Numerical Analysis and Reconstruction of the Temperature Regime of the Lena River Segment

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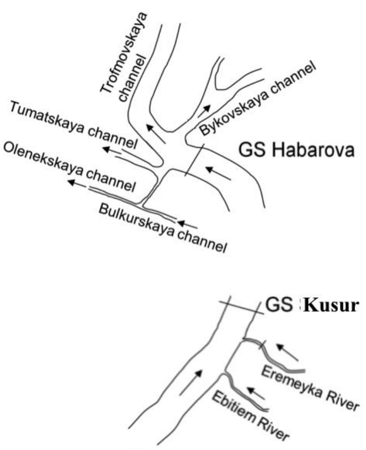
***Abstract*—The data series from several gauging stations on the Lena River are considered. The difference of the water temperature between Kusur station and 200 kilometers downstream to the north Habarova station often becomes anomaly large during open water season (June-September). The analysis of the observational data is presented. The non-representativeness of measurements on Kusur station is supposed; reconstruction of the real temperature regime on the base of the statistical and deterministic modeling as well as the optimization tools is carried out.**

***Keywords*—Lena River; times series analysis; heat exchange; finite-element modeling; optimizatiom;**

I. Introduction

The Lena River is located in the East Siberia and it is one of the largest rivers in the Arctic with the huge delta area. Water mass transport at the Lena River has great influence on the dynamics of the Laptev Sea and Arctic Ocean [1, 2]. Despite the importance of the Lena River, there are not many observational stations. The large territory and its complexity, as well as fragmentary data of stream temperature and discharge characteristics are lead to difficulties in providing correct analysis and numerical models of Lena River.

In that paper we analyse the available data on the water temperature and discharges rate of the Lena River at the basin outlet in the open water period (June–September). The analysis shows that there is a large negative difference of the water temperature between Kusur and Habarova GS (Fig 1.). We demonstrate that the water temperatures measured at Kusur station fail to represent the mean cross-sectional value but reflect the thermal conditions of the Lena River at this position in general. To verify this hypothesis and to explain mentioned difference the numerical experiments are set.



The objects on the map	Distance
Mouth of Ebitiem River – GS Kusur	~5 km
Mouth of Eremeyka River – GS Kusur	~1.5 km
GS Kusur – GS Habarova	~200km

Fig. 1. The scheme of gauging station locations

The discussion about possible reasons of it and numerical modeling of heat transfer and hydrodynamic processes for explanation of the temperature difference are the main goals of this paper.

II. Water temperature measurements and its analysis

The Kusur GS is located near Kusur Village at the site of the station carrying the same name. The width of the stream there is 2.4 km on average for the summer season. Measurements of stream surface temperatures are performed at the right bank of the Lena River.

Habarova GS is situated in the area of the delta head. The width of the channel at the cross section of Habarova GS is up to 1.0 km. Measurements of stream surface temperatures are performed on the right channel bank.

The Eremeyka River is a right inflow of the Lena River near the Kusur station. The station is located 2 km upstream from the mouth. Water temperature is measured at midstream.

Observational data from hydrological observations in the Siberian region, such as discharge, water and air temperature, ice thickness, dates of ice events, are collected and stored by the Russian Hydrometeorological Service [3].

The fluctuations of mean monthly water temperatures in the surface layer, as a rule, correlate with the dynamics of mean air surface temperatures in the same area [4]. For August and September, their results are statistically significant at almost 100% confidence level. For the summer months the water temperature is increased from mouth of the Lena River in the south to the its delta to the north [5, 6]. However, the average surface water temperatures observed at Habarova GS are much higher for the ice-free season than measured at Kusur GS located 200 kilometers upstream (Fig. 2). Fig. 2 also demonstrates that the difference of the water temperature between Habarova GS and Kusur GS grows from June to September. It means, that the formation of the differences follows the decrease in temperature at the downstream Lena River area.

