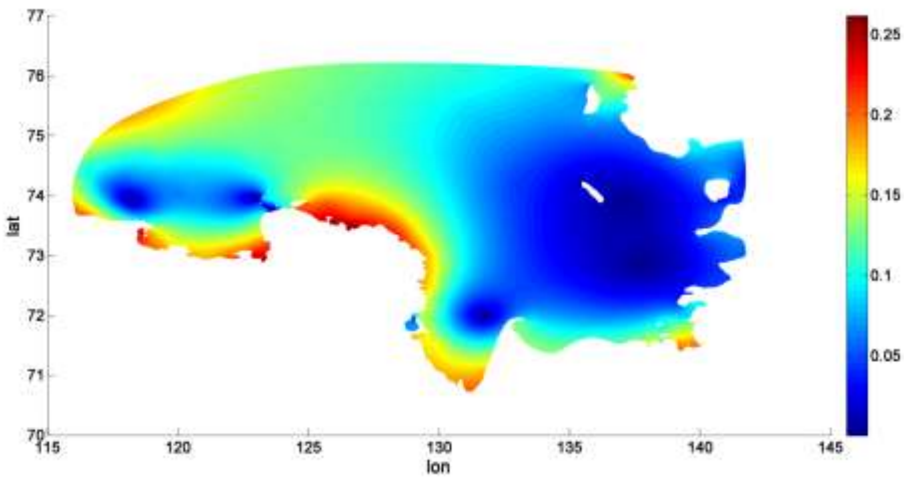
Table 1. The error of different models against coastal tide gauges for the M_2 constituent.

	AO-FVCOM with stations coord. corrections (R<40km)	East Siberian shelf model	AOTIM5	TPX07.1	TPXO6.2	Simulation based on AOTIM5	Simulation based on TPXO7.1	Simulation based on designed open boundary conditions	Simulation based on designed open boundary conditions with stations coord. corrections (R<20km)
$Error \cdot 10^2$	30.94	41.07	45.74	36.86	50.78	33.09	19.61	15.24	3.61

$$Error = \frac{1}{N}\sum_{i=1}^{N}\left(\left(1 + \left(\frac{S_{am}(i)}{O_{am}(i)}\right)^2 - 2 \cdot \cos(S_{ph}(i) - O_{ph}(i)) \cdot \frac{S_{am}(i)}{O_{am}(i)}\right)^{\frac{1}{2}}\right),$$

where S_{am}, S_{ph} - simulated amplitude and phase respectively, O_{am}, O_{ph} - observed amplitude and phase respectively, $N = 10$ - number of stations.

a)



b)

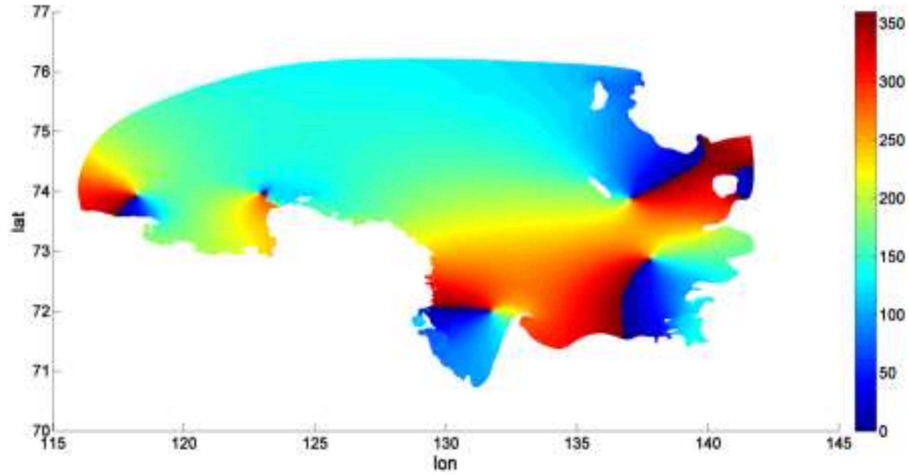


Fig. 2. The results of simulation with designed open boundary condition for amplitude and phase for M_2 constituent: a) Amplitude, m, b) Phase, deg.

Temperature and salinity patterns variability

We compare salinity and temperature fields in mixed layer under the ice in simulations with and without atmospheric forcing, tidal dynamics, with different temperatures of freshwater and using different techniques for freshwater input. We present here only a schematic overview of the results obtained.

