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Numerical simulation of forming temperature anomalies in the Laptev Sea*

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Abstract. Based on the numerical modeling, a possibility of the existence of the temperature anomalies in the Laptev Sea shelf areas due to the heat sink of the Lena River is investigated. To determine the heat flow at the outlet to the sea, the linear regression formulas to connect the river water temperature to the air temperature are used. It is shown that the temperature anomalies caused by the river runoff can reach 2 °C, but these anomalies exist only during the summer season.

1. Motivation

The East Siberian shelf is controlled by Siberian rivers discharge, ice formation/melting, and exchange with the Arctic Ocean and the adjoining seas. The Lena River is one of the largest arctic rivers flowing into the Arctic Ocean and contributes about 15 % of the total freshwater flow into the Arctic. The amount and variation of this freshwater inflow critically affect the salinity and the sea ice formation, and may also exert a significant control over the global ocean thermohaline circulation. However, the research into the heat fluxes from the rivers into the ocean has not received much attention yet. The observational data available for the Lena River reveal some climate and biological data change in the past few decades. Also, changes in hydrographic and meteorological conditions are observed in the Lena Delta [1, 2]. Further changes in the water budget, geomorphology are expected to take place in the near future [1, 3, 4]. The daily discharge maximum has a tendency to occur earlier over the last 70 years [5]. As a result, the changes are also observed in food webs [6]. In [7] was found that the Lena water temperature in the flood period has increased at the Tabaga station up to 2 °C as compared to the values of 1950, and that it had contributed to the coastal erosion and hance, to the chemical water composition. Note that most biological communities and species are very sensitive to changes in the water temperature regime and water chemistry [6, 8], so that restructuring the ecosystem may follow.

This suggests that the Lena River heat flux may have a considerable impact on the thermal conditions of the Laptev Sea in the summer season. The river water temperature is one of the most important parameters for

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the ecosystem life. An increase in the bottom water temperatures may affect the stability of the submarine permafrost of the Laptev Sea shelf, resulting in methane release into the ocean waters and atmosphere.

An analysis of the observational data for the period of 2007–2008 has revealed positive temperature anomalies in the surface layer of the Laptev Sea near the Lena River delta [9]. Using the numerical simulation, we investigated the two issues. The first one was to determine to what extent these anomalies of the sea water temperature can be triggered by the heat flux coming from the waters of the Lena River. The second issue was to evaluate the lifetime of such anomalies due to the river flow and the impact of these anomalies of the Arctic Ocean water state.

On the other hand, the question arises how to take into account the temperature of the incoming river water. Few data are available and observation posts were historically located at a distance from the river mouth.

2. The ocean model

Our investigation was based on the coupled regional ocean-ice model which includes the ocean numerical model developed in the ICMMG SB RAS [10, 11] and the ice model CICE-3.14 [12]. The ICMMG regional Arctic-North Atlantic ocean model [10, 11] has been developed in the Institute of Computational Mathematics and Mathematical Geophysics (Siberian Branch of the Russian Academy of Sciences) to be integrated for the period of several decades. The ocean model in question is based on the conservation laws for heat, salt and momentum. The model uses conventional approximations: Boussinesque, hydrostatic and "rigid lid". After separating of the momentum equations from the external and the internal modes, the barotropic equations are expressed in terms of a stream function. The mixed layer parametrization 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. The temperature and salinity conditions at this boundary allow the free advection out of the model domain and the seasonal PHC 2.1 distribution [13] is substituted in the case of the inward directed advection.

The ocean model has been coupled with the sea-ice model CICE 3.14 [12]. 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 $1° \times 1°$. At 65° N, the North Atlantic spherical coordinate grid is merged with the displaced poles of the Arctic grid [14]. The horizontal grid size in the Arctic varies from 34 to 50 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.

The initial temperature and salinity data are adopted from the PHC winter climatology [13]. Driven with daily atmospheric forcing from 1948 to 2012 (NCEP/NCAR reanalysis [15]), the model allowed us to simulate the climate changes in the Arctic Ocean caused by variations in the atmospheric circulation.

