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Modeling the impact of the Lena River on the Laptev Sea summer hydrography and submarine permafrost state*

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Abstract. We have simulated the influence of the Lena River heat and fresh water flux on the Laptev Sea shelf water state based on the coupled regional ocean-ice model and the subsea permafrost model. The numerical results show the variability of the summer hydrological fields on the shelf caused by the atmosphere dynamics variability. We have obtained the eastward spreading of the Lena River water and a negative salinity anomaly to the east of the Lena Delta during the cyclonic regime and northward freshwater advection from the Lena Delta during the anticyclonic regime. The heat flux caused by the summer river run-off increases the bottom water temperature in the Laptev Sea shelf and can affect the submarine permafrost state.

Introduction

Our knowledge of the hydrography of the East Siberia shelf seas and their climate impact on the Arctic Ocean is limited, first of all, because of the inaccessibility of the region. The East Siberian sector of the Arctic shelf (ESAS), including the Laptev Sea and the East-Siberian Sea, is the shallowest and widest shelf region of the World Ocean. The importance of the region is defined, first of all, by the fact that the Siberian shelves supply freshwater to the Arctic Ocean halocline due to the river run-off from the Lena River and a number of other rivers draining the Siberian shield areas and the adjacent land regions.

The Laptev Sea water circulation is characterized by an intensive interaction between the marine water masses of the Arctic Ocean and the river run-off and depends mostly on the atmosphere dynamics and the state of the ice cover [1]. Starting from May, when the Siberian shelf seas are covered with ice, the increased river runoff promotes the development of the low salinity eastward current (Figure 1). This current, originating from the Lena River Delta and following the coast from west to east, extending to the

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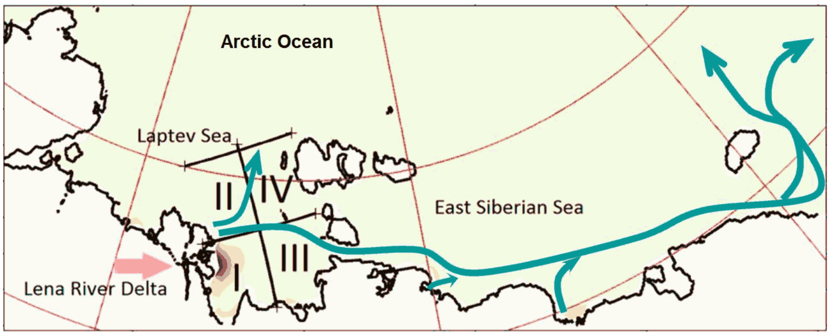

Figure 1. An idealized path of the Siberian Coastal Current [2]

Chukchi Sea, is known from the observational data as the Siberian Coastal Current (SCC) [2].

As the ice melts, the atmosphere dynamics starts to play an increasingly important role. The observational data reveal that the wind forcing makes the Laptev and the East Siberian seas hydrography be highly variable [3–5]. The wind driven redistribution of the river runoff over the Siberian shelf was first proposed in 1972 [6]. Based on the 1956 and 1961 data measurements analysis it was shown that the eastward diversion of the Lena River water resulted in a negative salinity anomaly to the east of the Lena Delta in the course of the cyclonic regime and in the northward freshwater advection from the Lena Delta in the course of the anticyclonic regime. Later [2, 7] it was confirmed that the SCC has been focused as a narrow jet along the coast under the cyclonic atmospheric conditions, while during the anticyclonic atmospheric circulation it was less expressed.

In contrast to the studies of the salinity distribution in the Arctic shelf waters, due to the influence of the river runoff, minor attention has been paid to the issue associated with the study of the role of the heat coming from the river waters. In our previous publication we considered the heat flux from the Lena River [8] into the shelf of the Laptev Sea, restoring the Lena river outlet temperature based on the linear regression and the atmosphere reanalysis data. The numerical simulation with the coupled ice-ocean model has shown that the Lena river heat flux results in 1–2° temperature increase in the shelf water during the summer season.

