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Features of the Water Temperature Long-Term Observations on the Lena River at Basin Outlet

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Abstract: The water temperature characteristics of the Lena River at basin outlet during the summer season (June to September) are investigated. The analysis is based on a long-term data series covering the period from the beginning of observations (1936) to the present time (2012) at Kusur (Kyusyur) gauging station and complementary data at several stations downstream and one station upstream. These complementary data are rarely used, but their analysis is important for understanding processes in the basin outlet area. The differences between the stream surface temperatures at Kusur station and Habarova (Yu. A. Khabarova) station 200 km downstream to the north have almost always been anomalously large and negative during open water season from July to September since the beginning of observations. The description of this difference and the analysis of its possible causes are major focuses of the article. To sort the problem out, we consider the large observational database in terms of the hydrology and morphology of the Lena River delta and main channel area collected from different sources and apply statistical and deterministic modelling approaches. The inability of water temperature measurements, which were taken near the right river bank, to represent the mean cross-sectional temperature at Kusur station is addressed. We also analyze the water temperature trends at both Kusur and Habarova stations.

Zusammenfassung: Untersucht wurden die Charakteristika der sommerlichen (Juni bis September) Wassertemperaturen am stromabwärtigen Beckenauslauf der Lena. Die Arbeit basiert auf langen Datenserien vom Beginn der Beobachtungen (1936) bis heute (2012) an der Kusur (Kyusyur) Pegelstation und auf ergänzenden Daten verschiedener Pegelstationen stromabwärts und einer Station stromaufwärts. Diese zusätzlichen Daten werden selten genutzt, aber ihre Analyse ist wichtig für das Verständnis der Prozesse im Bereich des Beckenauslaufs. Die Temperaturunterschiede der Stromoberfläche an der Kusur-Station und der Habarova (Yu. A. Khabarova) Station 200 km stromabwärts nach Norden sind seit Beginn der Beobachtungen immer ungewöhnlich groß und negativ während Juni bis September, der Zeit der offenen Gewässer. Die Beschreibung dieser Unterschiede und die Analyse ihrer möglichen Ursachen stehen im Mittelpunkt dieser Arbeit. Zur Lösung dieses Problems berücksichtigen wir die große hydrologische und morphologische Beobachtungsbasis, die von verschiedenen Quellen zur Lena und den Wasserläufen des Deltagebietes zur Verfügung stehen und wenden statistische und deterministische Modelle an. Die Problematik der Verwendung von Wassertemperaturen, die nahe am rechten Flussufer gemessen worden sind, als Mittelwerte des Stromquerschnitts bei der Kusur Pegelstation, wird besonders angesprochen. Eine Analyse der Entwicklung der Wassertemperaturen an den Pegeln Kusur und Habarova schließt sich an.

Keywords: Kusur Station, non-representativeness of measurements, long-term data series, heat balance, Lena River hydrodynamics.

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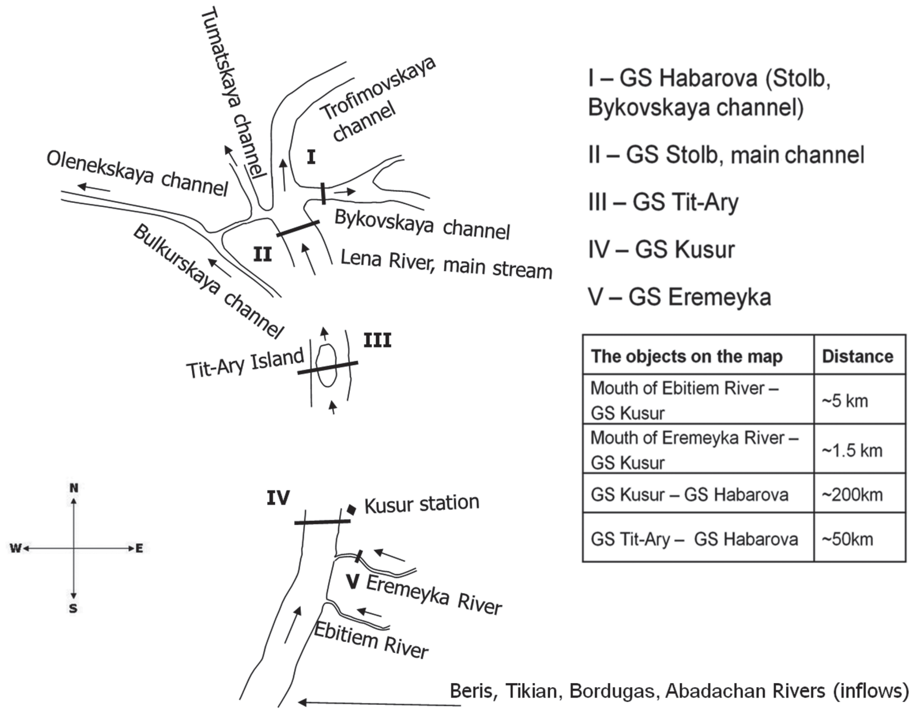
INTRODUCTION (1)

The Lena River is one of the largest rivers in terms of flow in the Arctic with the largest delta. Water mass characteristics at the Lena River basin outlet are particularly important for dynamics of the Laptev Sea and the Arctic Ocean as a whole (e.g., Yang et al. 2005, Dmitrenko et al. 2008, Morison et al. 2012, Fedorova et al. 2015). Observational data available for the Lena River suggest an on-going change in climate and biological factors over the last 50 years (Yang et al. 2002, McClelland et al. 2006, Kraberg et al. 2013). For example, Costard et al. (2007) found that the Lena water temperature in the flood period had increased by up to 2 °C at Tabaga Station, as compared to the values in 1950, and that this increase had contributed to coastal erosion and modified the chemical water composition. Note, that the permafrost underlies 78-93 % of the Lena River watershed, with continuous permafrost extending south to 50° N (Zhang et al. 1999).

The Lena River Delta has a large number of freshwater channels, the three largest of which empty into the Laptev Sea on average 65 %, 22 % and 5 % (Trofimovskaya, Bykovskaya and Olenekskaya channels respectively) of the total river discharge (Magritskiy 2001) (Fig. 1); the mean annual runoff volume of the river from 1935 to 2012 was about 539 km^3 (RosHydromet 2016). However, given the large territory of the Lena River basin and its outlet area in particular, direct measurements pertaining to the river are still insufficient. The high morphological complexity of the region adds to the problem. As a result, the existing analyses of stream temperature and other discharge characteristics at the basin outlet are still fragmentary.

The goal of this paper is to analyse the available data on the water temperature of the Lena River at the basin outlet in the summer ice-free period (June–September). The analysis is based on long-term data series at Kusur (Kyusyur) hydrological station from the beginning of observations mainly to 2012, and additionally at several downstream hydrological stations and one upstream hydrological station. In recent literature, the data on the Lena discharge and water temperatures at the Lena Basin outlet are, as a rule, taken at Kusur station (Peterson et al. 2002, Yang et al. 2002, 2005, Liu et al. 2005, Costard et al. 2007). The data from the basin outlet area additionally considered in the current study are rarely used, but their analysis is critical for understanding the complexity of processes in the region. The analysis reveals the existence of a large negative difference between the surface water temperatures at Kusur gauging station (GS) and at Habarova (Yu. A. Khabarova) GS (Fig. 1), located 200 km to the north in the beginning of the Bykovskaya channel, during the open water



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
GS Tit-Ary – GS Habarova	~50km

Fig. 1: The scheme of gauging station (GS) locations at Lena River basin outlet.

Abb. 1: Lage der Pegelstationen (GS) und Wasserläufe im Unterlauf und Delta der Lena.

season (from July to September). The warming of the water downstream from Kusur raises questions because it cannot be explained by the heat exchange with the atmosphere. The analysis of factors that may be responsible for it is a major focus of this paper. We discuss whether the water temperature observations at Kusur GS represent the mean stream temperature and show that they fail to represent the mean cross-sectional value but reflect thermal variability of the Lena River at this position. We carry out numerical experiments to verify this hypothesis and to explain the mentioned difference.

The paper is organized as follows. Section (2) describes the data set used in this work, the hydrological stations and measurement techniques. Section (3) contains analysis of water temperature tendencies at Kusur and Habarova stations. Section (4) deals with the surface temperature difference and its analysis. Section (5) contains description and results of the numerical experiments. In Sections (6) and (7) we provide the discussion and conclusion respectively.

DESCRIPTION OF HYDROLOGICAL STATIONS, MEASUREMENT TECHNIQUES AND THE AVAILABLE DATA SET (2)

In this section, we list the long-term data available and used and the measurement techniques. We also describe the GS at which these data have been collected.

Measurement techniques and available data

Since the late 1930s, relevant data from hydrological observations in the Siberian region, such as discharge, water temperature, ice thickness, dates of ice events (ice cover formation and decay), are quality controlled and archived by the Russian Hydrometeorological Service. They are available in hydrological yearbooks in local centres of hydrometeorology and environmental monitoring and are partly available on the web (Hydrologival Yearbooks 1936–2010, RosHydromet web source). Table 1 lists the long-term data available from the Russian Hydrometeorological Service, which are used in this study. We also used CTD (Conductivity-Temperature-Depth probe of Sea & Sun Technology) data on water temperature profiles obtained in August 2017 at the cross-section of Habarova GS (Stolb, Bykovskaya channel) and in the main channel several kilometres upstream (Fig. 2). These data were collected during the Lena cruise in 2017 which was a Russian-German venture. Apart from the meteorological data presented in Table 1 the additional data as shortwave and longwave radiation fluxes, air temperature, wind speed and humidity were derived for the considered area (where and when these data were not available from the direct observations) from the National Oceanic and Atmospheric Administration database (NCEP/NCAR Reanalysis, web source).

