Bull. Nov. Comp. Center, Num. Model. in Atmosph., etc., 17 (2019), 21–30

Simulation of the near-bottom water warming in the Laptev Sea in 2007–2008*

M. Kraineva, E. Golubeva, G. Platov

Abstract. The Laptev Sea, one of the most severe Arctic shelf seas is the focus of the international research on account of a pronounced climate change (warming of the atmosphere temperature, lengthening of the summer open-water season, reduction of the ice extent, rapid coastal erosion). In recent years, as compared to the long-term historical data, warming in the near-bottom water of the Laptev Sea with the analysis of hydrographic data was detected. The observations made also provide the evidence of episodic warming in the near-bottom waters recorded in the winter period. In this study, based on the numerical modeling, we are trying to simulate the heat transfer from the sea surface to the bottom layer and to detect the lifetime of the near-bottom temperature anomalies. For our study, we used a high-resolution three-dimensional regional model of the Laptev Sea, nested in a large-scale coupled ice-ocean model of the Arctic and North Atlantic. Carrying out the numerical experiment for the period from September 2006 to September 2008, we have obtained positive temperature anomalies in the near-bottom water in the winter of 2008 caused by the intensive surface warming in the summer of 2007.

Keywords: Arctic Ocean, Laptev Sea, climate variability, numerical modeling.

1. Introduction

The Laptev Sea is a marginal sea of the Arctic Ocean (Figure 1). On the south, it is bounded by the northern coast of Siberia and extends from the Taymyr Peninsula and Severnaya Zemlya on the west to the Novosibirsk Islands on the east. A line joining the Arctic Cape (formerly, Cape Molotov on the Komsomolets Island of the Severnaya Zemlya group) to the northern extremity of the Kotelni Island (the New Siberian Islands) is considered to be the northern boundary of the sea according to the Limits of the Oceans and Sea, proposed by the International Hydrographic Organization [1]. More than half the sea (53 %) is a gently sloping continental bank with an average depth of about 50 meters; moreover, the bottom regions south of the 76th parallel are located at a depth of less than 25 meters. In the northern part of the sea, the bottom abruptly breaks off to the ocean bed with depths of the order of one kilometer (22 % of the sea area) [2]. The Laptev Sea is one of the

*Supported by RFBR under Grants 17-05-00396, 17-05-00382 and Presidium of RAS No. 51. We gratefully acknowledge the support of the staff of the Siberian Supercomputer Center SB RAS for providing us with their supercomputer facilities.

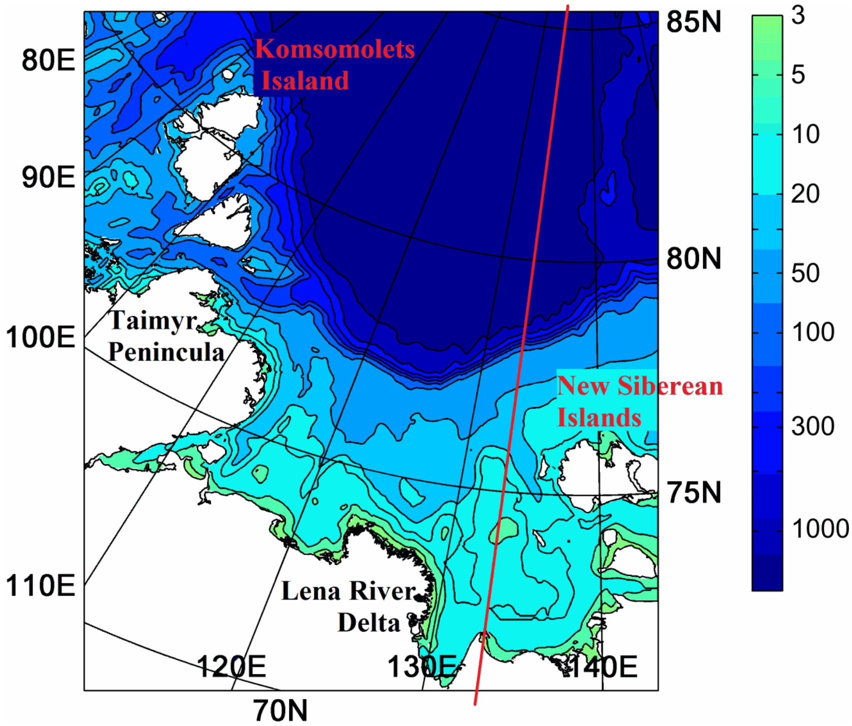

Figure 1. Region of the Laptev Sea. Red line shows a location of the section for the analysis of the simulated results

most severe among the Arctic seas. With the exception of a short summer period, the sea surface is under the ice cover. Moreover, the Laptev Sea is one of the main suppliers of the sea ice to the Arctic. After its formation, the offshore-directed winds push the ice away from shallow coastal zone towards the central Arctic Ocean. The first-year ice that survives during the summer period melts and turns into the second-year ice being transported further and contributes to the long-range transport of biota and biogeochemical material across the Arctic.