Increasing the water temperature in the Laptev Sea shelf can affect not only the basic hydrological components, but also the state of the sediments, which are primarily composed of the permafrost [9]. It is believed that the submarine permafrost is represented by the negative temperature-bottom sediments and distributed in the shallow part of the Arctic seas shelf with water depths up to 100 m. The bottom water temperature plays a significant role in the current state of the submarine permafrost, because it specifies the frozen soil thawing depth.

The warming in the water layer may bring about the submarine permafrost thawing and cause a release of methane into a water column. Observations of the methane concentrations were conducted over a shallow study area located in the southern Laptev Sea, east of the Lena Delta [10]. Extremely high concentrations of dissolved methane are annually being observed since 2005. This area was documented as a high-emissions-activity site serving as a source of methane coming to the atmosphere.

In this paper, we are trying to evaluate the thermal effect of the Lena River on the shelf water and the subsea permafrost state.

1. The method of investigation

1.1. Regional ice-ocean model. The investigation of the river heat flux on the shelf water state was based on the coupled regional ocean-ice model [11, 12] developed in the Institute of Computational Mathematics and Mathematical Geophysics (Siberian Branch of the Russian Academy of Sciences).

The ocean model is based on the conservation laws for heat, salt and momentum and on conventional approximations: Boussinesque, hydrostatic and rigid lid. After the separation of the momentum equations into the external and internal modes the barotropic equations are expressed in terms of a stream function. The mixed layer parameterization as vertical adjustment is based on the Richardson number. No-slip boundary conditions are used at the solid boundaries. Specified mass transports at open boundaries and at river estuaries are compensated by transports through the outflow boundary at 20° S. This ocean model has been coupled with the sea-ice model CICE 3.14 [13].

The model domain includes the Arctic and the Atlantic Ocean north of 20° S. The grid resolution for the North Atlantic is chosen to be $0.5^\circ \times 0.5^\circ$. At 65° N, the North Atlantic spherical coordinate grid is merged with the displaced poles grid in the Arctic. The horizontal grid size in the Arctic varies from 10 to 25 km. The model version used here has 38 unevenly spaced vertical levels. A minimum depth of the shelf zone is taken to be 20 m.

1.2. Experimental design. The initial temperature and salinity data are adopted from the PHC winter climatology [14]. Driven with the daily atmospheric forcing from 1948 to 2012 [15], the model allowed us to simulate the climate changes in the Arctic Ocean caused by variations in the atmosphere circulation.

Two numerical experiments were carried out to study the river heat flux effect on the shelf water hydrography and submarine permafrost state. In Exp. 1 the zero heat flux at the sea-river boundary was taken, as we consider the river temperature to be the same as the shelf water temperature.

In Exp. 2 the Arctic rivers temperature data from [16] were used at the boundary point corresponding to the river estuaries.

It is assumed that the submarine permafrost on the Laptev Sea shelf was formed on the land during the glacial period when the sea level was decreasing. To study the permafrost dynamics we set a paleogeography scenario of the last glacial climatic cycle (the last 120 thousand years). We use a heat transfer model in sediments taking into account the phase transitions for the calculation of the thermal field in the sediments and the definition of the upper and lower boundaries of the permafrost zone [17]. Mathematical equations of the model and the paleogeography scenario to estimate the generation and degradation of the permafrost at the East Arctic shelf are given in [18]. In our calculations, the condition at the upper boundary of the spatial domain is specified by the bottom water temperature obtained in the course of the simulation with the numerical ice-ocean model.