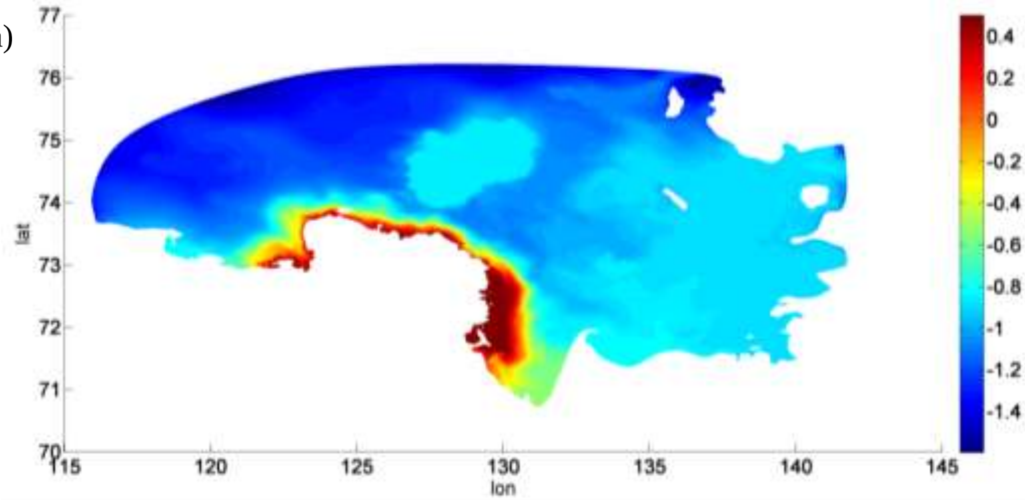
The surface salinity to the north and west from Lena Delta is mainly determined by the local wind pattern. East of the Lena Delta, the temperature and salinity patterns are dominated by plume internal dynamics driven by freshwater discharge and accompanying changes in the sea surface height and density field in the presence of Coriolis force and are largely insensitive to the atmospheric forcing, this fact being reflected in the background hydrography (Dmitrenko et al. 2010a).

Tides play a significant role in water mass modification through vertical mixing of seawater properties in the mixed layer. In general, plume velocities induced by winds and plume internal dynamics exceed residual tidal velocities, especially east of the Lena Delta where tides are weak.

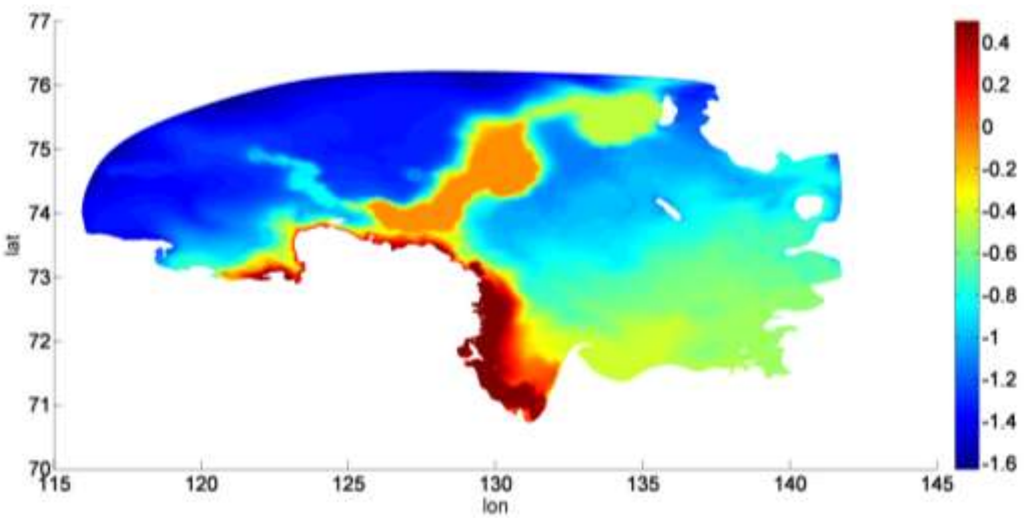
Increasing the discharge water temperature influences only little the freshwater plume dynamics. It can, however, have some impact on the volume of net sea-ice melting, which is not considered here. Bauch et al. (2013) found that significant volumes of net sea-ice melting are observed only in case of river water spread to the central Laptev Sea. Their study showed that the local melting of the sea ice is coupled to river water. Note that the central-eastern Laptev Sea is a shallow region with the depth less than 20 m even north of 75.5˚. The shallowness of the region may assist northward propagation of temperature signal from Lena water to the north if northward winds dominate in the second part of the summer. The stable stratification in that time and presence of thin layer of fresher water strengthen the effect. Note that in 2008 in the middle of July the observational Lena water temperature near the mouth reached 20˚C. We may hypothesize that if the freshwater plume spreads to the central Laptev Sea and not towards the East-Siberian Sea, the warm water of Lena River would lead to active ice melting in the adjacent area and a corresponding decrease in albedo and changes in heat flux balance.