The Laptev Sea water temperatures range from −1.8°C on the north to −0.8°C on the south-east parts. In the summer season, the sun warms the surface layer up to 8–10°C in the ice-free bays and up to 2–3°C in the open sea, and the temperature remains close to 0°C under the ice cover. The water salinity is significantly affected by the thawing of ice and river runoff, most of which is contributed by the Lena River.

For many years, international programs and expeditions have been working in the Laptev Sea region (for example, “AVLAP-2002”, “LAPEX” “Polynia”, “Laptev Sea System”, “Lena”, “TRANSDRIFT”) aimed at observation, and studying the climatic changes in the natural environment of the

Laptev Sea region. The most important among them are: warming of the atmosphere temperature, lengthening of the summer open-water season, reduction of the ice extent, rapid coastal erosion. The analysis of the summer hydrographic data for the period of 1920–2009 has detected warming of the bottom water layer by 2.1°C over the east Siberia coastal zone [3]. The observations from the two moorings that were deployed in the Laptev Sea north of the LenaDelta from September 2007 to September 2009 have shown more than 3°C increase in the bottom water temperatures on the mid-shelf as compared to the long-term mean data [4]. This anomaly was considered to be a consequence of non-typical high summer time surface water temperatures. Moreover, remnants of the relatively warm bottom water were observed on the mid-shelf from September 2007 until April 2008. The observations for 2012/2013 period also provide the evidence of episodic warming in the near-bottom waters on the Laptev Sea central shelf, which maintained positive temperatures for $\sim$2.5 months, reaching a maximum of +0.6°C by mid-January 2013 [5].

A question on an increasing of near-bottom temperature deserves special attention because large parts of the Laptev Sea are thought to be underlain by the submarine permafrost as a result of their exposure during the Last Glacial Maximum, when the global sea levels fell down by, approximately, one hundred meters [6]. The ocean bottom water temperature is a significant factor affecting the subsea permafrost distribution and gas hydrate stability [7].

In our previous study [8], the interannual variability of the Laptev Sea hydrology caused by the atmospheric dynamics was investigated based on a three-dimensional large-scale coupled ice-ocean model. Using a high-resolution nested numerical model of the Laptev Sea we have analyzed in greater detail the differences in the Laptev Sea circulation, forced by different modes of the atmospheric dynamics during the summer seasons of 2007 and 2008. In addition, we have shown the possibility of the surface heat transfer into the deeper layers during the autumn season resulting in a warming in near-bottom water. In the present paper, to study a possible lifetime of the anomalous warm water coming into the bottom layer of the region due to intensive mixing with surface waters, we consider the two-year period from September 2006 to September 2008.

2. A numerical model and experimental design

For our study we used a system of the nested ocean numerical models developed in the Institute of Computational Mathematics and Mathematical Geophysics (ICMMG). The system is based on a large-scale three-dimensional regional coupled ocean-ice model SibCIOM (Siberian Coupled Ice-Ocean Model), which consists of a large-scale ocean model of ICMMG [9, 10] coupled with the CICE ice-snow model [11]. The large-scale model domain includes the Arctic and the Atlantic Ocean north of 20°S. We used a three-polar grid with the grid resolution for the Atlantic chosen to be $0.5^\circ \times 0.5^\circ$ and an average grid spacing of about 18 km in the Arctic Ocean. The vertical grid used has 38 unevenly spaced vertical levels with a maximum resolution of 5 m in the upper 20-meter layer. For the description of the shelf dynamics, the system also includes a regional high resolution sigma-model of the Laptev Sea, which is based on the Princeton Ocean Model [12] with a modification of the advection scheme and the pressure gradient treatment according to [13]. The horizontal resolution of the model varies from 2 to 5 km. The details of the algorithm of the interaction algorithm between the large-scale and shelf models are described in [14].