2. Numerical results

2.1. The Laptev Sea summer hydrography variability. In order to be sure that our numerical model represents the spatial-temporal variability in the Arctic shelf, known from the observations, we have numerically analyzed the velocity and salinity fields. The river water discharge begins its increase in May when the sea shelf zone is still covered with ice. As the ice melts, the atmosphere dynamics starts playing an increasingly important role. Until mid-June the shelf seas are still covered with ice, so a pronounced type of the summer circulation in the shelf seas mostly develops in July and in August provided the predominance of a certain type of the atmospheric forcing [3–5, 19].

The results of the 3D modeling present the spatial-temporal variability of the summer hydrological fields on the Laptev sea shelf including the periods of cyclonic and antycyclonic surface circulation (Figure 2). According to our calculations the eastward flow is steadily present during the cyclonic atmospheric circulation (see Figure 2c). The salinity front develops in surface waters and spreads along the coast of the Laptev and the East Siberian Seas. In the case of forming a local cyclone in the eastern part of the Laptev Sea, the salinity front can be oriented along the New Siberian Islands (see Figure 2b). During this period, according to the simulation results, the salinity increases in the central part of the Laptev Sea due to the influx of more saline water from the middle Arctic zone.

In the course of the anticyclonic circulation in the Laptev Sea (see Figure 2a), the salinity front is oriented according to the prevailing wind field, and can shift to the north-east or north-west (see Figure 2b). An intensive northward flow in the central part of the sea provides a fresh water transport towards the edge of the shelf zone. The inflow of more saline and colder

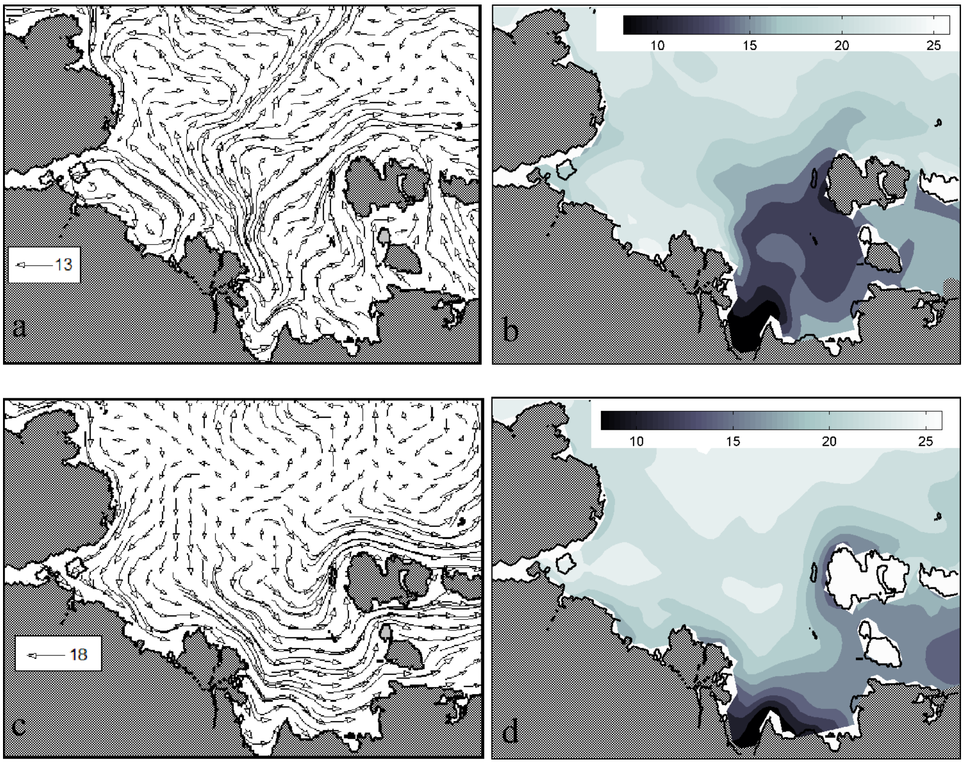

Figure 2. Simulated monthly averaged (August) surface circulation (a, c) and salinity (b, d) during anticyclonic (a, b) and cyclonic period (c, d)

water is simulated in the eastern part of the sea in the bottom layer (not shown).