The Russian Hydrometeorological Service carries out measurements of water and air temperatures two times per day, at 8 a.m. and 8 p.m. Until 1993 in the USSR, the stream temperatures were measured at regional hydrologic stations on a 10-day basis (the 10th, 20th, and 30th days of each month) and were taken twice, at 8 a.m. and 8 p.m., on each observation day (State Hydrologic Institute 1961). Measurements of the surface water temperatures covered the period from the end of spring, when the water temperature is close to zero, to the fall, a few days after the freezing of the water surface. The observations at every hydrological station were made in flowing water; a cup with a thermometer was placed approximately 0.5 m below the water surface for five to eight minutes and retrieved carefully for a quick recording of temperature. The possible measurement error was estimated as 0.05-0.1 °C during different period of times according to the Tiksinsky and Yakut Territorial Administration for Hydrometeorology and Environmental Controls.

Station	Data type							
	Surface water temperature	Surface air temperature	Wind conditions	Date of max. daily water temperature	First ice appearance date in fall	Humidity	Discharge rate	Elevation
Kusur	daily 2002–2012 10 days 1936-2002	daily 2002–2011 monthly 1978–2002	3 hours 2002–2011	1936–2012	1986–1990 1999–2007	daily 2002–2011	daily 1936–2012 monthly 1935	daily 2002–2012
Habarova	daily 2002–2012 10 days 1951–2002	daily 2002–2011	—	1951–2012	1886–1990 1999–2007	—	—	—
Eremeyka	daily 2002-2012 10 days 1974–2002	daily 2002–2011	—	2002–2012	—	—	monthly 1974–2012	daily 2012
Lena River watershed	Linear trend coefficients for the surface air temperature seasonal 1976–2011				Deviation from the mean air temperature value for the period 1961–1990 annual 1936–2011			

Tab. 1: Time resolution of available data for the warm season, which were used in current work.

Tab. 1: Zeitlicher Rahmen für die in dieser Studie genutzten Daten.

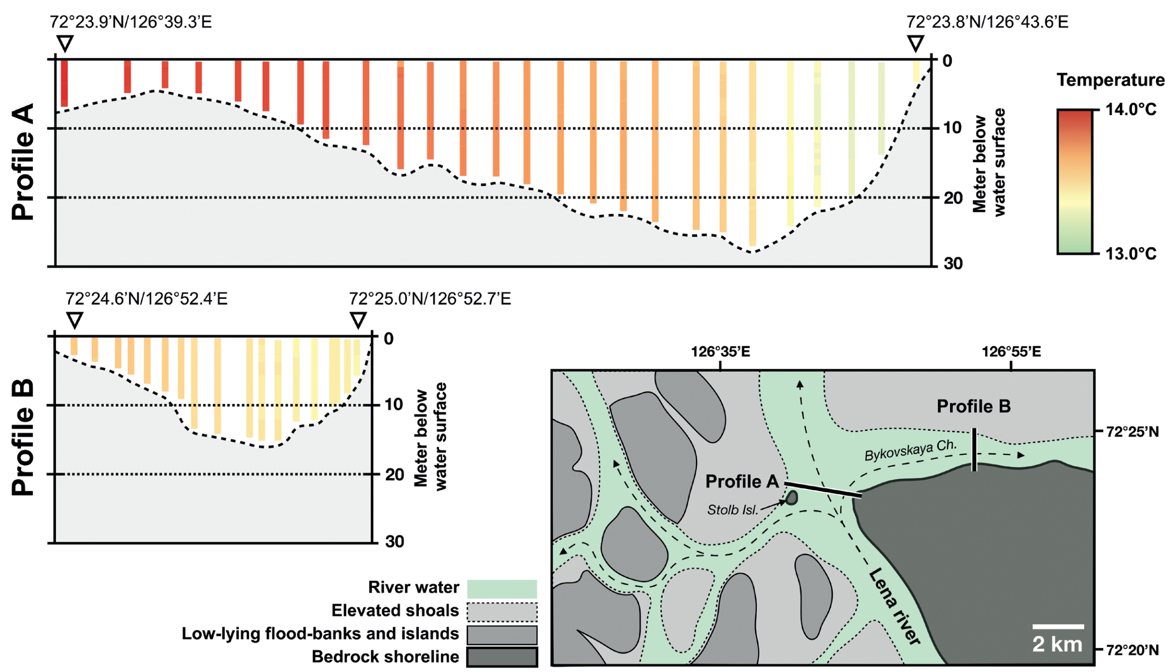


Fig. 2: The stream temperature profiles (°C) at the cross-section of Habarova GS (profile B) and in the main channel several kilometres upstream (profile A) from CTD measurements, which were taken in August, 2017. Depth is counted down from the free surface.

Abb. 2: Temperaturprofile (°C) der Lena im Stromquerschnitt der Pegelstation Habarova (Profile B, Bykovskaya channel) und über den „Hauptkanal" (Profil A) wenige km stromauf nahe der Insel Stolb; nach CTD Messungen im August 2017.

Description of the gauging stations (GS)

Kusur GS (70.70° N, 127.65° E)

Kusur GS is located near Kusur Village at the site of the station carrying the same name (Fig. 1). The width of the stream there is 2.4 km on average for the summer season. The catchment area is about 2.43 million km². Measurements of stream surface temperatures are performed at the right bank of the Lena River at a distance ~3 m from a bank. The transverse profile of the riverbed in the area of Kusur GS is shown in Figure 3. Kusur GS has been fully operated since 1936, opened since 1934 (e.g., Hydrological Yearbook 1966, RosHydromet web source). At present the elevation of zero of gauge equals to -1.41 m (Baltic system of elevations). The water level varies in average from 16.5 m (in the beginning of June) to 7.8 m (late August) during the warm season (June–September) due to seasonal discharge variations (Fig. 4).

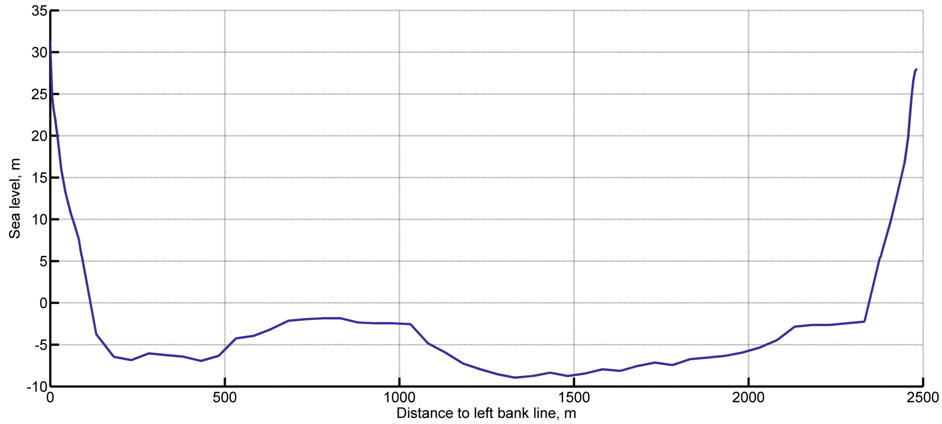


Fig. 3: The transverse profile of the riverbed in the area of Kusur GS based on observations in 2012, first decade of June, (m).

Abb. 3: Querprofil über das Strombett im Bereich der Pegelstation Kusur; Beobachtungen in den ersten zehn Tagen Juni 2012 (m).

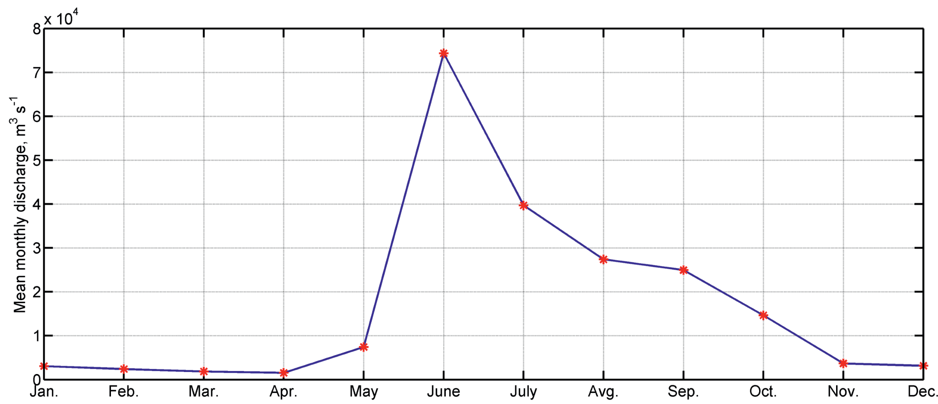


Fig. 4: The mean monthly discharge for the period from 1935 to 2011, (m^3 s^{-1}).

Abb. 4: Mittlere monatliche Abflussmenge der Lena im Zeitraum 1935 – 2011 (m^3 s^{-1}).

Habarova GS (Stolb, Bykovskaya channel 72.42° N, 126.72° E)

Habarova GS (former 'Stolb, Bykovskaya channel') is situated in the area of the delta head at the beginning of the Bykovskaya channel (Fig. 1). 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. Habarova GS has been operated since 1951, opened since 1950 (e.g., Hydrological Yearbook 1966, RosHydromet web source).

Tit-Ary (71.99° N, 127.09° E)

Tit-Ary gauging station is situated on the east side of Tit-Ary Island, which consists of alluvial deposits. The river channel, with a width of about 12 km, is divided into two branches by the island. The island is 20 km in length, 7 km in width and 30 m in height and is located 1.2 km from the main shipping channel. The left branch is shallow. Water temperature is measured on the east side of the island. The Tit-Ary GS operated for 15 years from 1976 till 1990 (e.g., Hydrological Yearbook 1983, RosHydromet web source).

Eremeyka (70.41° N, 127.24° E)

The Eremeyka River is a right tributary of the Lena River with a catchment area of 9.70 km^2. The gauging station is located 2 km upstream from the mouth. Water temperature is measured at midstream. Eremeyka GS has been operated since 1974 (e.g., Hydrological Yearbook 1981, Roshydromet web source).

STREAM TEMPERATURE CHARACTERISTICS AT THE BASIN OUTLET (3)

In this section, we focus on long term data for surface water temperatures at Kusur GS, which are usually taken as representative for the whole basin outlet zone, and Habarova GS, situated in the delta head area, 200 km downstream from Kusur GS (Fig. 1).