3. Data and methods

For including the heat flux supplied to the Laptev Sea shelf with river waters, we need to know the river water temperature. Since 1930s, according to the standard procedures for hydrometeorological observations in the former USSR, the stream temperatures were observed at the regional hydrological station Kusur three times a month (the 10th, 20th, and 30th day). These data are now available from the R-ArcticNET [16].

The hydrological station Kusur is located about 100 km to the south from the Lena River outlet to the Laptev Sea. Consequently, the water temperature in the river outlet and the Kusur station can significantly differ. Figure 1 demonstrates the points, we have worked with. Points 1 and 3 are the points of our interest, where we want to determine the river temperature. Points 2 and 4 are the nearest data of the air temperature from the NCEP/NCAR Reanalysis which we used as atmospheric forcing.

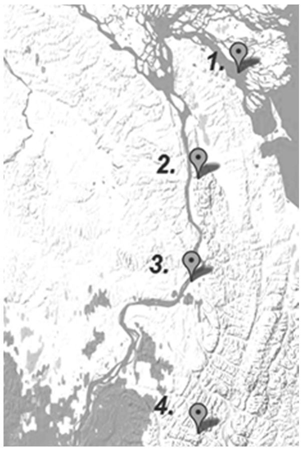

Figure 1. Modeling points:
at the Lena River delta:
1 — 72.037° N, 128.64° W;
2 — 71.4262° N, 127.5° W;
at the Lena Kusur station:
3 — 70.68° N, 127.35° W;
4 — 69.5217° N, 127.5° W

There are several approaches to modeling the river water temperature. The two approaches are most frequently used: deterministic and statistical models. Deterministic models make use of the mathematical representation of the underlying physics of the heat exchange between the river and surrounding environment. Such models can include stream geometry, hydrology and meteorology like input data [17–19]. The advantage of the statistical models (such as linear or nonlinear regression models) is their relative simplicity and minimal data requirement. The ridge regression is good to use, when independent variables have a high correlation. In dealing with seasonality, it is better to use the ridge regression. Non-parametric models offer advantages when analyzing the relationships between the water temperature and environmental variables. The description of statistical water temperature models is given in [20].

In [21], in order to understand the climatic influence on the river thermal conditions, there were examined relationships of the air temperature vs. the water temperature over the Lena River basin as a whole. The monthly basin mean air temperature with the stream temperatures collected on the 20th day of the month at the basin outlet was correlated. The results show statistically significant (95–99 % confidence level) positive correlations between the stream and the air temperatures during the open water season. The correlations are higher in August and September (statistically significant at the 99 % confidence level), indicating to a stronger association of the stream temperatures with the air temperature in the late open water season. These results show that the air temperature has a strong association with the stream thermal characteristics in the Lena basin. According to this paper, the water temperature in the Lena River can be calculated as

$$T_w = \begin{cases} 0.7317\,T_a - 3.9560 & \text{in June,} \\ 0.7615\,T_a + 2.7873 & \text{in July,} \\ 1.2245\,T_a - 1.9432 & \text{in August,} \\ 0.8099\,T_a + 2.5627 & \text{in September.} \end{cases}$$

It is important to note that linear and nonlinear regressions are used mainly for daily averages or weekly means. In our disposal we had the mean monthly air and water temperatures. The spatial-temporal resolution of our model enables us to use these data.

First, we examined the linear relationships based on the data collected at the Kusur station during 1948–1995. The air temperature data at the height of 2 m at Point 4 (69.5217° N, 127.5° W) were taken from the NCEP/NCAR Reanalysis. The correlation between the air temperature and the observed water temperature is 0.849, 0.665, 0.886, and 0.735 for June, July, August, and September, respectively. Figure 2 represents the water temperature

