Simulation of near-bottom water warming in the Laptev Sea

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Abstract. A coupled ice-ocean model forced by atmospheric reanalysis data is used to examine a change in the bottom layer of the Laptev Sea on a scale of several decades. The model shows that since the mid-1980s there has been a warming of bottom waters in the shelf region. Analyzing values of bottom temperature averaged over a decade, we show that since 2005 the intensity of warming of the bottom layer has increased. The main reason for this is disappearance of ice cover in summer accompanied by an influx of heat into the surface layer of the sea. Also, an essential factor is the dynamic state of the atmosphere. The intensification of surface currents due to wind action promotes mixing of waters and heat transfer to the bottom layer of the sea. The heat anomalies entering the near-bottom layer of the sea during the autumn cooling could exist during the winter period.

1. Introduction
The Laptev Sea is one of the marginal Arctic seas. On the south, it is bounded by the northern coast of Siberia. On the west, it is separated from the Kara Sea by the Taymyr Peninsula and Severnaya Zemlya and from the East Siberian Sea by the Novosibirsk Islands on the east. The Laptev Sea northern limit is marked geographically by a line running the Arctic Cape to the northern extremity of the Kotelni Island (the New Siberian Islands) according to the Limits of the Oceans and Sea proposed by the International Hydrographic Organization [1]. About 53% of the sea has a depth of about 50 meters, and the coastal regions south of the 76th parallel have a depth of less than 25 meters. 22% of the area is situated in the northern part of the sea, where the bottom abruptly breaks off to the ocean bed with depths of the order of one kilometer [2].

The Laptev Sea has always been considered one of the harshest polar seas, with water temperatures close to freezing for most of the year. Hydrological observations carried out on the Laptev Sea shelf in 1920-1990 showed a significant increase in the bottom temperature (up to 2.1 degrees) in the shallow part of the shelf, which began in the mid-1980s [3]. Later observations showed that the process of warming of the bottom layer of the sea continues. More than 3°C warming in the bottom water on the mid-shelf compared to the long-term mean data was detected in the observations obtained by two moorings north of the Lena Delta from September 2007 to September 2009 [4]. Evidence of the near-bottom warming reaching a maximum of +0.6 °C by mid-January 2013 on the Laptev Sea was provided by the observations for 2012/2013 [5].

The studies carried out in [6] are presented in the form of an archive of data on changes in water temperature and heat content of the upper ocean layer (OHC-ocean heat content, http://159.226.119.60/cheng/). To assess changes in the shelf seas, we averaged monthly data over ten years (1990-1999, 2000-2000, 2001-2019) and considered deviations from similar values for 1960-1989. These data show a positive trend in assessing the heat content of the Laptev Sea shelf over three decades (Figure 1).
The main purpose of this work is to analyze the change in the near-bottom temperature of the Laptev Sea on a scale of several decades based on three-dimensional numerical modeling with a coupled model of the ocean and sea ice and to identify regions in which the temperature increase is most noticeable.

2. Model

2.1. Coupled Ice-Ocean model

In this study, we used the three-dimensional regional coupled ocean-ice model SibCIOM (Siberian Coupled Ice-Ocean Model) [7,8] developed at the Institute of Computational Mathematics and Mathematical Geophysics (Siberian Branch of the Russian Academy of Sciences). The ocean model includes a general circulation ocean model based on conventional approximations: Boussinesq, hydrostatic, and “rigid lid”, and an embedded mixed layer parameterization [9]. The ocean model was coupled with the CICE v3 model, which is based on the thermodynamics of elastic viscous-plastic ice [10] and the multi-category sea ice thermodynamics [11]. The sea ice advection utilizes a semi-Lagrangian scheme [12]. To take into account the peculiarities of ice cover formation in the Laptev Sea, we use the most straightforward fast ice parameterization based on climatology; namely, we set to zero the ice velocity in the shallowest part of the Laptev and East Siberian Seas (a depth of < 30 m) for the period from 30 October to 1 June.

We run the SibCIOM in a domain of the Arctic and Atlantic Oceans north of 20° S. The numerical three-polar grid with displaced poles in the Arctic Ocean uses 0.5° x 0.5° resolution for the Atlantic Ocean. In the Arctic the horizontal grid size varies from 10 to 25 km with an average grid spacing of about 18 km. The model used 38 unevenly spaced vertical levels with a maximum resolution of 5 m in the upper 20-meter layer. The minimum depth in the Arctic shelf zone was taken to be 20 m.