The large-scale model SibCIOM is forced by CORE-II Atmospheric Reanalysis data [15] for the period started from 1957. Started from September 1, 2006 with the initial hydrology data, that were interpolated up to September 2008, the data obtained from the large-scale ocean and ice model run were immediately used every time step as the boundary condition in the Laptev Sea high resolution simulation.

3. The simulation results

The main part of the Laptev Sea is isolated from the path of the Atlantic and Pacific Waters, which are considered to be the main heat supplies for the Arctic Ocean. The only sources of warming for the Laptev shelf waters are the sun and the river water. As our investigation is aimed at demonstrating the possibility of existence of warm anomalies in the near-bottom water in the winter season, in our analysis, we concentrate on the period from September 2006 to the spring of 2008. First of all we consider the atmospheric condition for the summers of 2006 and 2007. From our point of view, the summer air temperature data during these periods did not show significant differences between 2006 and 2007 (Figure 2). But it is worth noting that August and September in 2007 were warmer than those in 2006.

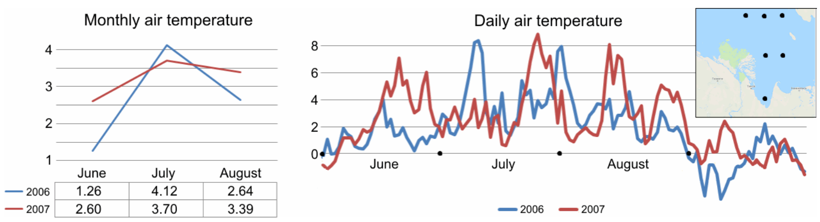

Figure 2. Monthly and daily averaged air temperature (°C) at the level of 2 m above the surface. The data were taken from the re-analysis CORE II and averaged by 6 points which fall into the Laptev Sea region

The observations [16,17] and several modeling studies [8,18] have shown that the atmospheric dynamics largely determines the circulation in the Laptev Sea and plays a large role in spreading the fresh water of the Lena River across the Laptev Sea. This freshwater plume of the Lena River water can significantly change the water stratification stability in the region and promote or block an intensive mixing and heat transfer from the surface to the bottom layers. The monthly averaged sea surface pressure, used in this run for the summer period is quite different for 2006 and for 2007 (Figure 3). The analysis for the sea-level pressure fields shows that in the summer of 2006 the anticyclone mode above the Laptev Sea in July and in August could form an "offshore" circulation and a stable stratification preventing the water layers mixing. Although we started a high-resolution experiment only on September 1, the basic large-scale model has formed the temperature and salinity fields under the same atmospheric forcing.

The picture of the monthly averaged surface circulation, obtained with a high-resolution model for September 2006, shows an intensive offshore current near the eastern boundary of the Lena River Delta and the eastward current in the middle part of the Laptev Sea (Figure 4).

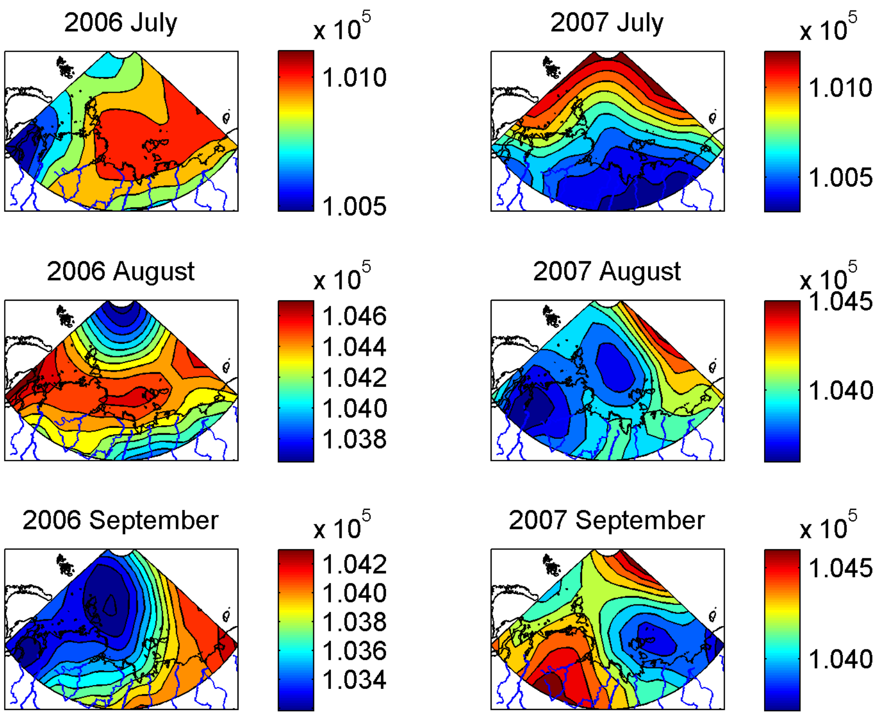

Figure 3. The monthly averaged sea-level pressure (in mbar) for the summer of 2006 and the summer of 2007 for the region including the Laptev Sea. The data from CORE II re-analysis

