This manuscript is accepted for publication in Hydrology Research on 19-08-2019

Revising Contemporary Heat Flux Estimates for the Lena River, Northern Eurasia

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Abstract

The Lena River heat flux affects the Laptev Sea hydrology. Published long-term estimates range from 14.0 to 15.7 EJ·a^{-1}, based on data from Kyusyur, at the river outlet. A novel daily stream temperature (T_w) dataset was used to evaluate contemporary Lena R. heat flux, which is 16.4±2.7 EJ·a^{-1} (2002-2011), confirming upward trends in both T_w and water runoff. Our field data from Kyusyur, however, reveal a significant negative bias, -0.8°C in our observations, in observed T_w values from Kyusyur compared to cross-section average T_w. Minor Lena R. tributaries discharge colder water during July-September, forming a cold jet affecting Kyusyur T_w data. Major Tw negative peaks mostly coincide with flood peaks on the Yeremeyka R., one of these tributaries. This negative bias was accounted for in our reassessment. Revised contemporary Lena R. heat flux is 17.6±2.8 EJ·a^{-1} (2002-2011), and is constrained from above at 26.9 EJ·a^{-1} using data from Zhigansk, ca 500 km upstream Kyusyur. Heat flux is controlled by stream temperature in June, during freshet period, while from late July to mid-September, water runoff is a dominant factor.

Keywords: permafrost hydrology; Russian Arctic; the Lena river; stream temperature; heat flux

Introduction

The terrestrial and marine compartments of the global system are connected via material and energy fluxes (Huntley *et al.* 2009). In this view, rivers act as major links between continents and oceans, discharging water and delivering associated fluxes to the coastal zone. In the Arctic, the largest rivers bear an important thermal imprint on the adjacent Arctic Ocean regions (Francis *et al.* 2009). Flowing from south to north, they are immense heat conveyor belts affecting sea water temperature, ice conditions and general water circulation in the Arctic and North Atlantic (Nummelin *et al.* 2016). Terrestrial runoff to the Laptev Sea during summer months allows important heat accumulation in the pycnocline, that affects the thermal state of submarine permafrost (Golubeva *et al.* 2015) and retards ice formation in autumn by 5-6 days (Kirillov 2006). Significant sea ice production in the Laptev Sea compared to total Arctic Ocean ice budget and a direct link between warm freshwater input and ice formation (Dmitrenko *et al.* 2009; Gutjahr *et al.* 2016) both add importance to the correct heat flux estimates.

Heat flux/runoff is a product of water discharge Q and stream temperature T_w hence it can be affected by changes in both hydrologic and thermal regime under contemporary climate change (van Vliet *et al.* 2013; Park *et al.* 2017). Recently, numerous studies have been focusing on hydrologic change in large Arctic catchments (St. Jacques & Sauchyn 2009; Yang *et al.* 2015; Tananaev *et al.* 2016; Georgiadi *et al.* 2017) and riverine heat flux assessment in its potential relation to global change (Yang *et al.* 2005, 2014; Lammers *et al.* 2007; Lui & Yang 2011; Fofonova *et al.* 2017; Magritsky *et al.* 2017).

Published mean annual heat flux estimates of the Lena R. vary from 14.03 EJ·a^{-1} (1950-1990; Liu & Yang 2011) to 15.2 to 15.7 EJ·a^{-1} (1935-2012; Lammers *et al.* 2007; Georgiadi *et al.* 2017; Magritsky *et al.* 2017). The accuracy of these estimates relies on the data availability from long-term observation network and the quality of these data. Daily T_w data are mostly unavailable for Russian rivers; hence all previous estimates were based on 10-day averages, that could introduce averaging bias. Moreover, multiple concerns were expressed since 1930s that T_w data from Kyusyur GS are negatively biased because of cold water jet occurring along the right bank in the gauge cross-section (Reinberg 1938). Modeling-based analysis performed by Fofonova *et al.* (2017) supports these concerns and casts doubts on the representativeness of the stream temperature data collected at Kyusyur GS. Their modeling exercises suggest observed T_w at Kyusyur being *ca.* 0.8°C lower than midstream temperature or cross-section average. These model outputs, as well as previous discussion on the matter, lack direct field-based proof. Based on these conclusions, Magritsky *et al.* (2017) tweak their heat flux estimate from 15.59 to 16.59 EJ·a^{-1} to account for potential negative bias in the Kyusyur GS T_w data, but this 1.0 EJ·a^{-1} increase lacks any justification in their paper.