The ice-ocean model is forced by daily surface data from atmospheric NCEP/NCAR reanalysis data [13]. Zero ice and ocean velocity and 2-m thick ice and climatology for temperature and salinity were used as initial conditions [14].

The model took into account the inflow of Bering Strait (annual 0.8 Sv) and the average seasonal runoff from the hydrological station measurements [15] for the largest rivers in the region, among which are the Siberian rivers Yenisei, Ob, Lena, Indigirka, Olenek, Yana, and Kolyma. The rivers’ fresh water flux was calculated on the basis of the assumption that the river water has zero salinity. The specified mass transports at open boundaries and the river inflows are compensated by transports through the outflow boundary at 20° S. To take into account the rivers’ heat flux into the sea, we used monthly temperature data from [16].

![Figure 1](image-url)
3. Simulation

3.1. Decadal warming in the near-bottom layer of the Laptev Sea shelf

In our previous study [17], the interannual variability of the hydrological fields of the Laptev Sea caused by the variability of atmospheric dynamics was investigated based on a three-dimensional large-scale coupled model of the ocean and sea ice. Based on an analysis of the simulation results, we have shown the possibility of transferring heat accumulated in the surface layers in summer to deeper layers during the autumn season. In continuation of this study, we considered the possibility of existence of long-term heat anomalies in the bottom layer of the sea in winter [18]. A numerical experiment using a high-resolution ocean model (2-5 km) was carried out over a biennium from September 2006 to September 2008 using atmospheric reanalysis data (https://data1.gfdl.noaa.gov/nomads/forms/core/COREv2.html). Based on the results of numerical modeling, we obtained a warmer sea state for the summer of 2007 compared to 2006. The state of the atmosphere in the region contributed to more substantial warming of the surface waters in the summer of 2007 as compared to the same period in 2006. The seawater circulation system in 2007 was also significantly different from the situation in 2006. The flow directed towards the coast contributed to additional mixing in the coastal waters and the flow of heat into the bottom layer. The warm bottom layer of the eastern part of the sea was preserved during the winter period of 2008.

To study the question of warming of near-bottom waters in the Laptev Sea shelf on a scale of several decades, we have performed a numerical simulation of the large-scale variability of the Arctic Ocean circulation and the sea ice state caused by the variability of the atmosphere during the period from 1948 to 2014. To identify regions of most intensive warming in near-bottom waters of the Laptev Sea during different periods, we made several averagings of three-dimensional temperature arrays obtained in the numerical experiment. We defined the basic period from 1960 to 1975 and calculated the temperature T-base by averaging the annual temperature arrays. Also, we figured averaged temperature arrays for 10-year periods: for I-period - T_{1985-1994}, for II-period T_{1995-2004} and for III-period T_{2005-2014}. Further, we will analyze the deviations of the obtained temperature fields averaged over ten years from the basic distribution.

Our simulations, forced by the atmospheric reanalysis, show an increase in the average temperature of the bottom layer for 30 years in 1985-2014 relative to 1960-1975 in the shelf area of the Laptev Sea (Figure 2a) and a decrease in the ice volume in summer and autumn (Figure 2b). In most of the shelf zone, the near-bottom water temperature deviations are within 0.2°C. The simulations show the highest values of temperature anomalies in the area of the Lena Delta. In the area where the river waters enter the sea, they reach 0.8°C. Temperature anomalies up to 0.3°C arise around the delta and the coastal part of the sea. In the deep-water part of the sea, we obtain an increase in the bottom temperature relative to 1960-1975 in the Vilkitsky Strait and at its outlet (up to 0.6°C). Along the continental slope, where the trajectory of Atlantic waters passes [19], both positive and negative anomaly values arise. In our results, this corresponds to the variability of the Atlantic waters' trajectory in different periods.

To clarify the situation in the shelf zone, we compared the distribution of surface and near-bottom temperature for the basic period with average ten-year distributions. Figure 3 shows the results of an intensified process of both surface (Figure 3a-c) and near-bottom (Figure 3d-f) temperature increase. In general, the picture of deviations in the near-bottom temperature relative to the basic period is consistent with similar surface distributions for the corresponding time intervals. We obtained the most significant agreement between the surface and bottom temperature deviations in 1985-1994. This period shows the smallest temperature change relative to the basic period, both in the bottom (Figure 3d) and surface layers (Figure 3a). A time series of the ice volume in the shelf zone (Figure 2b) shows that before 1990 the sea ice covered a significant part of the shelf and helped isolate the surface layers of the sea from heat input in summer.
Figure 2  
(a) Region of the study and names used in the text. Distribution of near-bottom temperature anomalies in the region of the Laptev Sea $T_{1985-2014} - T_{base}$;  
(b) monthly averaged ice volume change (in km$^3$) on the Laptev Sea shelf. Red line shows average value for corresponding time period.