It should be noted that we have not revealed any important difference between Exp. 1 and Exp. 2 when analyzing the velocity fields. Obviously, the primary effect from the river heat flux could be seen in the state of the sea ice. The most important difference between the two experiments was obtained in the region of the Lena River Delta. The results simulated show a decrease in the ice thickness caused by the river heat in the vicinity of the Lena River Delta in spring and in summer. In June, the heat coming with the river water results in the ice melting in the immediate vicinity of the river. Anomalies of the ice thickness during this period reach 50 cm with an average ice thickness of 2 m in this region. Moreover, ice compactness in this region is reduced by 10 %. For the sea ice, this heat is most important at the beginning of the summer season, because in the next period a rise in the air temperature plays the major role in the ice melting process, and a difference between the experiments is not observed. According to our numerical simulations, the heat input coming from the Lena River waters

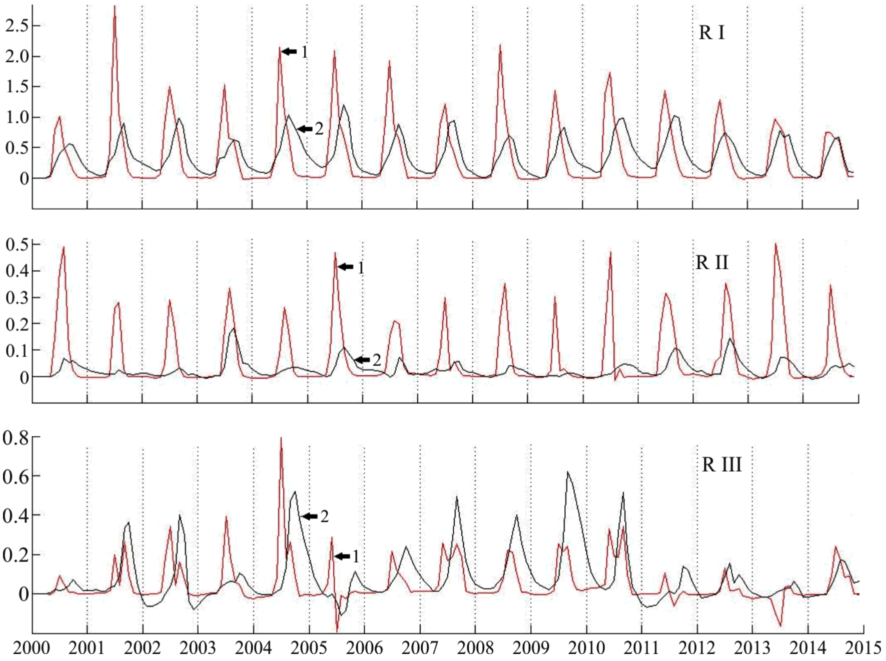

Figure 3. Temperature anomalies caused by the river run-off and averaged over Regions I–III for the surface (1) and bottom (2) layers

as compared to the contribution of the atmosphere to the Laptev Sea region is estimated from 5 to 10 % in different periods.

For a regional analysis, the eastern part of the Laptev Sea was divided into 4 subregions (see Figure 1). Averaging over the region helps to understand the duration of the existence of temperature anomalies due to the temperature of the incoming river water and also shows the main direction of the river water heat distribution over the shelf of the Laptev Sea in different years (Figure 3). The highest values of temperature anomalies are recorded in Region I, located in the vicinity of the output of the Lena River and to south of it. The maximum of the averaged temperature anomaly is observed in June and is equal to 2.5. The maximum values are recorded at a depth of 5 m, which corresponds to the mixing process of the sea and the river waters. The existence of a temperature anomaly in Region II is associated with the flow of water towards the north. In Region II, the maximum temperature anomaly shifts by 1 month as compared to Region I.