This paper employs a daily T_w dataset at Kyusyur GS (2002-2011; Fofonova *et al.* 2017) to evaluate mean annual heat flux from daily and 10-day average data and to compare these values in search for potential averaging bias. Field data from our 2018 observations of stream temperature distribution in the Kyusyur GS cross-section are used to 'ground-truth' the existence of a cold near-bank jet and its effect on T_w values measured at the gauge cross-section. Contemporary heat flux of the Lena R. is then reevaluated based on daily T_w values and several thermal regime scenarios, and is constrained from top with heat flux estimate at Zhigansk GS, *ca.* 500 km upstream Kyusyur.

Study site

The Lena River, with basin area at the outlet *ca.* $2.43 \cdot 10^6$ km^2, drains vast areas of Eastern Siberia from Lake Baikal and Transbaikalia to Anabar Plateau and west slopes of the Verkhoyansk Range, and enters the Laptev Sea forming the largest delta in the Arctic (Fig. 1, left). Its mean annual runoff at the outlet equals 575 km^3 (2002-2011), and is increasing in recent decades (e.g., Tananaev *et al.*, 2016). The catchment is almost entirely underlain by permafrost, either continuous or discontinuous (Zhang *et al.*, 1999).

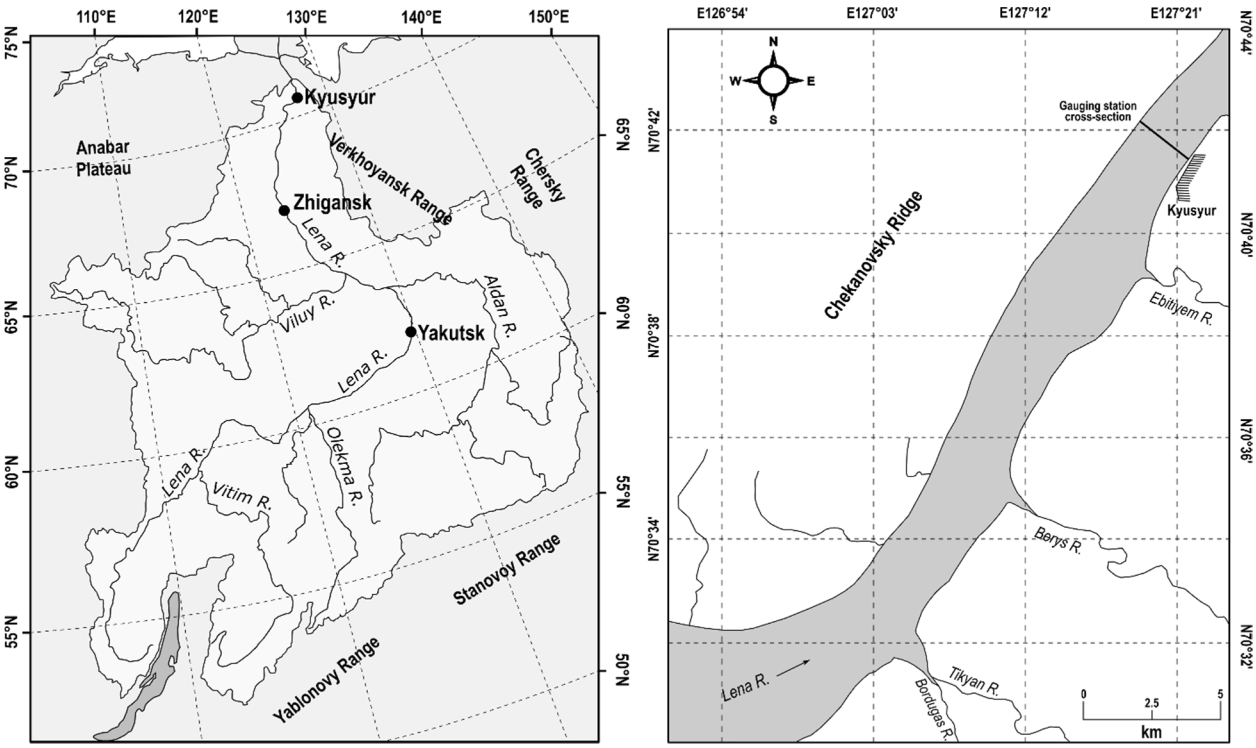

Fig. 1 The Lena R. basin (left) and Kyusyur GS location within the Lena R. valley (right)

Long-term hydrological monitoring at the Lena R. outlet is performed at Kyusyur, at a gauging station operated by Russian Hydrometeorological Agency (Roshydromet) since 1935 to present (Fig. 1, right). The Lena R. flows here in a single channel about 2.5 km wide. The left bank is high and rocky, a minor spur of the Chekanovsky Ridge with elevation from 200 to 300 m a.s.l., dissected by numerous water tracks and several minor river valleys. The right bank is an alluvial terrace rising gently toward the Kharaulakh Ridge, a northernmost spur of the Verkhoyansk Range, where elevations range from 500 to 800 m. Numerous minor tributaries flow into the Lena R. from the right (Fig. 1, right), all draining the westward slope of the Verkhoyansk Range.