At the lower reaches of the Lena River (main channel, delta head area) the observations available for us showed that the water temperature vertical distribution is almost uniform, except for the skin surface layer, due to very high level of turbulent pulsations within the Lena River main stream and delta head area (Fig. 2). The typical Reynolds numbers (the ratio of product of mean flow velocity and mean depth to kinematic viscosity) for the summer season in the region from Kusur GS till Habarova are order of 10^7, which means that the flow is highly turbulent. The available hydrological notes also confirm that the vertical temperature distribution is nearly uniform within cross-section at both Habarova GS and Kusur for the entire ice-free period (Reinberg 1938). Therefore, we assume that at the considered Lena River stations (Fig. 1) the surface water temperature can be replaced by the water temperature. In Table 2 we present water temperature assessments within different periods of time at both stations.

		Period		
		1936 – 2011	1951 – 2011	1976 – 2011
(a) Kusur gauging station		Probability of '0' hypothesis (= 'no trend'), p, '+' indicates p < 0.1((1-p) • 100 % > 90 %) and is followed by trend assessment		
	June	0.322	0.1729	0.3552
	July	0.222	0.0757, + 0.13 °C/10 years	0.02049, + 0.23 °C/10 years
	August	0.0497, + 0.13 °C/10 years	0.1692	0.582
	September	0.7573	0.9143	0.941
	June through September	0.19	0.0832. + 0.08 °C/10 years	0.0981, + 0.1 °C/10 years
(b) Habarova gauging station		—	1951 – 2011	1976 – 2011
		Probability of '0' hypothesis (= 'no trend'), p, '+' indicates p < 0.1((1-p) • 100 % > 90 %) and is followed by trend assessment		
	June	—	0.07287, + 0.13°C/10 years	0.2613
	July	—	0.1164	0.00407, + 0.25 °C/10 years
	August	—	0.4704	0.05793, + 0.16 °C/10 years
	September	—	0.8189	0.1707
	June through September	—	0.07038, + 0.07 °C/10 years	0.00498, + 016 °C/10 years

Tab. 2: Water temperature assessments within different periods of time, in particular propability *p* of null hypothesis "no trend" for different periods of time: (a) at Kusur GS; (b) at Habarova GS. "Plus" indicates that the 1 - *p* >0.9, which means the presence of trend with the level of statistical significance higher than 90 %.

Tab. 2: Wassertemperatur zu verschiedenen Zeitperioden an den Pegelstationen (a) Kusur (GS) und (b) Habarova (GS).

All trends found here are positive indicating the increase in the water temperature. The coefficients of the linear trends for the monthly averaged water temperatures are given (°C/10 yr) in the brackets. Of course, the minimum level of statistical significance can be chosen higher or lower to determine the presence of trend, however, our goal is to show the overall dynamics.

If we consider the period from 1951 to 2011 (Habarova GS has been operated since 1951) there is a tendency of the water temperature increasing during the early summer by 0.13 °C per decade at Kusur GS and Habarova. The estimations for the period 1976 to 2011 are different. If for the early summer there is a deceleration of the water temperature growth, the mid-summer is characterised by the acceleration of the growth. Also, Table 2 shows that the period from 1976 to 2011 is characterized by more rapid water temperature increasing at the both considered stations. The same is valid for the air temperature within the Lena River watershed (IGCE 2018 web source). However, the water temperature behaviour at Kusur GS and Habarova is slightly different during this time. The water temperature at Habarova GS demonstrates overall higher coefficients of the linear trends and higher level of statistical significance and has a tendency to increase during August. The difference in the behaviour of the stream temperatures at Habarova GS and Kusur situated ~200 km upstream indicates that the measurements at Kusur GS can be taken for analysis of water temperature changes in the delta head area (Fig. 1) with a caution. The mentioned difference can be largely explained by the exchange with the atmosphere. The fluctuations of mean monthly water temperatures usually follow the dynamics of mean air surface temperatures in the area closely (Johnson 2003, Hammond & Pryce 2007). A strong association between monthly stream temperatures at Kusur GS and monthly air temperatures in the Lena River basin outlet area has been shown by Liu et al. (2005). For August and September, their results are statistically significant at the 99 % confidence level. They have also shown that the correlations between the stream temperature and precipitation are very weak and statistically insignificant. Coefficients of the linear trends for the air temperature averaged over warm season (May–September) given in the annual reports on climate characteristics in Russia provided by the Institute of Global Climate and Ecology of the Federal Service for Hydrometeorology and Environmental Monitoring (IGCE, web source; Tab. 1) show temperature increasing up to 0.8 °C per decade (in average 0.6 °C per decade) for the period 1976 to 2011 for the northern area of watershed and up to 0.6 °C per decade (in average 0.5 °C per decade) for the watershed area upper Kusur GS.

Figure 5a demonstrates mean water temperature over warm season (June–September) and maximum summer temperature for various years. It clearly shows that the overall mean water temperature at Habarova GS (~10.76 °C, standard deviation over mean values of the different years is ~0.95 °C) is higher than at Kusur GS (~9.56 °C, standard deviation over mean values of the different years is ~1.15 °C). This is not true for the maximum values, which, for example, are close to each other quite often. For some years maximum at both station can reach 20 °C and higher. Figure 5b contains the information about time when the water temperature maximums are

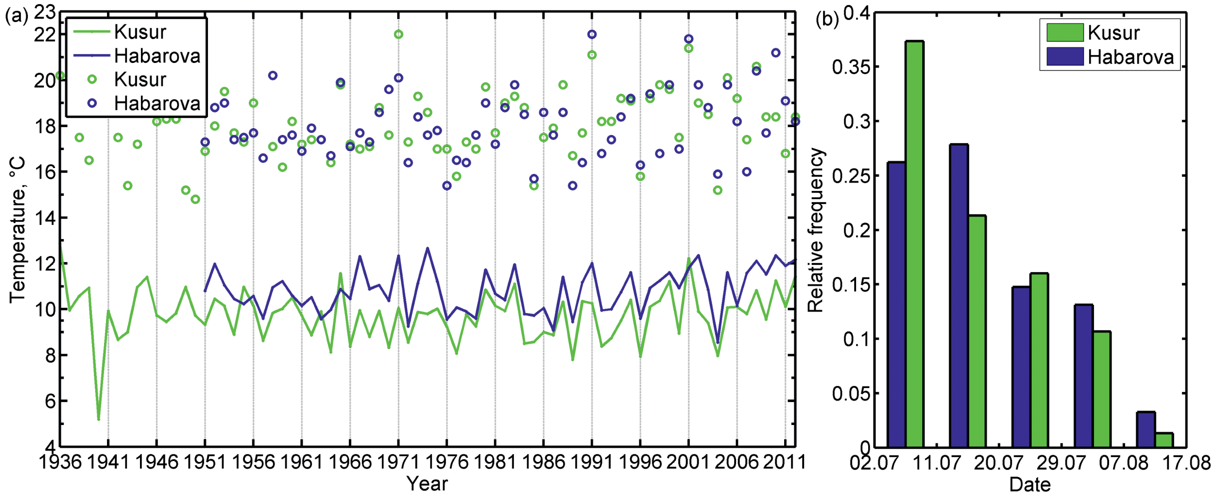


Fig. 5: (a) The averaged water temperature over the period from June to September at Kusur GS and Habarova for the years from 1951 till 2012, (°C). Dots indicate the maximum summer temperatures at both stations. (b): The relative frequency (observed probability) of summer maximum occurrence within 10-day intervals at Kusur and Habarova stations.

Abb. 5: Die durchschnittliche Wassertemperatur (a) für den Zeitraum Juni bis September an den Pegelstationen Kusur und Habarova für die Jahre 1951 bis 2012 (°C). Punkte stehen für die maximale Sommertemperatur an den beiden Stationen. (b): Relative Häufigkeit (beobachtete Häufigkeit) des sommer-Maximums innerhalb von 10 Tagen an den Stationen Kusur und Habarova.

reached. For both stations, the maximum water temperature is reached during July or the first half of August (Fig. 5b). However, for Habarova GS there is a shift toward a later date compared to Kusur GS. The calculated mean difference in the time, when the temperatures reach maximums, is about 2.3 days (standard deviation is 8.2 days) between Habarova GS and Kusur for the considered period (1951 to 2012). This is in agreement with the mean time (~2.4 days) it takes the flow to reach Habarova GS starting from Kusur GS during summer. The Pearson correlation coefficient between the dates, when maximum events take place at Habarova GS and Kusur, is ~0.6. It means that summer maximum of water temperature at Habarova GS is quite often caused by the heat accumulated upstream Kusur GS.