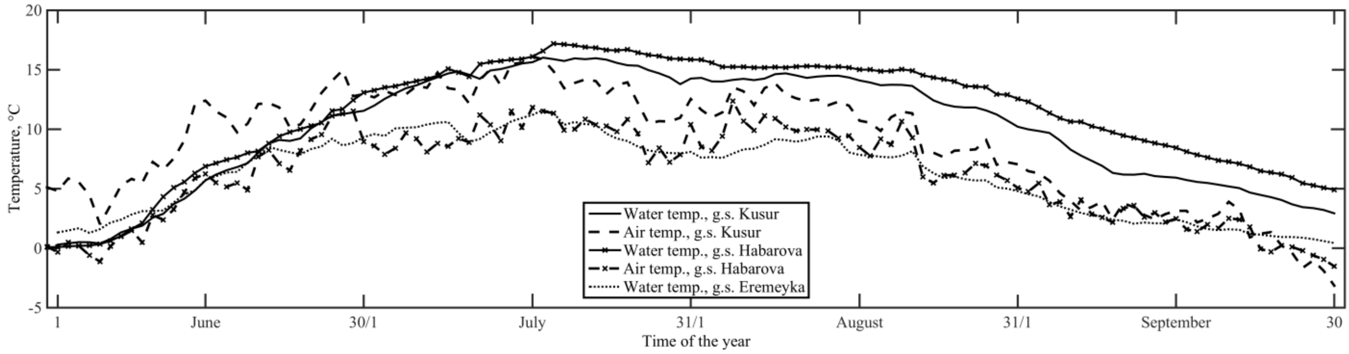


Fig. 2. The mean daily surface air and water temperatures measured at Kusur GS, Habarova and Eremeyka for the summer season (2002–2011)

Here we would like to discuss the possible causes of this large positive difference between water temperatures at Habarova GS and Kusur.

a) The anthropogenic factor cannot be the possible explanation due to very low population on that area and lack of plants or facilities.

b) Strong positive heat balance could be a feature that leads to such temperature increasing between two stations. The short-wave radiation is high because the sun is visible full 24 hours during summer period in Siberia region [7]. Despite the lower air temperature the water temperature still can increasing. Figure 3 shows the daily averaged values of the heat balance components for the period from 2002 till 2011. The wind speed, humidity and air temperature were taken from observations at the Kusur meteorological station (provided by Arctic and Antarctic Research Institute). The shortwave and longwave downward radiations were taken from the National Oceanic and Atmospheric Administration database [8]. The sensible and latent heat fluxes as well as upward radiation were calculated using Edinger formula [9]. The albedo of the Lena River water was set to 0.1.

The net heat balance (sum of net shortwave and net longwave radiation heat fluxes, sensible and latent heat fluxes) logically tends to decrease from June to September within the studied area, what is nearly opposite to behavior of difference between water temperatures at Habarova GS and Kusur.

c) The heat exchange with a riverbed is missing in our calculations. However, during July - August the heat transfer between the riverbed and water stream should be minor due to the due to the characteristics of Siberia region [10].

d) Ice conditions and as a result additional latent heat fluxes with large magnitude can also be a factor of influence. However, during July-September in the area of interest there is no floating ice.

e) The possible reason for this puzzling disagreement could be the non-representativeness of measurements at one or both the stations. We should stress that water temperature measurements at both station are taken near the right riverbank. The stream temperature measured near the bank does not always correspond to the true mean stream temperature. This highly depends on local conditions like inflows with different temperatures upstream, the shallowness of the water layer or other coastal effects.

We assume that the main reason for non-representativeness is the influence of relatively cold water from several small inflows represented by Tikian, Bordugas, Abadachan, Ebitiem and Eremeyka Rivers. The mouths of these rivers are located approximately between 20 km and 1.5 km upstream from Kusur GS on the same river side. In the whole area of interest till Habarova GS there are no other inflows, which could affect the temperature measurements at the considered stations.