Figure 3. Simulated temperature anomalies in the Laptev Sea. Sea surface (left panel) and near-bottom (right panel):  
(a), (d) $T_{1985-1994} - T_{base}$;  
(b), (e) $T_{1995-2004} - T_{base}$;  
(c), (f) $T_{2005-2014} - T_{base}$.
The deviation field for the next decade shows a massive increase in the surface temperature in the western part of the sea and in the vicinity of the Lena Delta (Figure 3b). The numerical model shows that the average ice volume in the shelf decreased compared to the previous period (the red line in the figure) in all three months, and in some years the ice volume was near zero (Figure 2b). The distribution of near-bottom positive temperature deviations (Figure 3e) includes both the part that corresponds to surface heating and the tongue spreading towards the Novosibirsk Islands. The extent of this tongue exceeds the corresponding area of surface anomalies, reflecting the contribution of heat transfer by currents.

The picture of sea surface temperature deviations in the decade 2005-2014 (Figure 3c) shows the most substantial warming among the three periods. In this period, the time series of ice volume in the region (Figure 2b) is close to zero value in summer each year. The sea-surface heat flux increases as the ice cover disappears, and the ice-free period's duration increases. Also, the contribution of the wind to the formation of currents increases and, accordingly, the role of surface currents increases in the heat transfer. Figure 3c shows the surface distribution of the average temperature anomalies obtained as a result of modeling. It reflects the consequences of the thermal and dynamic state of the atmosphere in the corresponding decade. In the picture presented, we see the largest anomalies in the coastal zone (Figure 3c). However, the tongue of positive values, which in 1995-2004 we were able only to outline (Figure 3b), is now quite clearly presented. It corresponds to one of the possible sea circulation modes -- the “off-shore” mode, according to Guay's [20] terminology, which characterizes the flow of water masses away from the coastal area. The picture of two main possible modes of surface circulation in the Laptev Sea simulated in the numerical experiment is shown in Figure 4. The second mode (“on-shore”), corresponding to the flow directed to the shore and the forming alongshore eastward current, is also present in our calculations. In our previous papers [17,18], we have showed that this mode promotes intensive vertical mixing and heat income into deep layers of the sea.

Figure 4. Simulated Laptev Sea circulation: a) off-shore mode; b) on-shore mode.

Figure 5 shows a time series of the bottom temperature at selected points during two years of the simulation period. On the basis of the presented distribution we conclude that: 1) sharp formation of bottom anomalies begins in August and continues through November, and this shows the contribution of the autumn mixing processes to the increase in the bottom temperature; 2) the local minima and maxima in the period from September to April indicate the possibility of advection of heat anomalies.
in the bottom layer; 3) heat anomalies that entered the bottom layer of the sea during the autumn cooling period can exist several months during the winter period.

![Near-bottom water temperature](image)

**Figure 5.** Time series of near-bottom temperature at three points. Simulation result.

In contrast to the previous periods, 1995-2004, in the last decade of simulation we obtain the most significant positive temperature anomalies along the sea coast. This reflects the on-shore mode formation during the open water period and intense vertical mixing with heat penetration into the bottom layers of the sea. In our simulations, on-shore circulation caused by the cyclonic regime of the region atmosphere most often established in September.

### 3.2. Role of the river heat flux in the warming in near-bottom waters

Further analysis of the numerical results involved examining the role of rivers in this process, particularly the effect of heat supplied with their waters. Earlier in our paper [17] we considered the influence of the Lena River heat inflow on the state of the Laptev Sea hydrological and ice fields on the scale of a single year. The paper considered the results of modeling the movement of heat anomalies caused by a heat inflow of the Lena River, combined with the system of sea currents. To highlight the role of the thermal component of the river runoff, we analysed the results of two numerical experiments, namely, experiment 1 - taking into account the heat of the river runoff based on the use of the climatic average monthly temperature [16] and experiment 2 - assuming the absence of heat inflow from the rivers. The fresh water flux was used in the same way as in experiment 1. Now, we examine possible changes in the bottom layer temperature and heat accumulation over long periods. We analysed the difference between the two experiments' bottom temperature values averaged over the ten-year periods indicated earlier in this section.