WATER TEMPERATURE MEASUREMENTS INCONSISTENCY AND ITS ANALYSIS (4)

Typically, the water temperature in the Lena River gradually decreases towards its mouth in summer months due to river's south-north orientation (Zotin 1947, Liu et al. 2005, Fig. 1). In the lower reaches of the Lena River the presence of a deep valley and wide-open areas to the north and northwest, together with the Lena-Vilui lowlands to the south, facilitates unhindered entry of cold air masses (Burdikina 1961). However, water temperatures measured at Habarova GS for all years of observations are on average higher for the summer season than measured at Kusur GS (Figs. 5a, 6) located much further upstream (Fig. 1), i.e. the measurements indicate a significant increase in water temperature from the south to the north. At the same moment, the measured air tempera-

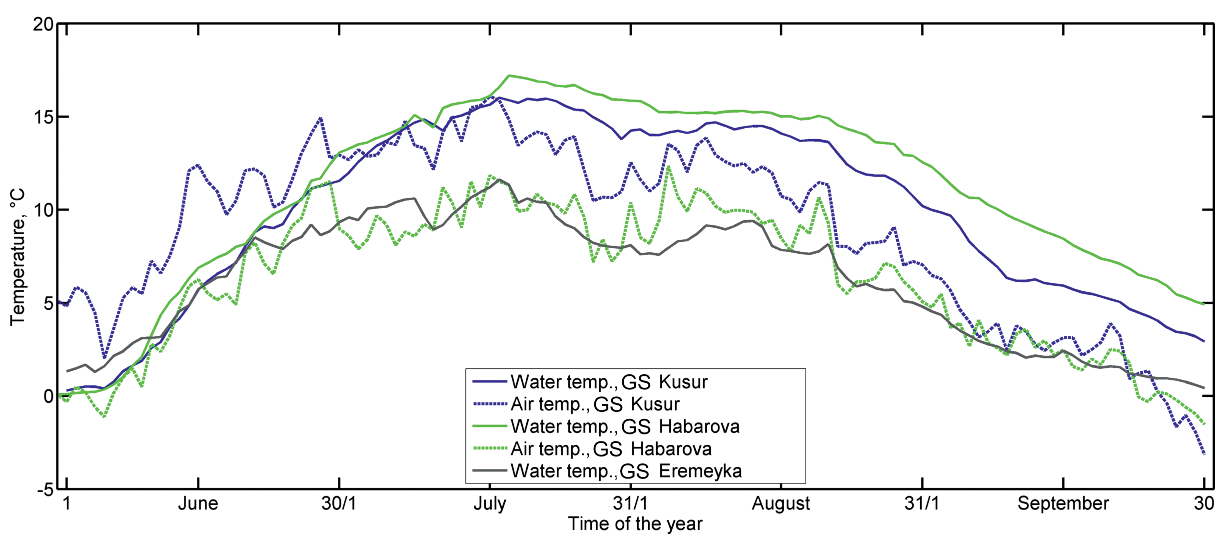


Fig. 6: The mean daily surface air (2 m) and water temperatures measured at Kusur GS, Habarova and Eremeyka for the summer season 2002 to 2011 (°C).

Abb. 6: Mittlere tägliche Lufttemperatur (2 m Höhe) und Wassertemperatur an den Pegelstationen Kusur, Habarova und Eremeyka in der Sommersaison der Jahre 2002 bis 2011 (°C).

ture remains below water temperature for both stations (Fig. 6). Figure 6 also clearly shows that the difference between water temperatures at Habarova GS and Kusur increases from June to September. Note, Figure 6 reflects the behaviour of the difference from July to September for each considered year despite of the inter-annual variability. However, in June the situation greatly varies year to year and day to day in a sense that the difference can be large negative (e.g., up to -5 °C in 2007), large positive (e.g., up to 6.5 °C in 2009), or more often nearly zero. Such behaviour of difference in June can be explained by the ice conditions. Floating ice still can be presented in the river till the end of June depending on the year.

Below, we discuss the influence of factors, which potentially can cause this large positive difference between water temperatures at Habarova GS and Kusur:

(a) *The anthropogenic factor* as a possible explanation should be discarded given the very low population density and the absence of industrial facilities and dams at the site under consideration.

(b) *The details of the river-atmosphere heat exchange* could be a possible missing factor. The summer period is characterized by a strong short-wave radiative forcing, especially until 7 August during the polar day period (Langer et al. 2011). Despite the lower air temperature, the water temperature can still increase due to the short-wave radiation. Figure 7 shows the daily average heat balance for the period from 2002 to 2011. The albedo of the Lena River water was set to 0.1. The sensible heat fluxes were calculated using the Edinger et al. (1974) formula. The wind speed, humidity and air temperature were taken from observations at Kusur meteorological station (provided by the Arctic and Antarctic Research Institute (AARI), Tab. 1). The shortwave and longwave incomeing radiations were taken from the NCEP/NCAR Reanalysis. The net heat exchange with the atmosphere (sum of net radiative and turbulent fluxes) at Kusur GS and Habarova is positive during the period from June to mid-August and negative during September. However, even positive net heat exchange can provide only weakly pronounced heating (commensurate with the measurement error) of the water column in the area from Kusur GS to Habarova. For some years the net heat exchange becomes negative in the middle of August or even in the beginning of August. In the area of Habarova GS cooling starts earlier due to lower air temperatures (Figs. 6,7). Also, the net heat exchange decreases from June to September within the studied area (weakly pronounced heating is gradually replaced by water cooling), which is nearly opposite to the behaviour of the difference between water temperatures at Habarova GS and Kusur. We can summarize that the two important factors: heat exchange with atmosphere within the studied area and heat accumulated upstream from Kusur GS, which should largely explain the mean monthly stream temperature values, fail to do so at Habarova GS.

(c) *The heat exchange with the river bed* is still missing in our reasoning. However, it is most likely that during July–August heat is transferred from the water to the river bed when the net radiation balance is positive (Fig. 7). This can be seen for the lakes in the area, which have smaller heat content (Boike et al. 2015), but nearly unmovable sediments. In the work by

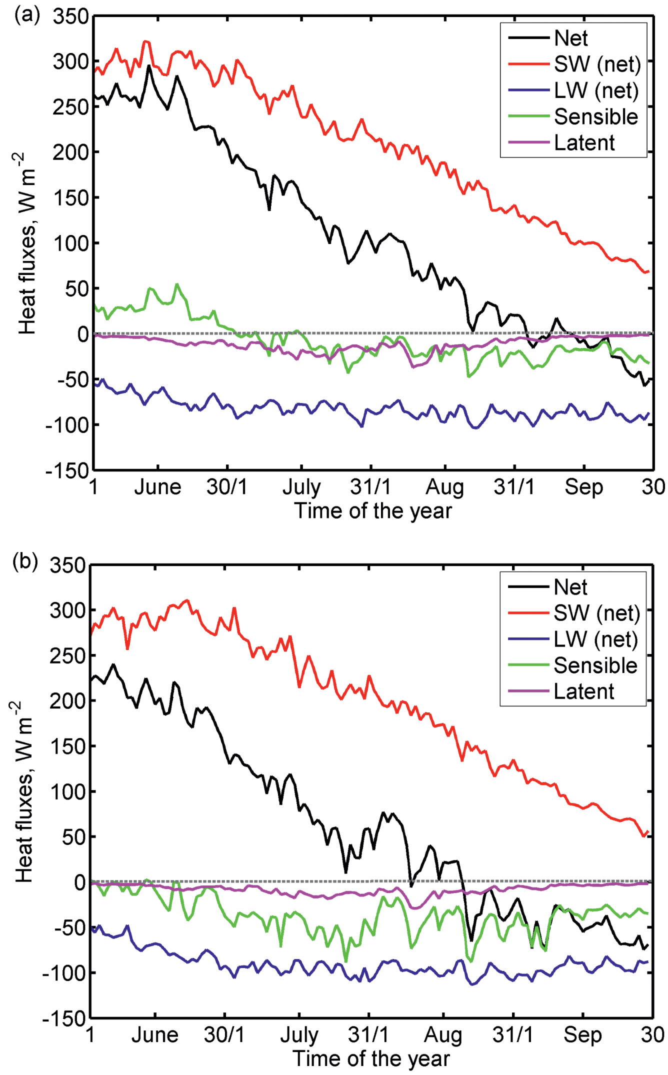


Fig. 7: The heat energy exchange at the air-water interface at (a) Kusur GS and (b) at Habarova GS: net shortwave (SW) and longwave (LW) incoming radiations, sensible and latent heat fluxes and net heat exchange (Net, which is sum of radiative and turbulent fluxes) averaged on each summer day between 2002 and 2011 (W m^{-2}). Dashed lines indicate position of zero.

Abb. 7: Durchschnittlicher täglicher Wärmehaushalt zwischen Wasseroberfläche und Atmosphäre an den Sommertagen (Juli – September) der Jahre 2001 bis 2011 an den Pegelstationen (a) Kusur und (b) Habarova. Die punktierte Linie beschreibt die Nulllinie (W m^{-2}).

Boike et al. (2015) for the lakes situated on Samoylov Island, the temperature in which reaches 15 °C, the heat fluxes from the water to the sediment layer did not exceed 3 W m^{-2} for the summer season. Only in the fall the opposite heat fluxes from sediments to river water should be expected. This reasoning also serves as an argument against the presence of large positive differences between water temperatures measured at Habarova GS and Kusur in summer and stresses the inconsistency between the expected and measured water temperature at Habarova GS. Some details about this issue will be presented in the next sections.

(d) The possible reason for this puzzling disagreement could be the *non-representativeness of measurements* at one or both stations. We should stress that water temperature measurements at both stations are taken near the right river bank. 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. On the other hand, the Lena River within the main channel has very strong vertical and lateral mixing during summer season (Fig. 2) and we have already proved above that the *vertical* water temperature distribution is close to a uniform one within the main channel and in the beginning of the Bykovskaya channel. Here, however, a question still remains about the cross-sectional water temperature distribution taking into account that the *cross-sectional* width is two orders of magnitude larger than the depth of the channel (Fig. 3).

According to the results of temperature surveys in 1979 and 1985 provided by the Hydrometeorology and Environmental Monitoring Centre in Tiksi, the temperature measurements at Habarova GS are representative. The absolute differences between surface temperatures near the bank and midstream did not exceed 0.2 °C.

However, several hydrological notes from 1930s, 1950s and 1980s (provided by service of hydrometeorology and environmental monitoring in Tiksi) reported that the water temperature measurements at Kusur GS lack representativeness. The differences between the weighted average and near coast stream temperatures ranged from 1 to 3.5 °C and always remained positive (the measurements have been done in July and August). Based on observations in 1936, the mean ratio of these temperatures was found to be 1.2 for the warm season (June–September) (Reinberg 1938, Zotin 1947). Taking into account the technique of measurements and the river bed profile (Fig. 3), which shows a sharp increase in depth near the shore, we can 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 (Ebetem) and Eremeyka Rivers (Fig. 1). The mouths of these rivers are located approximately between 20 km and 1.5 km upstream from Kusur GS on the same river side (Balashov & Tamarskiy 1938). In the whole area of interest till Habarova GS there are no other inflows, which could affect the temperature measurements at the stations considered, except for possible subsurface inflows, which are out of our control. The observed daily course of the Eremeyka water temperature near the mouth averaged over the period from 2002 to 2011 is shown in Figure 6. Unfortunately, we do not have water temperature data for other small rivers, but assume that their water temperature behaviour is similar to Eremeyka, taking into account their respective watershed sizes and positions. The main question, which arises here, is the possibility of cold right bank current formation, which persists until Kusur GS. The mean annual volumes of the Ebitiem and Eremeyka runoffs are only 0.4 and 0.0034 km^3 respectively (these estimates are provided by Centres of Hydrometeorology and Environmental Monitoring in St. Petersburg and Tiksi), for other small rivers we can only guess that it is about 0.2 km^3 based on information about the watershed squares and width of the river channels. Therefore, the water from Ebitiem River, entering ~5 km upstream from Kusur GS (Fig. 1), would dominate the cold current formation, if it is presented.