The change in the structure of heat fluxes (COSMO data with and without open polynyas) and in runoff temperatures do not significantly influence the propagation of the freshwater plume whereas the temperature pattern is changed in the whole mixing layer (Fig. 3). The temperature anomalies in the mixed layer mainly in the northern part of the Lena Delta vicinity if they are independent of salinity anomalies can be mainly explained by characteristics of heat fluxes.

a)



b)



c)

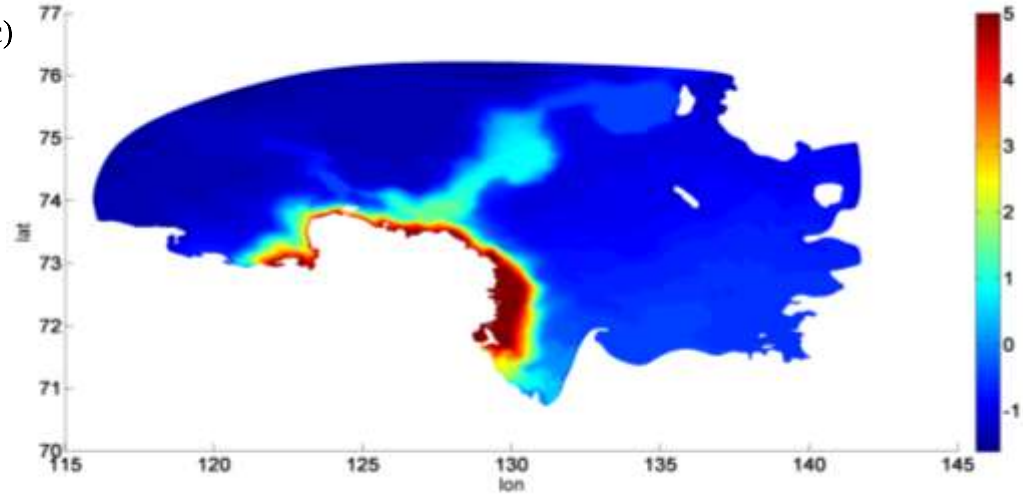


Fig. 3. The surface temperature fields [°C] at the end of May, freshwater runoff input from the boundary.
a) atmospheric forcing from COSMO with polynyas closed by thin layer of ice, the runoff temperature is 0.5 °C, b) same as in a), but with open polynyas, c) same as in b) but for the runoff temperature of 5 °C.

Because of weak winds in the region in the summer period, the details of the Lena runoff distribution over the Delta channels influences the simulated salinity patterns. That is why we tried to follow observations and local bottom topography in prescribing it. The Delta of Lena and its channels are not resolved in the model, so the Lena discharge distribution can be accounted for only approximately. We used two techniques to distribute the total volume runoff. In the first case the freshwater input was implemented as a boundary condition on the Lena Delta boundary. The spatial runoff structure followed the description in Magritsky (2001) with positions derived from the auxiliary topography. In that case, the freshwater is input through 1552 mesh edges so as to model the observed spatial distribution. In the second case, the freshwater input was added over some vicinity of the Lena Delta boundary, depending not only on spatial runoff structure, but on the depth too. The second technique allowed us to avoid anomalous water elevation in Lena Delta zone (maximum runoff in 2008 was observed at the end of May), to form the main freshwater channels and estimate the degree of influence of bathymetry data. In that case the freshwater input organized via the nodes (Chen et al. 2006), the amount of nodes, over which the freshwater is supplied, is 35198. The way how the Lena discharge is implemented is leading to certain differences, mostly at short simulation times, as can be seen comparing the left and right columns of Fig. 4. These differences become less pronounced in longer runs. The advantage of distributing the discharge over close vicinity of boundary is smoother elevation anomalies. The gradient of elevation may be rather high in the vicinity of channels if the discharge is implemented as the boundary condition.