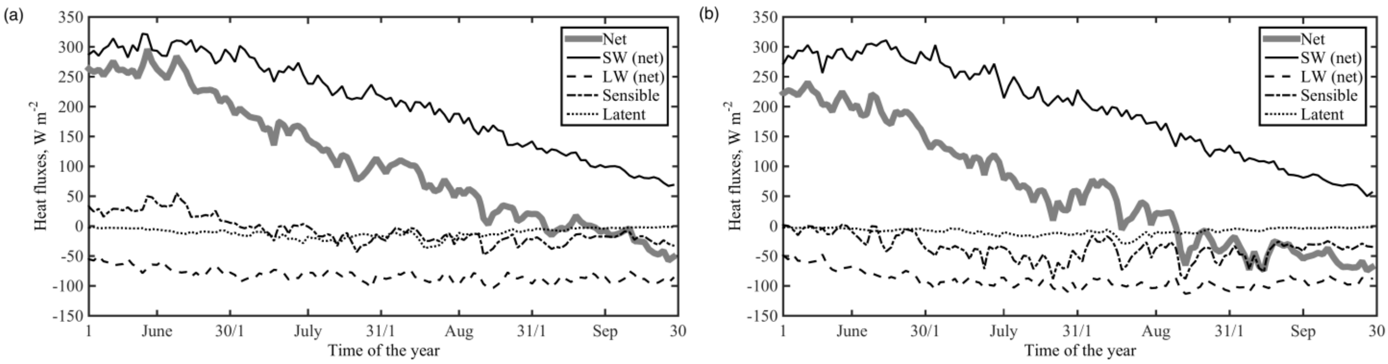


Fig. 3. The heat balance of a water surface: a) at GS Kusur; b) at GS Habarova

III. NUMERICAL EXPERIMENTS

To determine the influence of cold water from the small tributaries on water temperature measurements at Kusur GS and to calculate the water-air heat exchange we carried out two numerical simulations using finite-element software COMSOL Multiphysics, in particular, Computational Fluid Dynamics and Heat Transfer modules [11].

The main purpose of the first experiment is proving the hypothesis that very small tributaries upstream Kusur GS can influence the measurements taken near the right river bank. We have developed full 3D k-ε turbulence model, taking into account temperature and discharge characteristics of the main channel and tributaries 20 kilometers upstream the Kusur station.

The model domain was constructed as a box with a length, width and depth equal to 20000 m, 2400 m and 15 m respectively. The rectangular grid was generated with a resolution 100 m, 10m and 1m in along channel, cross-sectional and vertical directions respectively. The Lena River discharge was set to 25000 m^3/s what corresponds to the typical water velocities of about 1 m/s for 15 m depth. The water temperature in the tributaries was taken equal to Eremeyka water temperature at the appropriate time. Discharge rate for the Eremeyka River was available from observations, however, only on monthly scale. The discharge rates for the other tributaries were calculated approximately based on the available information about watershed square and shape of the channels and were scaled according to the behavior of the Eremeyka discharge.

Numerical simulations showed the possibility of a thin layer formation, about 170 meters from right river bank to midstream, of the relatively cold water due to the influence of tributaries. In our simulation we had neglected variation of the water viscosity and turbulent heat transfer coefficient, as a result the width of the mentioned layer varied negligible small. In an idealized case with plate equipped with heat sources the temperature distribution in the turbulent boundary layer follows the logarithmic low except thin wall layer for the flows with very high Reynolds. We received close to logarithmic profile of the water temperature distribution horizontally within the layer of 170 meters width. Assuming that the inflow velocity of tributaries is negligible small, we can describe midstream water temperature behavior using next approximation

$$(L-m)^{-1}\int_m^L f(x)\,dx = a\cdot T_e + b\cdot T_l \qquad (1)$$

$$a+b=1;\qquad a=\frac{Q_e}{Q_e+Q_L\,L/L_{cs}} \qquad (2)$$

$$f(x)=\frac{T_l-T_k}{\ln\left(L/m\right)}\cdot\ln\left(x/m\right)+T_k \qquad (3)$$

In presented formula T_e, Q_e are Eremeyka water temperature and total discharge rate from all small cold tributaries upstream, T_l, Q_l are Lena water temperature and discharge rate, L is width of the layer, where influence of cold water from tributaries takes place, L_{cs} is width of whole cross-section at the Kusur GS, m - the distance to the right river bank, at which the measurements of water temperature were taken (we set it to 3m), $f(x)$ is a function of temperature distribution, which depends on distance x to the right Lena River bank.