To find out the influence of water from the small rivers mentioned above on water temperature measurements at Kusur GS and to carefully estimate the water–atmosphere heat exchange we carried out several numerical experiments, which will be presented in the next section.

NUMERICAL EXPERIMENTS (5)

We made two numerical experiments using COMSOL Multiphysics, in particular, Computational Fluid Dynamics (CFD) Module (Wilkes 2002, COMSOL, web source). The CFD Module is a numerical simulation platform for computational fluid dynamics that accurately describes fluid flow processes both in the laminar and turbulent regimes. For full control over CFD models, there is an option for input additionally needed equations into the software.

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 and getting some quantitative characteristics of the influence. The second experiment has been designed to reproduce the temperature at Habarova GS using atmospheric forcing and results from the first experiment.

Simulation of the influence of tributaries upstream Kusur Station on measurements

The model domain was constructed as a box with a length and width equal to 25 km and 2.4 km respectively with several water/heat sources (Fig. 8). The depth of the channel was varying depending on the Lena discharge conditions, the width of the channel was fixed taking into account that the observed cross-sectional profile (Fig. 3) has nearly rectangular shape in the area of Kusur GS. The computational grid was generated with a resolution 100 m, 10 m and 1 m in along channel, cross-sectional and vertical directions respectively. Turbulent flow was simulated using the Reynolds-Averaged Navier-Stokes equations (Wilkes 2002). A k-epsilon (k-ε) turbulence model was used to parameterize both horizontal and vertical mixing. The wall functions (Launder 1988, Wilkes 2002, Craft et al. 2002, Suga et al. 2006) are used to describe the flow motion near the river bank. The roughness height was set to 3.2 μm and the roughness parameter was set to 0.26, which corresponds to a sandy, loam soil. For the first run the Lena River discharge and full depth were set to 25,000 $m^3\ s^{-1}$ and 15 m respectively (Fig. 8), which correspond to the typical discharge rate and water depth during August–September (Fig. 4). We decided to start with such conditions as soon as the maximum of the difference between water temperatures at different stations occurs during mentioned period of time. The atmospheric forcing was turned off. The tributaries were defined by mass flow rate boundary conditions. The tributary tangential velocity components were set to zero on the boundary. The geometry of the inflow mouths was defined as a rectangle with sides equal to 3 m in vertical direction and boundary side of one grid element along the Lena River channel. The water temperature in the tributaries was taken equal to the typical Eremeyka water temperature at the appropriate time. The total discharge rate for all tributaries was set to 70 $m^3\ s^{-1}$, which is typical discharge rate for August–September. Discharge rate for the Eremeyka River was available from observations on monthly scale for the period from 2002 to 2012 (Tab. 1). The discharge rates for the

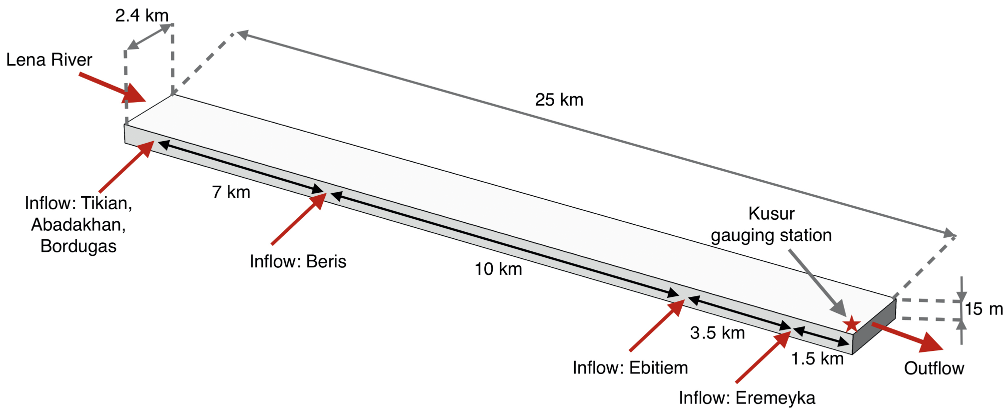


Fig. 8: The illustration of the model domain of the first experiment.

Abb. 8: Darstellung der Modellabmessungen für das erste Experiment.

other tributaries were calculated approximately based on the available information about the watershed squares and shape of the channels and were scaled according to the behaviour of the Eremeyka discharge for the summer season.

Numerical simulations showed the possibility of a thin layer formation, at about 170 m from the right river bank to the midstream, of the relatively cold water due to the influence of tributaries. Note one more time that the width of the channel is two orders of magnitude larger than the depth, and it was proved earlier that the vertical temperature profile is nearly uniform at this position. In our idealized experiment the difference between surface water temperature and bottom temperature did not exceed 0.2 °C.

Varying the turbulence schemes and discharge conditions of both the Lena River and its inflows we have found that the width of the layer, which is experiencing the impact of the small cold tributaries, remains nearly constant. There is a nearly linear dependence between the water level and discharge at Kusur GS during summer (June–September), except period from end of May to beginning of June characterized by the highest water level during the year, due to a nearly rectangular profile of the channel (Fig. 3). For these runs we used monthly averaged discharge values for the Lena River (Fig. 4) and its tributaries. For the tributaries calculated monthly averaged values over the period from 2002 to 2012 amounted to 132 $m^3 s^{-1}$ for June, 75 $m^3 s^{-1}$ for July, 61 $m^3 s^{-1}$ for August and 80.5 $m^3 s^{-1}$ for September.

In an idealized case with a plate equipped with heat sources the temperature distribution in the turbulent boundary layer follows the logarithmic law except for the thin wall layer for the flows with very high Reynolds numbers (Landau & Lifshitz 1987). In our case, setting the same temperature for all inflows, we obtained a close to logarithmic profile of the water temperature distribution horizontally within the layer of 170 m width. Experiments on sensitivity to resolution showed that the above mentioned grid resolution allows us to resolve the logarithmic layer. The correct production of the total kinetic energy in the viscous layer, which we cannot resolve (Versteeg & Malalasekera 2007), is ensured by the effective boundary conditions (Wilkes 2002).

Assuming that the inflow velocity of tributaries is negligibly small, we can describe the behaviour of near bank and midstream water temperatures using the following approximation:

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

$$a+b=1, \qquad a=\frac{Q_e}{Q_e+Q_l*\frac{L}{L_{cs}}}=\frac{1}{1+\frac{Q_l}{Q_e}*\frac{L}{L_{cs}}}, \tag{2}$$

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

In these formulas T_e, Q_e are the Eremeyka water temperature and total discharge rate from all considered small cold tributaries upstream Kusur GS, T_l, Q_l are the Lena water temperature and discharge rate, T_k is the water temperature measured at Kusur GS, m is the distance to the right river bank, at which the measurements of water temperature were taken (we set it to 3 m), L is the width of layer affected by the cold water from tributaries, L_{cs} is the width of cross-section at Kusur GS, $f(x)$ is a function of temperature distribution, which depends on distance x to the right Lena River bank (vertical profile of the temperature is assumed to be uniform). Equation (1) shows in which proportions relatively warm water of Lena River mixes with cold water of tributaries in the affected layer. The coefficients a and b are normalized weights (Equation 2), which depend on the ratio of the Lena and tributaries discharge rates and ratio of the affected layer and full cross-section widths. Equation (3) presents the result of first numerical experiment in analytical form: $f(x)$ follows the logarithmic law, L is the width of layer, which is characterized by relatively cold current presence.

Using equations. (1) to (3) the midstream water temperature, which is close to mean stream temperature $\left(\frac{L}{L_{cs}}<10\right)$, can be written as:

$$T_l=\frac{d\cdot T_k-a\cdot T_e}{b-c}, \tag{4}$$

$$c+d=1, \quad c=\frac{1}{1-\frac{m}{L}}-\frac{1}{\ln\left(\frac{L}{m}\right)}. \tag{5}$$

Using Equation (4), the mean, maximum and minimum difference between the midstream and near right bank temperatures were calculated for the whole period of available observations and for the particular years (Fig. 9). Total discharge from all tributaries was varying in a range from 300 to 17 $m^3 s^{-1}$ for the summer periods of different years (2002– 2012), the water temperatures for all tributaries were set equal to Eremeyka water temperature available from observations on a daily