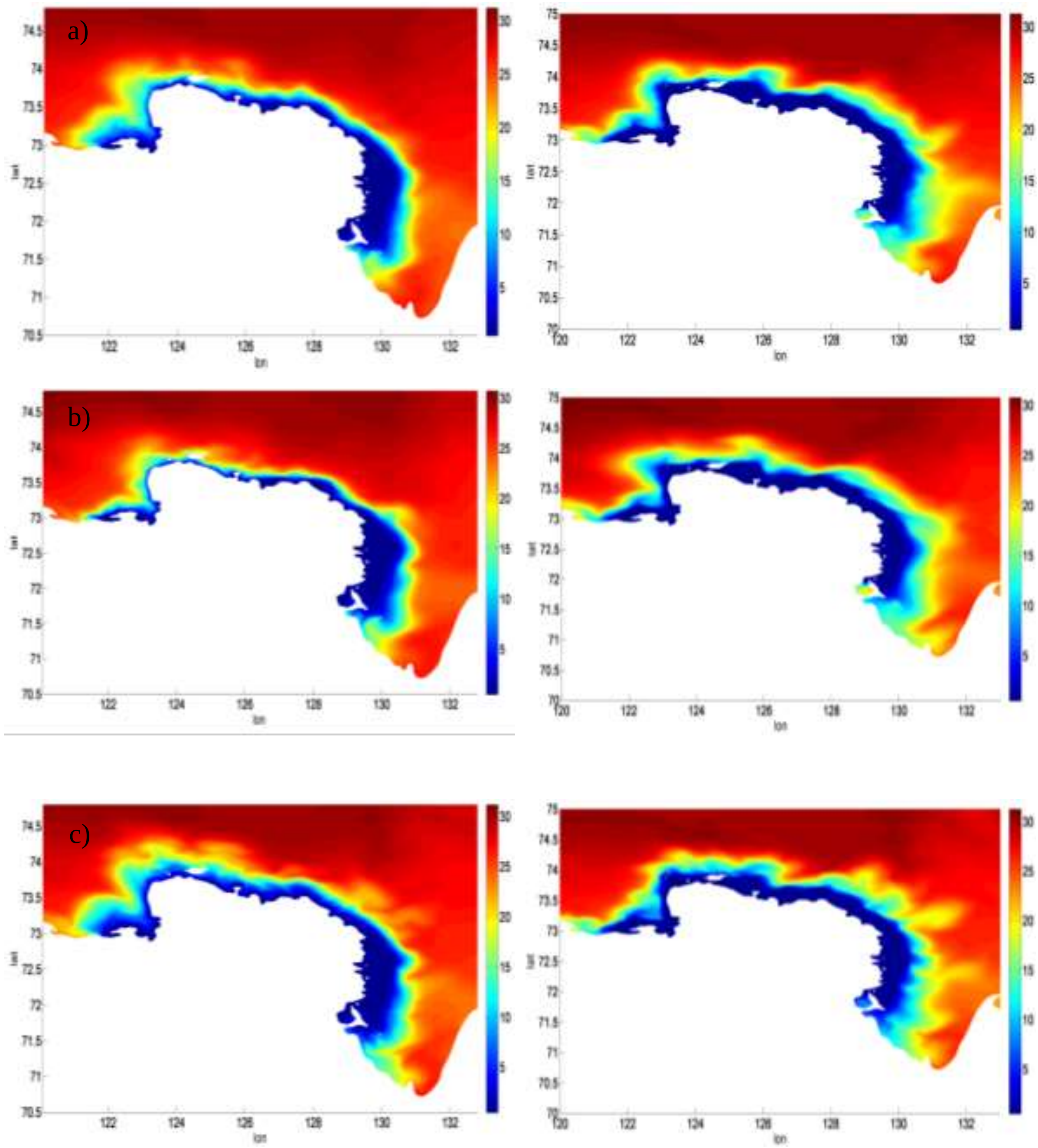


Fig. 4. (a) Surface salinity distribution simulated for the middle of May, 2008. (b) Same as (a), but in the absence of COSMO atmospheric forcing. (c) Same as in (a), but in the absence of tidal dynamics. The runoff is implemented as boundary condition (left column) and as distributed over some vicinity of the boundary (right column). Salinity is in practical scale.

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