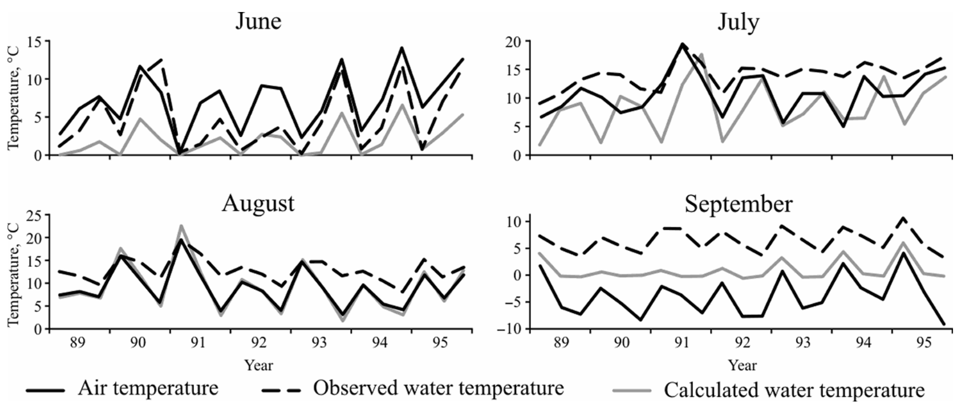

Figure 2. The observed and calculated water temperature at the Kusur station

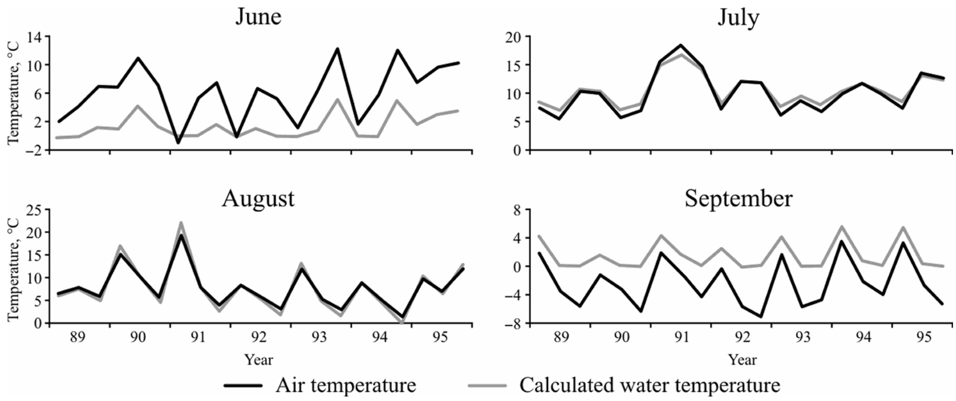

Figure 3. The calculated water temperature at the Lena River delta

calculated based on these regression relations and the observational data. In spite of the fact that the calculated water temperature is 2–4 °C lower than the observational data, it is easy to see a high correlation between the two temperatures. Used regression formulas specify the air temperature as the only independent variable, that is why we have obtained this difference. To have a better estimate of the water temperature, multiple regressions should be used.

We used the same regression formulas to define unknown temperature at the Lena River delta (Figure 3). For this purpose the air temperature was taken at Point 2 (71.4262° N, 127.5° W) from the NCEP/NCAR Reanalysis. At the same time, the extremes of the water temperatures were limited to 10 °C.

Third, we used the river temperature calculated at the Lena River delta to determine the Lena river heat flux into the Laptev Sea in the Arctic Ocean model and analyzed the sea water temperature anomalies caused by the river runoff.

4. Numerical experiments

The variability of the Arctic Ocean water masses state was simulated for the period of 1948 to 2010. The model was driven by the atmospheric data from the NCEP/NCAR reanalysis. Two numerical runs were conducted for estimating the influence of the Lena River runoff to the Laptev Sea shelf water temperature. In the first one, we consider the river temperature to be the same as the shelf water temperature. The second experiment was conducted in the period of 2000 to 2009. As the initial distribution there were used model fields obtained in the first experiment for year 1999. In the second experiment, during the summer season (June–September) the Lena River temperature was calculated from the regression relations (Figure 4).