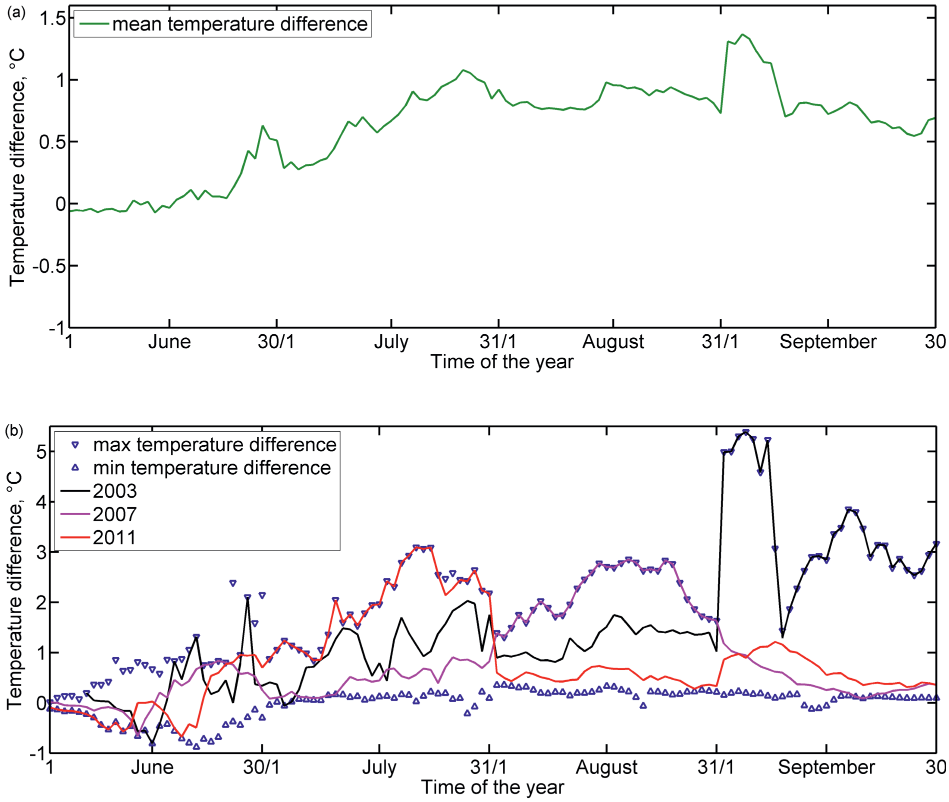


Fig. 9: (a) The simulated mean difference (2002–2012) between the midstream and near right bank water temperatures at Kusur GS (°C). (b) The simulated difference between the midstream and near right bank water temperatures at Kusur GS for particular years and maximums and minimums of the temperature differences for the whole period of time from 2002 till 2012, (°C).

Abb. 9: (a): Angenommene mittlere Temperaturunterschiede zwischen der Strommitte und dem rechten Flussufer (2002 bis 2012) an der Pegelstation Kusur (°C); (b): Simulierter Unterschied zwischen der Strommitte und dem unmittelbaren rechten Ufer an der Pegelstation Kusur für bestimmte Jahre sowie Maximum- und Minimum-Unterschiede für die Gesamtperiode 2002 bis 2012 (°C).

scale. The Lena River discharge and water temperature were taken from observations on a daily scale (Tab. 1).

Figure 9a demonstrates that the influence of cold tributaries increases from June to the beginning of September in general. The mid-stream temperature is on average higher by 0.8 °C than the near bank temperature during July–September. It means that the cold tributaries can explain, at least partly, the large positive difference between the temperatures measured at Habarova GS and Kusur. The tributaries can cause warming near right river bank at Kusur GS but mainly in June and only for some particular years. That is why in Figure 9b the negative values of the difference between the midstream and near right bank water temperatures in the middle/end of June appears. These negative values correspond to the higher temperature in the Eremeyka than in the Lena River. Figure 9b illustrates that the cooling influence of inflows can greatly vary and its magnitude can reach 5.5 °C under certain conditions. One of the strongest factors determining the influence is the ratio of discharge rates of the Lena River and its tributeries (equations (2) and (4)). In our simulation, we used monthly values of discharge for the tributaries and we kept discharge at the same level for the whole month. This explains why all maxima of the temperature difference for the particular month (July, August or September) are attributed to one particular year (Fig. 9b). So, in 2003 the tributaries have anomalously high mean September discharge rate, in 2007 the August discharge was higher than usual. However, the discharge rate influence can be enhanced or weakened by the water temperature in the tributaries. For example, in 2011 the discharge rate in July was smaller for tributaries than in 2003 (the Lena River discharge rate in July was nearly the same for both years), however, the temperature difference in 2011 is much higher than in 2003 (Fig. 9b). If the water temperature in Eremeyka and other tributaries is much colder than in the Lena River, then the non-representativeness of the measurements becomes more pronounced. At the end of August and beginning of September both factors are usually working: the discharge rate of the Lena River is decreasing (Fig. 4) and the temperature is increasing compared to that of tributaries, that is why 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 the large Lena River discharge rate (Fig. 4) 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 needed to determine the actual values of midstream Lena water temperature for particular dates. The curves presented for different years (Fig. 9b) do not reflect daily behaviour of the difference between the midstream and near right bank water temperatures realistically, because the discharge rates usually significantly vary during one month and it is hard to speculate about the typical seasonal curve of the discharge for tributaries. The above estimates for the midstream Lena water temperature present a useful benchmark, but contain a lot of uncertainties. For example, in our idealized experiment we did not turn on the atmospheric forcing, which can be a significant source of the surface stress and can both reduce the non-representativeness of the measurements or enhance it. If we add large wind stress to the system, then L cannot be considered as fixed in time anymore and the behaviour of $f(x)$ becomes more complex. However, winds with speeds 5-6 m s^{-1} were prevailing during the period of time under consideration, winds stronger than 18 m s^{-1} were not present.

Having shown the influence of small cold tributaries on the measurements at Kusur GS, we need to discuss the implications for the results and estimates provided in Section 3. These estimates were given for the near bank water temperature, which is not equal to the mean cross-sectional water temperature at Kusur GS. The midstream temperature is systematically higher than the temperature 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 temperatures in formation of the Kusur temperature (equations (2), (4) and (5)). The mean Lena contribution is 90 %, 88 % and 85 % in July, August and September accordingly. The water temperature in tributaries is also affected by the regional atmospheric forcing: the correlation coefficient between the monthly water temperature measured at Habarova GS and Eremeyka is ~0.86 and measured at Kusur GS and Eremeyka is ~0.88 (the data set of 148 points contains monthly mean values for open water season from 1974 to 2010, $p<0.01$). Thus, trend and mean heat balance estimates at Kusur GS can be taken with caution for the Lena River midstream at this position, but non-systematic component of the difference between the midstream and right river bank temperatures adds additional noise, which reduces the accuracy of the assessments. The mean net heat energy exchange at the air-water interface will be a bit smaller for the Lena River midstream compared to one presented in Figure 7 for July–September by about -10 to -20 W m^{-2} due to a higher gradient between the water and air temperatures. The estimates with higher accuracy require knowledge of daily discharge rates and temperatures for all tributaries closely upstream Kusur GS.

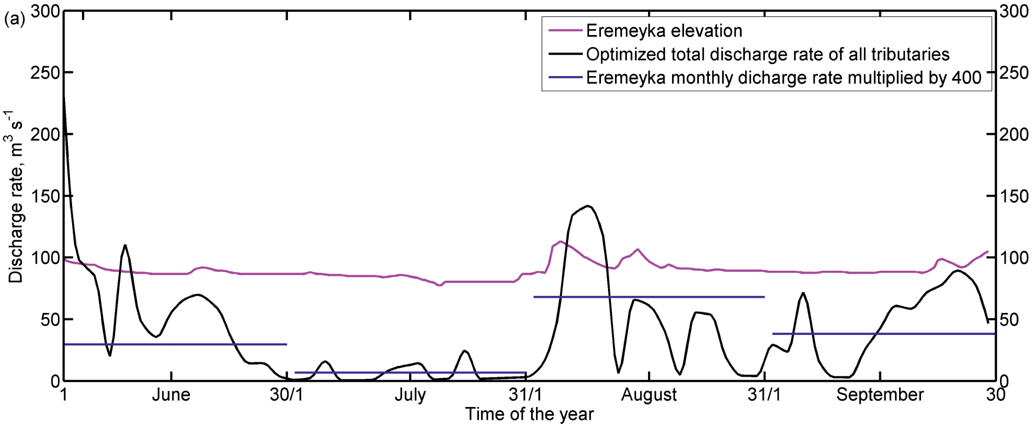
Simulation of the water temperature at Habarova GS

For the second experiment, we took a segment from Kusur GS till Habarova (~200 km) and turned on the atmospheric forcing. The second experiment represents a one-dimensional model of heat exchange with the atmosphere as soon as we assume water temperature uniformity in vertical direction and use equations (4), (5) to prescribe mean stream Lena temperature at Kusur GS. The goal was to reproduce the observed water temperature at Habarova GS for particular years using results of first experiment (Tab. 1). To use Equation (4) the information about total discharge from all tributaries is needed. We have monthly information about the Eremeyka discharge and can calculate approximately the discharge rates from other inflows on a monthly scale, but the total discharge variation on a smaller scale remains unknown to us. To identify the variation of the total discharge from all tributaries in time the optimization task was posed. The time step was set to 6 hours. The difference between the modelled and measured water temperatures at Habarova GS was minimized using 40 points equally distributed along the time line (June–September) for every simulated year. These 40 found discharges were connected using cubic splines.

To calculate the cross-sectional square of the channel we assumed its rectangular form, with the width and depth are being functions of coordinate, Lena River discharge rate and time. The triangular shape is typical for some Lena Delta channels however, the main channel can be closely characterised by the rectangular shape (Fig. 3). The mesh element size is set to 500 m. For the first step June–September of 2012 was chosen as a modelling period because additional information about the elevation for Eremeyka River was available (Tab. 1), which can indirectly serve as verification for obtained discharge course of tributaries solving optimization task. Note that the elevation measurements at Eremeyka are not influenced by the Lena because the elevation of zero of Eremeyka GS (36.28 m) is higher than the possible Lena's water level. For the second step, we tried to reproduce the temperature regime at Habarova GS for June–September of other years from 2002 to 2011 (demonstrated only partly here). The atmospheric forcing was derived from the NCEP/NCAR Reanalysis with time resolution equals to 6 hours and available observations (Tab. 1). According to the observations in June–July (Örek et. al 2013) the light penetration depth (by Secchi disc) is in the range 30-90 cm in the delta head area. We used this information to estimate the penetration depth of shortwave radiation. We used the observed daily data for the discharge and water temperature at Kusur GS and daily data for the water temperature in Eremeyka assuming that all other tributaries have similar water temperatures.