In contrast to Regions I and II, the temperature anomaly in Region III has some peculiarities. Almost regularly the surface layer has two small local maxima, the first maximum is observed in June and the second — in August. The first maximum is defined by the Yana River heat flux, and the second one is resulted from the Lena River water reaching Region III.

More significant for this region is an anomaly occurring every year in the bottom layers in the autumn months. Analysis of the spatial distribution of anomalies shows that this heat comes from Region I, which suggests that the coastal eastward flow is consistently simulated in the autumn period.

2.2. Impact of the Lena Rivers heat flux on the subsea permafrost state. The early results of our simulation indicate to the existence of the offshore permafrost within the vast Arctic shelf in the Laptev Sea [18]. In [20], we have taken into account the salt transport in the subsea permafrost dynamic model. The results of the simulation show the permafrost upper boundary deepening of ~ 6 m from 1948 to 2012 (≤ 9 cm/yr) in the shelf of the Laptev Sea eastward of the Lena River Delta (Exp. 1, Figure 4). Such a depth of thawing of frozen solids in the upper layer is defined, first, by their salt saturation due to migration of salts as a result of flooding of this part of the shelf by the sea waters.

Average annual water temperatures in shallow areas of the shelf reach small positive values as the shallow part of the Laptev Sea carries out the role of the Lena River estuary. The contact with rather warm waters and their penetration into the permafrost is the factor accelerating the degradation process of permafrost. In Exp. 2, we numerically investigated the response of the submarine permafrost to warming on the shelf with the influence of warm drainage of the Lena River. Changes in the ground temperature in the permafrost zone show up in its gradual increase until a depth of 8 m from the bottom surface (see Figure 4). The ground temperature at a

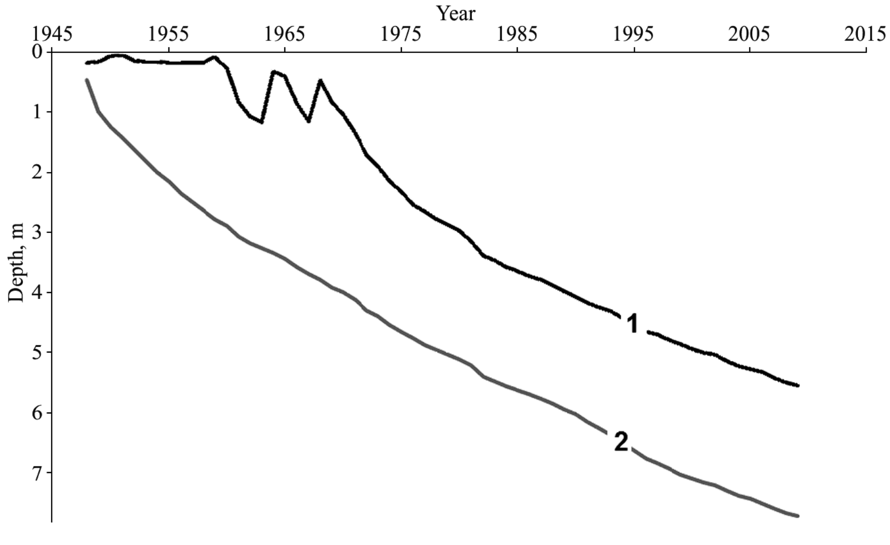

Figure 4. The location of the upper boundary of frozen sediments in Exp. 1 (1) and Exp. 2 (2)