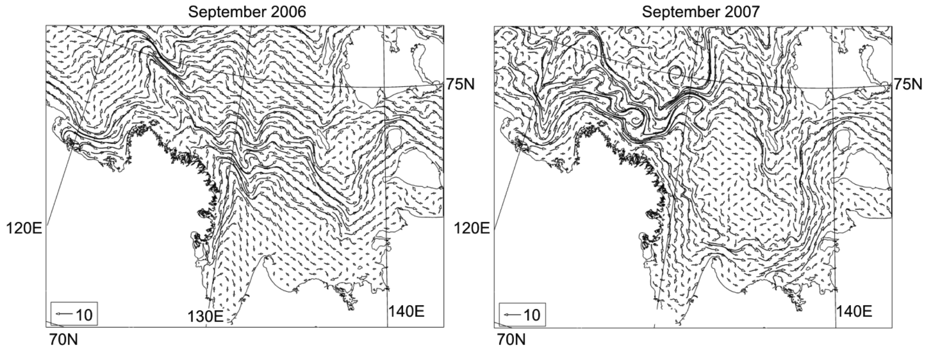

Figure 4. The Laptev Sea surface circulation, simulated in the numerical experiment and monthly averaged for September 2006 (left) and September 2007 (right)

At the same time, in 2007, the cyclonic mode of the atmosphere circulation (see Figure 3), which held for a long time during the summer season, brought about the alongshore current (see Figure 4). As it was shown in our previous paper [19], this current transports the freshwater plume eastward very close to the coastline. In general, this situation is favorable for the enhanced mixing in the middle part of the shelf due to weakening the stratification [16] and near the coast, due to the intensive downwelling.

In the next figures, describing the water temperature, we can see consequences of the differences in the atmospheric conditions for the two summer periods in the Laptev Sea. Not only the air temperature, but the surface circulation is responsible for the temperature distribution over the sea surface (Figure 5). It is easy to notice that in September 2007 the surface water temperature is higher than in September 2006: temperature maximum in September 2006 is 8°C and 10°C in 2007. Moreover the 5°C-isotherm locates farther from the coast in September 2007. Analyzing the subsequent winter distribution, we have detected a vast region with a positive water temperature kept near the bottom in the winter of 2008 (Figure 6). This is in contrast to the winter of 2007 when the shelf water temperature in the whole near bottom layer was below zero.

Figure 7 shows the sequential re-distribution of the surface heat accumulated in summer into deeper layers of the sea in the autumn-winter period. The heat accumulated in the summer of 2006, in the form of a positive anomaly of 0.2°C is present at the meridional section in January 2007 and then disappears. The temperature section for September 2007 shows a highly intensive warming not only of the sea surface but 20-meter layer. It is worth to note that the isotherms distribution shows an intensive mixing followed by the heat transfer. This significantly distinguishes the September distribution of 2007 from that of 2008. The value of the positive anomaly in January 2008 exceeds 1°C. Moreover, the domain around this warm anomaly

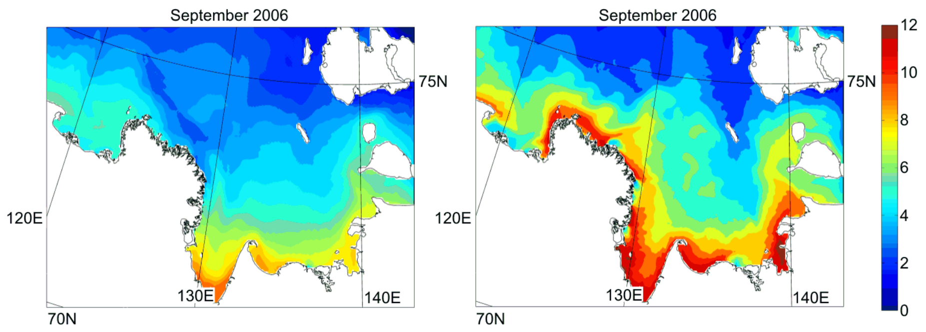

Figure 5. The monthly mean summer distribution of the simulated sea surface temperature