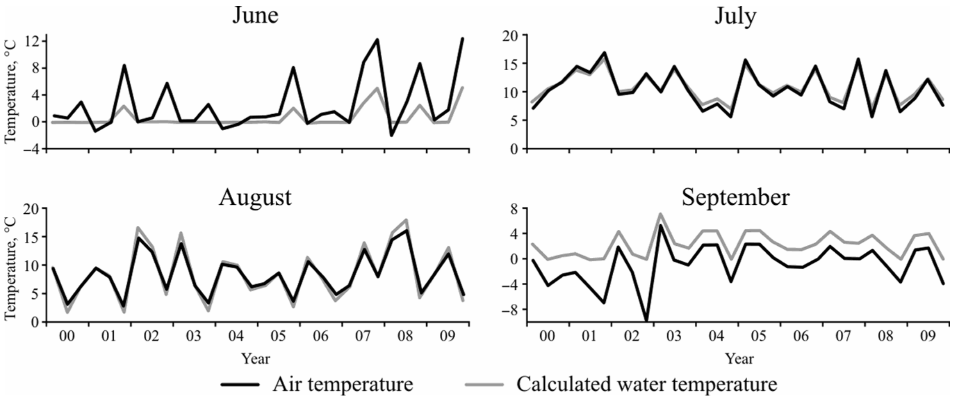

Figure 4. The calculated water temperature used in the second numerical run

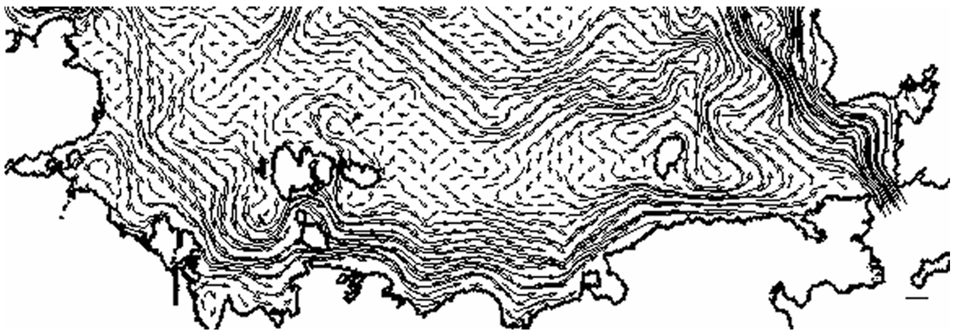

Figure 5. Flow field of the surface layer of the East Siberian Seas shelf

The main attention was given to the formation of temperature anomalies near the Lena River outlet and its further spread. A special attention was focused on 2007, because during this period, an extremely high water temperature in the Laptev Sea was fixed. As hypotheses of this anomaly, we can considere high temperature of the entering river water and abnormally warm state of the atmosphere above the sea. The simulation results restore the circulation pattern in the Arctic Ocean and its marginal seas. In accord with the resolution of the numerical grid, we have obtained only common features of the water circulation. Figure 5 clearly presents the eastward transport of waters in the seas of the East Siberian shelf, which promotes the transfer of the river waters to the east. The reanalysis data release high-temperature values at the Lena Delta in June, 2007 (see Figure 4), which could contribute to an increase in the sea water temperature and its further spread to the north-east system flows.

We defined an additional heating due to the incoming river water by considering a difference in the water temperature between the two experiments (Figure 6). The temperature anomaly in the shelf waters for August 2007 reached 1.8 °C. In the numerical model, such an anomaly is characteristic of the entire vertical column, indicating to intensive vertical mixing shelf waters near the Lena Delta. Apparently, in the models with a more detailed resolution with a more intensive flow a more pronounced propagation path of anomalies can be obtained. It should be noted that the results of the simulated temperature anomalies, caused by the Lena runoff have a local character and disappear during the autumn-winter period.

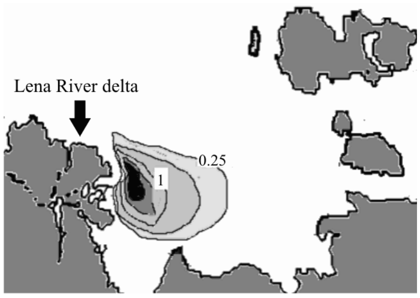

Figure 6. Spatial distribution of temperature difference between runs at the surface water in August 2007

5. Conclusion

We have restored the Lena-river outlet temperature on the basis of the linear regression and the atmosphere reanalysis data. Numerical run on the basis of coupled ice–ocean model has shown the Lena-river heat flux results in 1–2 °C temperature increasing in the shelf water during summer season. The resulting density stratification has allowed a more intensive vertical mixing of the water column leading to warming of the near-bottom layer in the ice-free Laptev Sea. The warmer water temperature near the seabed may also impact the stability of the shelf submarine permafrost.

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