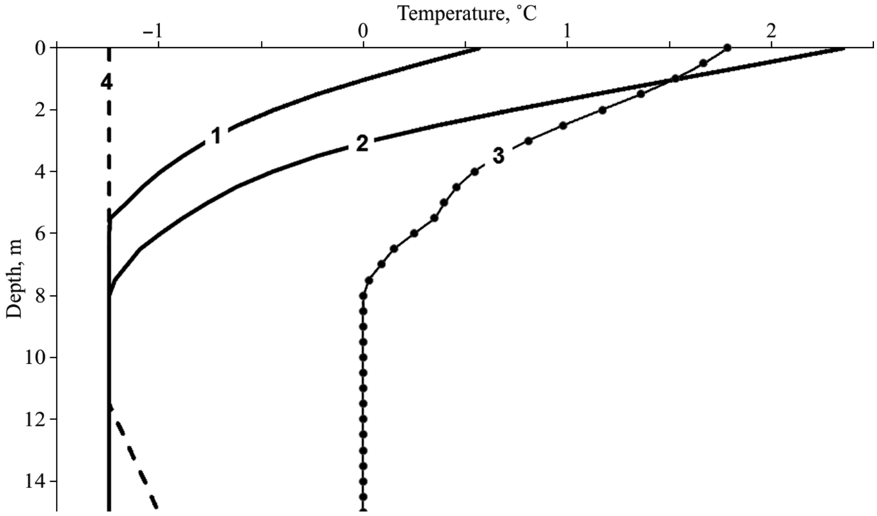

Figure 5. The calculated temperature in subsea permafrost for Exp. 1 (1) and Exp. 2 (2); the temperature difference between experiments (3); and the freezing point temperature (4)

depth of 1 m in Exp. 1 was observed to be 0 °C; in Exp. 2 it increased up to 1.5 °C due to the infiltration of an extra heat signal (Figure 5). Rising the soil temperature by 0.5–1.7 °C occurs only in the upper 4 m layer of the sediment. An increase in the bottom temperature in the area of Lena River in experiment Exp. 2 increases the layer of thawing by 2 m (see Figure 5). Therefore, the average speed of thawing of the permafrost solid with average temperature of −1.2 °C increasing from 9 to 12 cm a year due to an increase in the bottom sediments temperature in the summer period. This talik was formed as a result of seasonal thawing. It starts to deepen rapidly due to the heat diffusion even with further decrease in temperature of the top layer of the ground, and begins destroying the relict permafrost.

3. Conclusion

We have simulated the hydrography of the Laptev Sea region based on the three-dimensional numerical regional ice-ocean model using the atmosphere reanalysis data. Spreading the fresh and warm water from the Lena River over the Laptev Sea shelf was of our primary interest. Numerical results show the evidence of the relationship between the variability of the summer surface salinity over the Laptev shelves and the atmospheric circulation, which was established on the basis of observations [3–5, 19]. The numerical model simulates two main surface circulation patterns according to the atmosphere state: either cyclonic or anticyclonic. The eastward flow and spreading of fresh water are simulated during the cyclonic circulation. During the anticyclonic circulation, an intensive northward flow provides a fresh water transport towards the edge of the shelf zone. The heat flux from the Lena River ensures additional 10 % to the ice melting as compared to the contribution of the atmosphere to the Laptev Sea region. The highest values temperature anomalies, caused by the river run-off are simulated in the vicinity of the Lena River Delta. Spreading of these anomalies over the Laptev Sea shelf depends on the direction of the water circulation in summer season. Very important for us was to obtain warm temperature anomalies in the bottom layer of the coastal region. The thawing of the permafrost from top depends on the sea water temperatures near the sea floor. The simulation of the permafrost shows that a significant change in the permafrost depth occurs at the seafloor warming in the Arctic Sea. The submarine permafrost degradation from above is the most rapid in the near-shore coastal zone of the shelf and in the areas affected by the Lena River outflow. The influence of a heat signal in the bottom layer of water on the thermal regime of the bottom sediments in the area of the river delta was verified by the numerical calculations. The research has shown that an increase in the bottom temperature by 1–2 °C in the summer period brings about a growth of the speed of the submarine permafrost thawing in the area of warm river currents. In this case, the upper boundary of the permafrost has deepened by 2 m.

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