Using equations (1) - (3) the midstream water temperature, which is close to mean stream temperature (L/L_{cs} >10), can be received:

$$T_l=\frac{d\cdot T_k-a\cdot T_e}{b-c} \qquad (4)$$

$$c+d=1;\quad c=\frac{1}{1-m/L}-\frac{1}{\ln\left(L/m\right)} \qquad (5)$$

Using formula (1) the mean, maximum and minimum difference between midstream and near right bank temperature were calculated (Fig. 4).

Figure 4 shows that the influence of cold tributaries increases from June to the beginning of September in general. The mid-stream temperature is in average higher on 0.8 °C than the near bank temperature during July-September. It means that the cold tributaries can explain the large positive difference between temperatures measured at Habarova GS and Kusur.

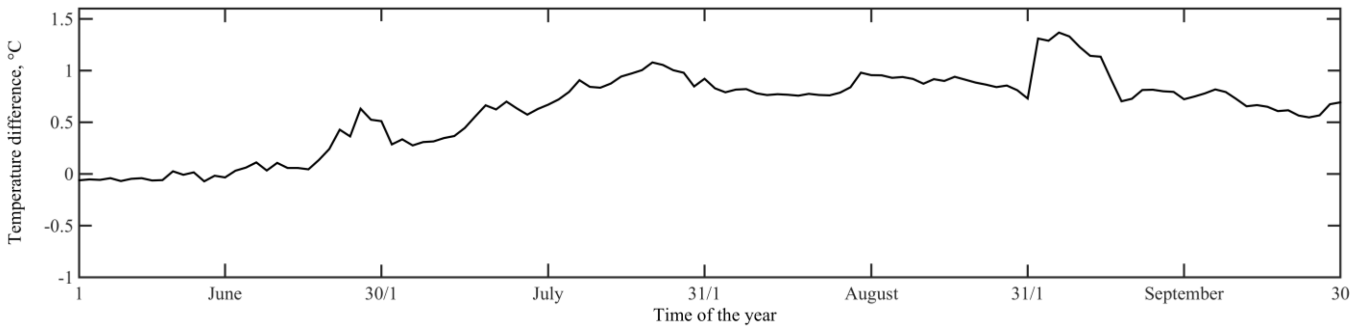


Fig. 4. The mean difference (2002-2011) between midstream and near right bank water temperatures at Kusur GS

The influence of the tributaries can be warming mainly in June and only for some particular years. If the water temperature in Eremeyka and other tributaries much colder than in the Lena River than the non-representativeness of the measurements becomes more pronounced. In the end of August, beginning of September both factors are usually working, the discharge rate of the Lena River is decreasing, the temperature compare to tributaries temperature is increasing, that is way, the curve of mean influence tends to increase from June till the beginning of September. In June (especially in the beginning) the influence of the cold tributaries usually nearly vanishes due to large Lena River discharge rate and small temperature gradients.

Unfortunately, we do not have daily values of the discharge rates and temperatures for all tributaries (daily water temperatures and monthly discharges are available only for Eremeyka), which are very important in determination of actual values of midstream Lena water temperature for particular dates. The presented curves for different years cannot be real date-to-date, because the discharge rates usually significantly vary during one month and it is hard to talk about typical seasonal curve of the discharge for tributaries. Above estimates for the midstream Lena water temperature present an useful benchmark, but contain a lot of sources of uncertainties.