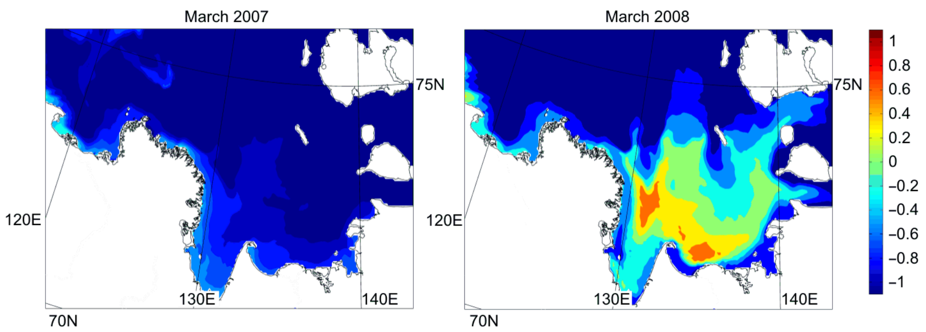

Figure 6. The monthly mean winter distribution of the simulated near-bottom temperature

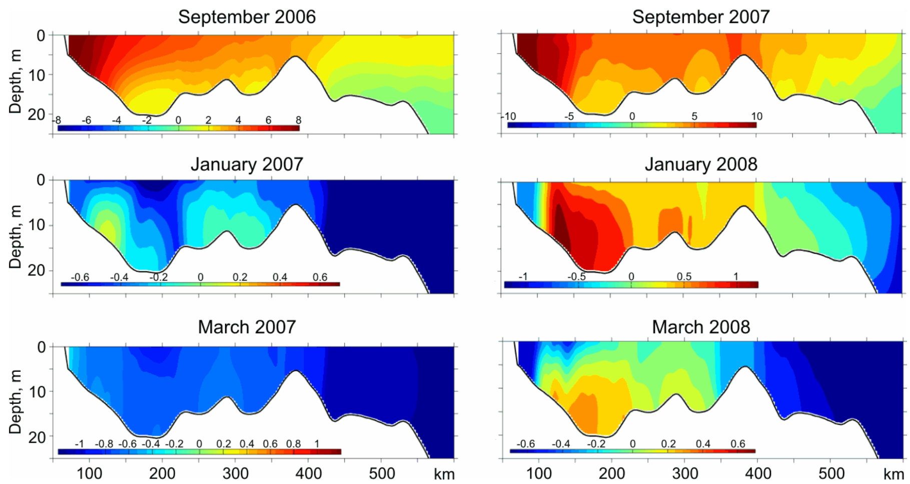

Figure 7. Cross-shelf transect (13.5° E) of monthly mean water temperature (°C). Simulation results

shows a positive temperature. A maximum temperature in March is about 0.3°C and the positive temperature values disappear in April.

It is clear that the positive water temperature obtained for January 2008 must have been reflected in the sea ice state. However, in the experiment carried out we did not take into account the reverse effect of the high-resolution model on the large-scale distribution.

4. Conclusion

In this study, we tried to understand whether it is possible that the heat accumulated during the summer period by the surface waters of the Laptev Sea are stored in the bottom layer during the winter period. The evidence of episodically occurring warm anomalies in the bottom layer of the sea is observed [3].

The numerical experiment was carried out using a system of embedded models of the ocean and sea ice and atmospheric reanalysis data. A large-scale model from 1957 up to 2014 was used; hydrological fields in the Laptev Sea were refined on the basis of a small-scale model from September 2006 to September 2008. Based on the analysis of the numerical experiment, we have shown a significant difference in the formation of the thermal structure of the sea in the summer 2006 and that in 2007 and subsequent changes in the winter of 2007 and in the winter of 2008, respectively. We expect that in the formation of the thermal distribution, in addition to the intense heating in the summer period, the dynamic factor of the atmosphere state, which determines the circulation of the sea, is of great importance.

According to the results of the numerical experiment carried out, the circulation of the Laptev Sea in the summer of 2007 contributed to the intensive mixing and the entry of the surface heat into deeper layers. The formed region of a positive temperature in the bottom layer of the sea existed until April 2008. In connection with the continuing climatic changes, characterized by an increase in the air temperature, an increase in the lifetime of the ice-free period and an increase in the cyclonic activity in the region, it can be assumed that the existence of regions with a positive temperature in the bottom layer of the sea in the winter season will be quite common.

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