Figure 10a demonstrates the total discharge from all small tributaries within the warm season of 2012, which is the result of optimization. As we mentioned before our analytical approach for the determining midstream Lena water temperature contains uncertainties, as a result optimized hydrograph can have oscillations, which are not attributed to the variation of the real total discharge from the tributeries. However, independently from previous estimates of the total discharge we obtained nearly the same range solving optimization task, however, with small mean value at about 41 m^3 s^{-1}. This is in agreement with the fact that in 2012 the mean summer discharge rate of the Eremeyka was smaller than usual. In Figure 10a the mean monthly discharge rate of Eremeyka River multiplied by 400 is also presented. Note that the Eremeyka discharge rate is smalller than the rates of other considered inflows, but we cannot neglect it as soon as Eremeyka is the closest inflow to Kusur GS. 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, except for June. However, in June the floating ice can be present, which would modify the water heat balance a lot. Figure 10b shows the simulated and measured temperatures at Habarova GS and demonstrates that they agree quite well, with mean error 0.4 °C. Comparing Figures 10b and 10c we can conclude that the warming influence of the atmosphere within the area studied (~200 km) due to large short wave radiation heat fluxes in June to beginning of July is limited to 0.5 °C (can reach 1.5 °C), in the end of July–August the warming effect can add about 0.2 °C to Habarova water temperature and then weakly expressed heating is gradually replaced by cooling. Figure 10c demonstrates the findings of previous experiments for 2012. The midstream temperature (close to mean stream value) at Kusur GS calculated using Equation (4) can be signifycantly higher than the right river bank temperature for some dates, up to 4 °C in the beginning of August for 2012, due to cooling influence of small tributaries upstream.

However, for some years we cannot explain large temperature difference between Habarova GS and Kusur, which can be up to 8 °C, even solving optimization tasks (we varied only total discharge from tributaries, its water temperature is taken as it



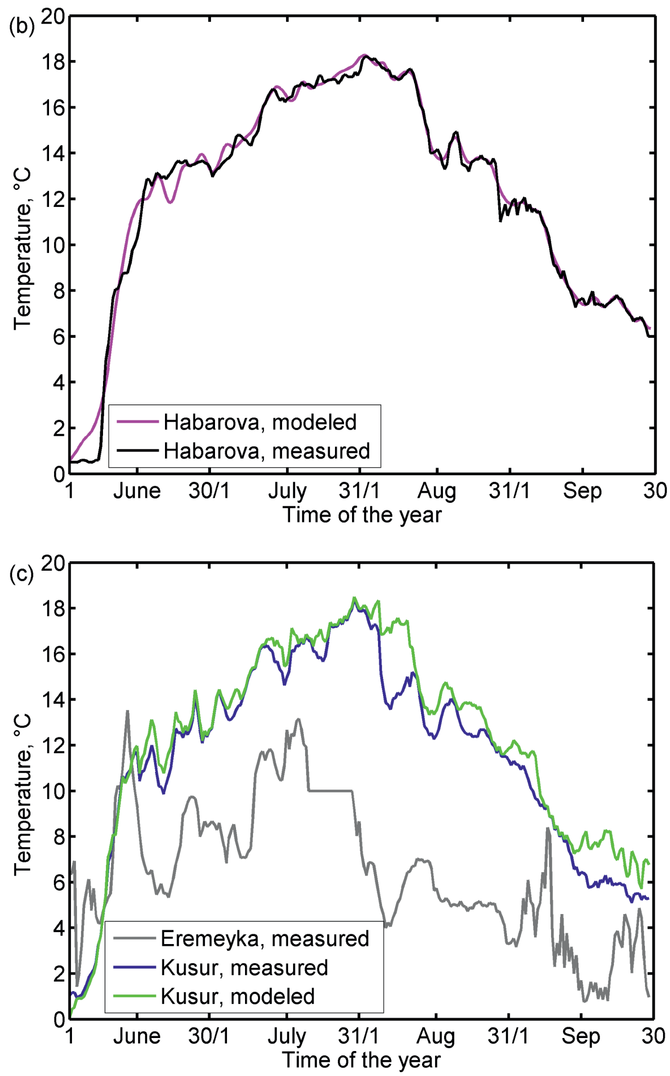


Fig. 10: Modelled and observed discharge characteristics for 2012. (a): Optimized total discharge rate of all tributaries close upstream Kusur GS and mean monthly discharge of Eremeyka River multiplied by 400, [m^3 s^{-1}], pink curve shows the elevation measured at Eremeyka GS, (cm). (b): Water temperatures, modeled and observed at Habarova GS, (°C). (c) Water temperatures modelled and observed at Kusur GS and water temperature observed at Eremeyka GS, (°C).

Abb. 10: Modellierte und beobachteter Ausstrom-Charakteristika für 2012. (a): Optimierte Ausstromrate aller Zuflüsse dicht stromauf von der Pegelstation Kusur und dem 400-fachen der mittleren Ausstromrate des Flusses Eremeyka (m^3 s^{-1}); rosa Kurve beschreibt die Erhöhung am Eremeyka-Pegel (cm). (b): Modellierte und beobachtete Wassertemperaturen am Habarova-Pegel (°C). (c): Modellierte und beobachtete Wassertemperaturen am Kusur-Pegel und beobachtete Wassertemperaturen am Eremeyka-Pegel (°C).

is), this occurs for some years in the beginning/middle of June (2009, 2011) and in the beginning/middle of September (2007). Due to missing information about ice conditions in June and its possible large influence on the water temperature measurements, we focus our attention only on September mismatch. Figure 11a shows the optimal total discharge rate from all tributaries and mean monthly discharge rate of Eremeyka River multiplied by 400 for 2007. The obtained range of discharge rate from 10 to 290 m^3 s^{-1} agrees with the estimations presented above (no upper and bottom limits were introduced for the total tributaries discharge rate during the optimization process). The difference between the modelled and measured temperatures is reasonable before September except for June (Fig. 11b), the mismatch between the modelled and measured temperature in the middle of July can be removed introducing a larger amount of points distributed along the time line used in optimization process. However, in the end of beginning to middle of September the difference between the modelled and measured temperatures at Habarova GS reaches ~6 °C. The inflows during this period of time have warming effect, thus a sharp drop in optimized discharge can be seen (Fig. 11). Note that the atmospheric forcing tends to rapidly cool the water from Kusur GS to Habarova in the middle of September. There is an indication in favour of an unaccounted source of heat in the middle of September 2007 from the riverbed in the area of the delta head or water temperature in the tributaries in reality was much lower than the observations show at least during a 10-day period. More analysis and observations are required to make further statements in this direction. Some considerations are presented in the next section.

Station	Mean temperature (°C) 1981 – 1990			
	June	July	August	September
Kusur GS	5.49	14	12.25	6.11
Tit-Ary GS	5.27	13.19	11.63	5.36
Habarova GS	6.48	14.56	13.24	7.62

Tab. 3: Surface water temperature measured at different gauging stations (GS) in June – September averaged over the period from 1981 to 1990.

Tab. 3: Mittlere Temperatur des Oberflächenwassers an verschiedenen Pegelstationen für die Jahre 1881 bis1990.

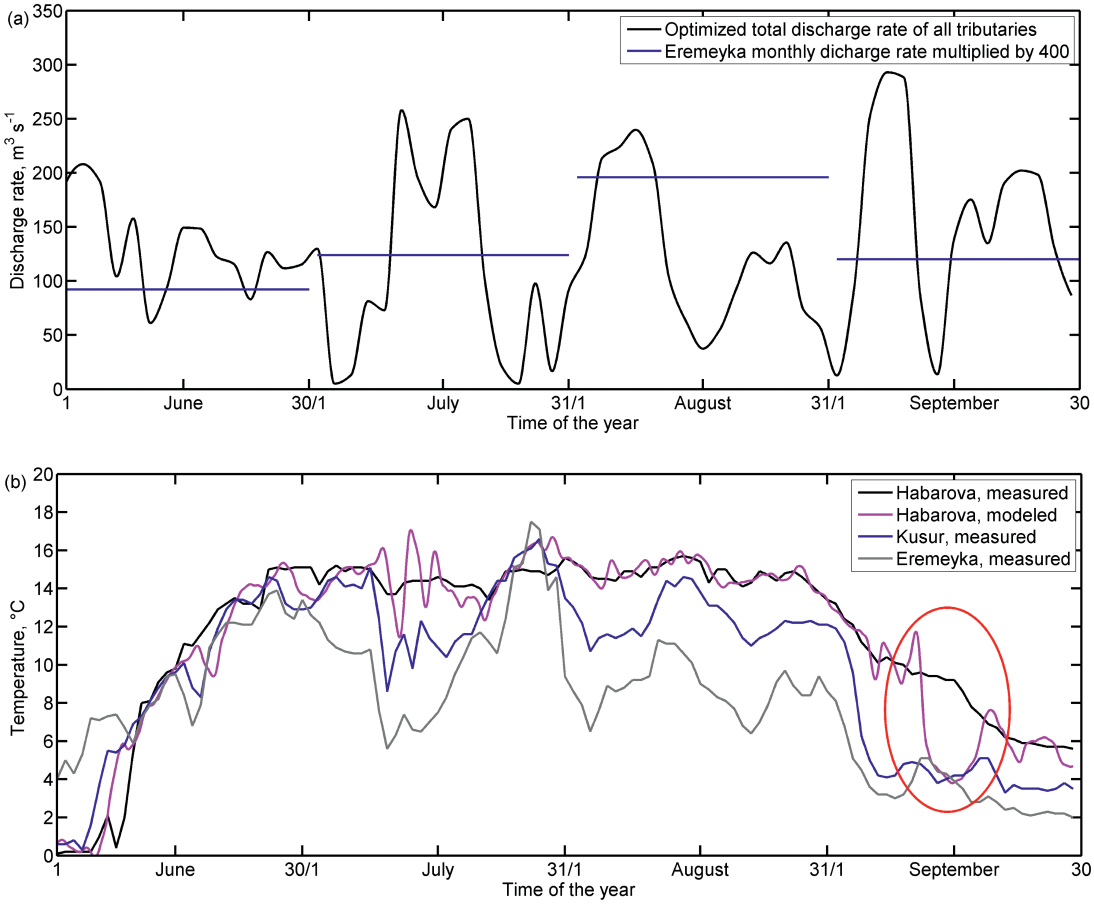


Fig. 11: Modelled and observed discharge characteristics for 2007. (a): Optimized total discharge rate of all tributaries close upstream Kusur GS and mean monthly discharge of Eremeyka River multiplied by 400, (m^3 s^{-1}). (b:) Water temperatures modelled and observed at Habarova GS, observed at Kusur GS and Eremeyka GS, (°C); red ellipse indicates the zone where it is impossible to reproduce the temperatures observed at Habarova GS by solving optimization task.