Analysing the obtained fields of the temperature difference, we realized that in the sea shelf zone the most remarkable changes caused by the heat inflow from rivers are concentrated in the vicinity of estuaries. Figure 6 represents the distribution of variances for the last ten-year period. The most significant deviation in the vicinity of the Lena estuary reaches a value of 1.2°C. The warm tongue water spreads to the south into the Buor Khaya Bight (0.2-0.4°C) and flows along the coast (0.1°C), following the Siberian Coastal Current trajectory. On most of the shelf, we obtained small (less than
0.1°C) deviations, which are not very significant compared to the changes caused by the atmospheric impact in the summer shrinking ice cover conditions.

Figure 6. Rivers’ heat flux impact on the near-bottom temperature. Average temperature difference (°C) \( T \) (river heat) – \( T \) (no river heat) during 2005-2014.

Significant positive values of the temperature difference, up to 0.6°C, were obtained on the Laptev Sea continental slope. This region corresponds to the area of passage of Atlantic waters [19]. Also, in the numerical model the waters of the Kara Sea enter this area through the Vilkitsky Strait and, accordingly, the waters of the Ob and Yenisei Rivers pass through the strait and carry their heat. The most significant values of the temperature difference in the bottom layer due to the river runoff in this region have been most noticeable in the last decade, 2004-2014. Perhaps this is a cumulative effect, but then the question arises about the localization of river heat anomalies. Other physical mechanisms are also possible in the Arctic Ocean waters’ complex stratification system, where most of the water masses have a negative temperature. All these questions require additional research.

4. Summary
In this study, based on numerical modeling using a three-dimensional ice-ocean model and atmospheric reanalysis data, we simulated the variability of the Laptev Sea hydrology and examined heat transfer from the sea surface to the bottom layer during 1960-2014. Our simulations of the Laptev Sea hydrology support recent observations of an increase in the near bottom temperature in the Laptev Sea Shelf.
We analyzed average ten-year temperature changes in a basic period, which was chosen from 1960 to 1975. Temperature changes in the bottom layer were compared with temperature changes in the surface and sea ice cover.

In the shelf region, the smallest warming in both the surface and bottom layers was obtained for 1985-1994. The most substantial warming of the Laptev Sea occurred in the early 2000s. During the last decade of our simulation, 2005-2014, the model showed an intensive increase in the average annual temperature of the surface and bottom layers. We believe that the process of warming taking place in the Laptev Sea shelf waters is closely related to disappearance of ice cover in summer and an increase in the ice-free period. Our results show near zero ice volume in the Laptev Shelf in summer each year during this period. An increase in the ice-free period contributes to a rise in heat input into the sea surface layers in summer. Also, the period of heat exchange increases due to convective mixing in autumn. In our model, a sharp formation of bottom anomalies begins in August and continues through November. The intensification of wind-driven currents in the ice-free sea promotes mixing of waters, heat transfer, and warming of the near-bottom layer of the sea. Episodic warming in the near-bottom layer can persist for several winter months. The positive anomalies of near-bottom temperature occupy the entire shelf part of the Laptev Sea. Their distribution pattern reflects possible directions of water circulation. The most significant anomalies (about 0.6°C) in the near-bottom layer are found along the sea coast. We believe that this is a consequence of the most frequent cyclonic regime of the atmosphere in the region in the autumn season, leading to on-shore circulation.

Along the continental slope, which is part of the Laptev Sea, we obtained both positive and negative anomalies in the near-bottom after a 30-year averaging. We believe that this corresponds to the variability of trajectories of Atlantic waters in the different periods.

Analyzing changes in the temperature of the bottom layer of the sea, we tried to highlight the role of rivers in this process, particularly the effect of heat supplied with their waters. The most significant deviation in near water temperature due to the rivers' heat flux was obtained in the vicinity of rivers of the Lena estuary. This deviation reaches a value of 1.2°C and spreads to the south into the Buor Khaya Bight (0.2-0.4°C).

We also obtained a result that is difficult to interpret at present. Significant positive values of the temperature difference due to the heat of the river, up to 0.6°C, were obtained on the Laptev Sea continental slope. A study of this finding will be carried out in the future.

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