Proving the influence of the small cold tributaries on the measurements at GS Kusur, we should say some words about the justice of the results and estimates, which was given above for near bank water temperature, for mean cross-sectional water temperature. The midstream temperature systematically higher than the measured at the river bank on a monthly scale for the period from July to September. However, we can estimate now the role of the Lena and Eremeyka water temperature in formation of the Kusur temperature (eq. 2,4 and 5). The mean Lena contribution is 90%, 88% and 85% in July, August and September accordingly. Also the water temperature in tributaries are also affected by the regional atmospheric forcing. The correlation coefficient between monthly water temperature measured at Habarova GS and Eremeyka is ~0.86 (the data set of 148 points contains monthly mean values for open water season from 1974 to 2010). Thus, we can assume that trend and mean heat balance estimates at the Kusur GS can be taken for the Lena River midstream (close to the mean stream temperature) with caution, but the not systematic component of difference between midstream and right river bank temperatures adds additional noise, which reduces the accuracy of the assessments. The mean net heat balance will be a bit smaller for the Lena River midstream compare to presented in Figure 3 for July-September by about 10-20 W/m^2 due to higher gradient between water and air temperatures. The estimations with higher accuracy require knowledge about daily discharge rates and temperatures for all tributaries closely upstream Kusur GS.

For the second experiment we took a segment from Kusur GS till Habarova and turned on the atmospheric forcing. As a modeling year 2012 was chosen, because additional information about the elevation for Eremeyka River was available. Note, that the elevation measurements at Eremeyka do not influenced by Lena because the elevation of zero of Eremeyka GS is higher than possible Lena water level. The atmospheric forcing was derived from National Oceanic and Atmospheric Administration database [10].

To identify the influence of the small tributaries upstream Kusur the optimization task was constructed for the total daily discharge rate from all tributaries, which is unknown, the difference between modeled and measured water temperatures at Habarova GS was minimized using 20 points equally distributed along the time line (June-September).

Figure 5, demonstrates the total discharge from all small tributaries within the warm season of 2012, which is a result of optimization task. Independently, from previous estimates of the total discharge we received nearly the same range, however, with small mean value at about 41 m^3/s. This is in agreement with a fact that in 2012 the mean summer discharge rate of Eremeyka was smaller than usual. In Figure 5 mean monthly discharge rate of Eremeyka River multiplied by 400 is also presented. Note, that the Eremeyka water doesn't play the major role in formation of cold right river bank current. The discharge rate of Ebitiem River (5 km upstrem Kusur GS) is more than 100 times larger than the rate of Eremeyka in average. It can be seen that the mean monthly discharge rates and elevation at the Eremeyka River are in agreement with the optimized daily discharge rates during summer season. However, as mentioned before, in June the floating ice can be presented, which would modify the water heat balance a lot.

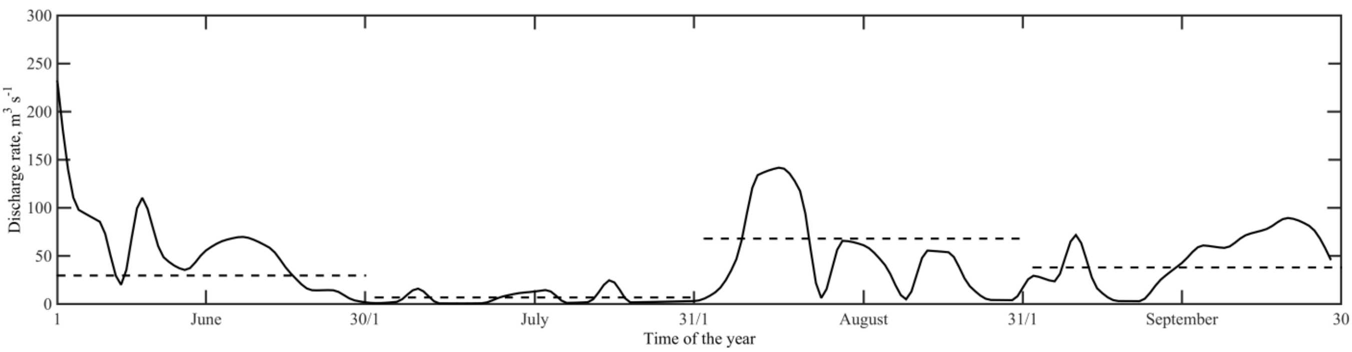


Fig. 5. The optimized total discharge rate of all tributaries close upstream GS Kusur is shown by solid line , dashed lines introduce mean monthly discharge of Eremeyka River multiplied by 400