Abb. 11: Modellierte und beobachtete Ausstrom-Charakteristika für 2007. (a): Optimierte Ausstromrate aller Zuflüsse dicht stromauf des Kusur-Pegels und das 400-fache des durchschnittlichen monatlichen Zustroms der Eremeyka Flusses (m^3 s^{-1}). (b): Modellierte und beobachtete Wassertemperaturen am Habarova-Pegel sowie beobachtete Werte am Kusur-Pegel und Eremeyka-Pegel (°C); rote Ellipse beschreibt den Zeitabschnitt zu dem es nicht möglich war das Modell an die am Habarova-Pegel beobachteten Temperaturen anzupassen.

DISCUSSION

The arctic location of the Lena Delta secures its position within the continuous permafrost. Frozen ground thickness in the region can reach 600 m (Grigoriev 1966), active layer thickness is rarely exceeding 0.8-1.2 m. Taliks usually occur below the large water bodies, such as lakes and river channels; talik zones are mostly "open" beneath the major channels and largest lakes, while remaining ones under the secondary branches and smaller water bodies are "closed". The presence of an "open" talik under the Lena River main channel within the studied area is very likely taking into account that the Lena River does not freeze completely down to the bottom during the winter season (Wankievicz 1984, Grigoriev 1993, Mikhaylov 2003). Channel alluvium is subject to deep seasonal freezing where it is either exposed or directly contacts the ice bottom during the winter low flow and freeze-up period. In high-energy environments, adjacent to the midstream, with normally coarser bed material grain sizes, the frozen state of the alluvium cannot be retained throughout the summer season due to lesser ice content and higher bed mobility. In contrast, aside from the midstream, a perennially frozen core can be retained in side bars subsequently merging with the floodplain or valley bottom permafrost (Tananaev 2015). Albeit scarcely studied in-situ due to technical limitations, frozen cores are believed to underlie the majority of bedforms within the Lena Delta region (Korotaev 2012). The processes of the stream – riverbed water exchange leave a question and can be an important factor, which influences the water temperature. But above reasoning stresses the possible cooling influence of the riverbed, especially pronounced during early summer and autumn seasons. However, we are forced to look on a possible warming effect of the riverbed due to the problem considered in previous section (Fig. 11b) and fact that the beginning of ice conditions at Habarova GS is observed on average several days later than at Kusur GS based on available observations from 1986 to 1990 and from 1999 to 2007 (Tab. 4). Ice formation is a complex process, but it largely depends on heat exchange with the atmosphere and heat stored in the river (Antonov 1961). The date of fall ice appearance is taken as the date of formation of stable slush ice run (shuga drift) and drift ice (in this sense, the presence of small inflows upstream Kusur GS should have minor influence on observations). Despite the difficulty in determining this date, Kusur GS is considered to be one of the most representative for surveillance regarding ice phenomena (Antonov 1961). Given that the air temperatures are nearly equal at Kusur GS and Habarova for the first decade of October and cooling influence of the atmosphere

Station	Year													
	1986	1987	1988	1989	1990	1999	2000	2001	2002	2003	2004	2005	2006	2007
Kusur GS	06 Oktob.	05 Oktob.	11 Oktob.	07 Oktob.	09 Oktob.	02 Oktob.	06 Oktob.	05 Oktob.	07 Oktob.	30 Sept.	09 Oktob.	06 Oktob.	07 Oktob.	07 Oktob.
Habarova GS	10 Oktob.	08 Oktob.	18 Oktob.	09 Oktob.	12 Oktob.	05 Oktob.	08 Oktob.	13 Oktob.	11 Oktob.	09 Oktob.	13 Oktob.	08 Oktob.	13 Oktob.	14 Oktob.

Tab. 4: Date of the first appearance of ice in the fall at gauging stations Kusur and Habarova.

Tab. 4: Datum des ersten Auftretens von Eis im Herbst an den Pegelstationen Kursur und Habarova.

within the area studied, we can suggest that the shift in the beginning of ice conditions is mostly explained by the impact of heat stored in the sediments. The accumulative environment of the Lena Delta significantly limits sediment delivery to the marine zone. Following the inter-annual variability of the river flow, the annual suspended sediment load (SSL) varies from 16.6 to 26.2 × 10^6 t, as measured at Kusur GS (Holmes et al. 2002, Korotaev 2012). The vast majority of SSL passes by the Kusur crosssection in early summer when snowmelt events provide around 85 % of the total water discharge. Suspended sediment concentrations, on average, peak later than does the discharge, reflecting the dominant role of more distant material sources and the erosion-limiting setting of the Lena lower reaches (Tananaev 2015). According to the results presented in Tananaev & Anisimova (2013) and Alekseevskiy (2004), annual bedload flux at Kusur GS is 14.9 10^6 t. Bed material transport occurs mostly during snowmelt floods (78.5 %). This is followed by rain-induced events (19.5 %) and the summer low flow period (2 %) (Tananaev & Anisimova 2013). The vast majority of sediment material is retained within the riverine part of the delta. Presumably, the whole volume of bedload material is retained within the delta in large bedforms

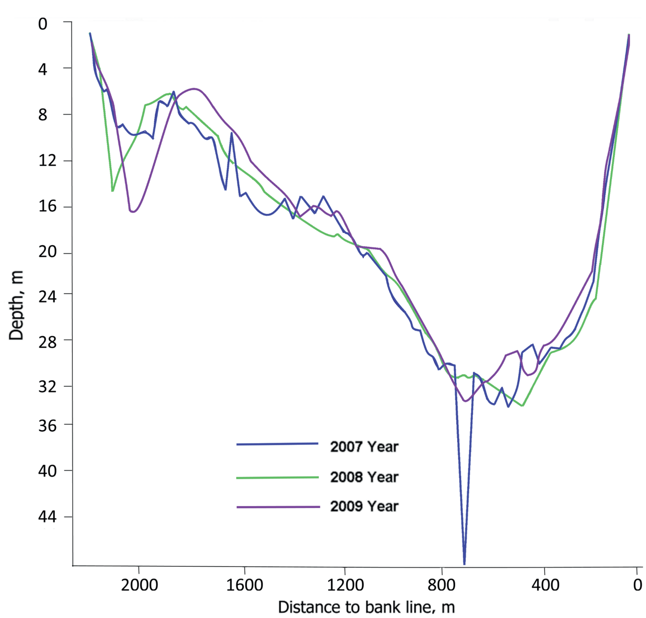


Fig. 12: The Lena riverbed profile in the area of Habarova GS measured in August of different years, main channel, (m). Figure taken from Bolshiyanov et al. (2013) and adapted.

Abb. 12: Flussbettprofil des Hauptkanals der Lena im Bereich des Habarova-Pegels (m) gemessen jeweils im August der Jahre 2007, 2008 und 2009. Quelle: Bolshiyanov et al. (2013) verändert.

especially in the delta head area. Only 10 to 17 % of the total suspended material is delivered to the Laptev Sea margin (Rachold et al. 1996, Peregovich et al. 1999). Sediment associated heat flux is expected to have higher impact within the deposition area, which includes delta head area and beginning of Bykovskaya channel, where Habarova GS is situated. Based on the results of the expedition in August 1955, 1959 in the Bykovskaya channel, no frozen soils in the furrows have been found, bed deposits were composed by sands, pebbles and boulders through entire depth of observations, which was ~8.5 m (Ivanov 1967). We can conclude that the heat fluxes from sediments to the Lena water in the delta head area is larger than these in lakes estimated by Boike et al. (2015) during fall season (September–October), to have precise estimations additional observational data are needed. However, the picture, which we obtained for 2007 (Fig. 11), remains very questionable. Even if we suppose that sediment strata actively start losing their heat in the beginning of September, we cannot explain such warming without introducing additional large positive heat flux from the river bed between Kusur GS and Habarova. There is an evidence for the presence of a variety of cavities and groundwater flow systems on talik under the main channel. Exactly in August 2007 wedge cavity was detected, which was closed by sands in 2008 and 2009, in the delta head area (Fig. 12), this fact opens more questions about dynamics in the system river-water – river-bed and indicates necessity of future investigation in this direction.

CONCLUSION

This paper analyses water temperature characteristics in the outlet area of the Lena River during the summer season (June –September) based on a long-term data series covering the period from the beginning of observations to the present time at Kusur GS and complementary data at several stations downstream and one station upstream. Based on our analysis, we conclude that the measured water temperature at Kusur GS close to the right river bank does not represent the mean stream temperature, underestimating it in July–September. The water from the small Lena River tributaries (Eremeyka, Ebitiem, Beris and others) 1.5-22 km upstream Kusur GS usually forms relatively cold right bank current, which influences the measurements. The ratios of the discharge rates of the Lena River and small inflows upstream and water temperature gradient of the inflows and Lena River are the major factors which control the difference between the midstream (close to mean stream) and near right bank temperature, which is usually largest in the end of August, beginning of September. The mid-stream temperature is in average higher by 0.8

°C than the near bank temperature during July–September. However, the cooling influence of inflows can greatly vary and its magnitude can reach 5.5 °C under certain conditions. To recover the midstream temperature reliably the information about discharge and temperature conditions in the inflows should be collected.

At both Kusur GS and Habarova GS there is a tendency toward increasing water temperature. The estimates varies in a limit 0.07-0.25 °C per 10 years for different months and different stations (Tab. 2). 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 the measurements at Kusur GS should be taken for analysis of water temperature changes in the delta head area with a great caution.

There are indications in favour of an unaccounted source of heat in the late summer to beginning of fall from the riverbed to the water in the area from the Kusur GS till Habarova GS. More analysis and observations are required to make further statements in this direction.

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