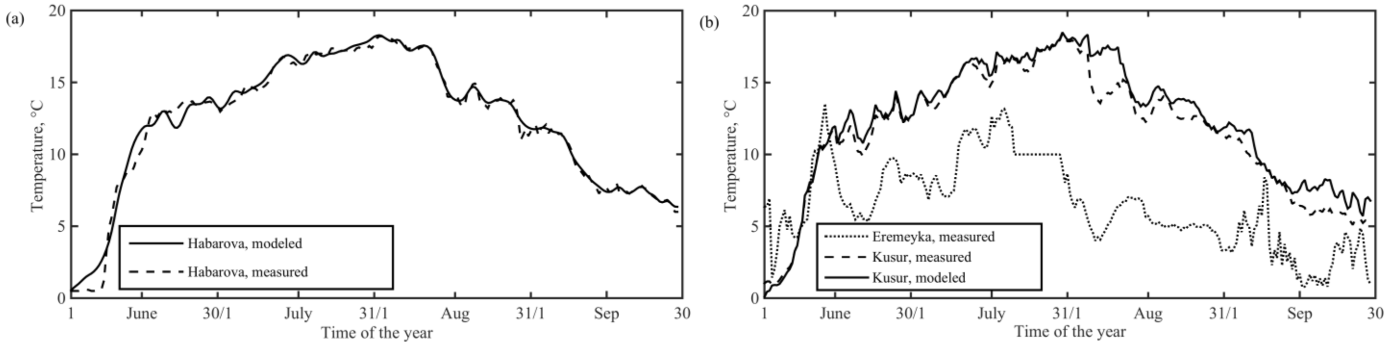


Fig. 6. a) Water temperatures measured and observed at Habarova GS; b) Water temperatures measured and observed at Kusur GS and water temperature observed at Eremeyka GS.

Figure 6a shows simulated and measured temperatures at Habarova GS and demonstrates that they are agree quite well with mean error 0.4 °C. Comparing Figure 6a and 6b we can conclude that the warming influence of the atmosphere within studied area due to large portion of short wave radiation in June/beginning of July is limited to 0.5 °C (can reach 1.5°C), in the end of July-August the warming effect adds at about 0.2°C to Habarova water temperature and then slow, weakly expressed heating is replaced by cooling. The midstream temperature at Kusur GS can be significantly higher than the the right river bank temperature for some dates, due to cooling influence of small tributaries upstream.

IV. CONCLUSION

This paper analyses water temperature characteristics in the outlet area of the Lena River during the summer season (June–September). Based on our analysis, we conclude that the measured water temperature in the surface layer at Kusur GS reflects the dynamics of the mean stream temperature in general but incorrectly characterizes the value of the mean stream temperature, underestimating it in July-September due to the non-representativeness of the measurements at the right bank. The water from small Lena River tributaries 1.5-20 km upstream GS Kusur forms relatively cold right bank current. The ration between the discharge rates of the Lena River and small inflows upstream and water temperature gradient of inflows and Lena River are the major factors, which control the difference between the midstream and near right bank temperature. The mid-stream temperature is in average higher by 0.8 °C than the near bank temperature during July-September. However, numerical experiments show that the cooling influence of inflows can greatly vary and its magnitude can reach 5.5 °C under certain conditions. Presented numerical methods allow reconstructing missed data. Such methods can also be used for verification of the obtained measurements.

The difference in the behaviour of stream temperatures at Habarova GS and Kusur and non-representativeness of the measurements at Kusur GS for the whole cross-section indicate that measurements at Kusur GS should be taken for analysis of water temperature changes in the delta head area with a great caution.

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