The Kyusyur gauging station is located within the settlement limits, on the right bank of the Lena R., and is equipped with a pile water stage gauge. The gauging station is presently active, but open-access publication of the station data had ceased in 2012.

Materials and methods

This study is based on a daily stream temperature T_w dataset at Kyusyur GS, spanning from 2002 to 2011 and presented by Fofonova *et al.* (2017). This dataset originates from Tiksi Branch of Yakutian Hydrometeorological Centre, regional division of Russian Hydrometeorological Agency (Roshydromet). These data are used to: (a) calculate annual heat fluxes based on daily T_w and water discharge data; (b) compare these results with estimates based on 10-day T_w averages; (c) revise contemporary heat flux estimates.

On the Roshydromet network, T_w is measured twice daily at 8am and 8pm, near the bank, using a standard mercury thermometer with a cup-protected bulb to eliminate thermal inertia on reading. The thermometer is left submerged for at least 5min, then a reading is taken with 0.1°C accuracy upon thermometer retrieval. Stream temperature is measured daily but is only published as 10-day averaged values, and raw observed data are virtually inaccessible for the scientific community. Therefore, most heat flux estimates for Russian rivers are products of mean 10-day T_w and water discharge values (e.g. Lammers *et al.*, 2007; Magritsky *et al.*, 2017).

The ArcticGRO T_w data, collected in Zhigansk, *ca.* 500 km upstream Kyusyur (Holmes *et al.*, 2018), are used in the analysis. These data are obtained using the same technique as described above, but are collected bi-monthly and refer to the temperature at the moment of observations, and not a daily average. Monthly averages were calculated from observed values, and heat flux was estimated based on these averages.

Daily water discharge Q data are essential for the heat flux calculations. This study uses daily Q values at two gauging stations, Lena R. at Kyusyur and Yeremeyka R. at Kyusyur, provided by Tiksi Branch of Yakutian Hydrometeorological Centre. Daily Q values, reported by Roshydromet offices, are not observed directly, but recalculated from long-term 'stage-discharge' curves. Water stage is observed twice daily at 8am and 8pm at pile water stage gauges at both gauging stations in question. A graduated steel rod is used to obtain water level reading relative to a closest submerged pile top, which is translated to water stage (above local datum) and used in water discharge calculation. The accuracy of long-term stage-discharge curves is estimated to be within 5%.

Riverine heat flux/runoff HF, J, is calculated as:

$$HF = C_p \cdot \rho \cdot Q \cdot T_w \cdot n \cdot t, \quad (1)$$

where C_p is specific heat of water, generally variable with temperature but kept constant at 4186 $J \cdot kg^{-1} \cdot K^{-1}$ throughout this study; ρ is water density, 1000 $kg \cdot m^{-3}$, Q is water discharge, $m^3 \cdot s^{-1}$; T_w is stream temperature, °C; n is number of days in the calculation interval; t = 86400 seconds in a day. Statistical calculations were done in RStudio (2019), an integrated development environment for R language, using function *groupwiseMean()*, package 'rcompanion' (Mangiafico, 2019).

Field data on stream water temperature distribution were collected in Kyusyur in mid-August 2018, on the falling limb of a major rain-induced flood event originating from the southern part of the Lena River basin. In the field, water temperature was measured from a boat with an EXO-2 multiparameter sonde equipped with an internal temperature sensor, accurate to 0.1°C with 0.01°C resolution, and a pressure/depth sensor. The sonde was used to observe water temperature at various depths along seven transects at the gauging station cross-section, and one longitudinal transect extending from the Ebitiyem R. mouth to the Lena R. right bank (Fig. 1, right).

Results

The Lena River T_w and heat flux, 2002-2011

The open-water period at the Lena R. outlet starts around early June. The stream temperature rises above 0.2°C several days before the ice breakup, on 2 June (average, 2002-2011). At this moment, water discharge peaks, exceeding 100 000 $m^3 \cdot s^{-1}$ (Fig. 2, left). Both Q and T_w vary greatly at the falling limb of the freshet, affecting the variability in resulting heat fluxes. The spring freshet signal fades away by mid-July. Low-flow period ends by mid-August, then water discharge oscillates until freeze-up because of numerous rain floods originating from the Lena R. headwaters.

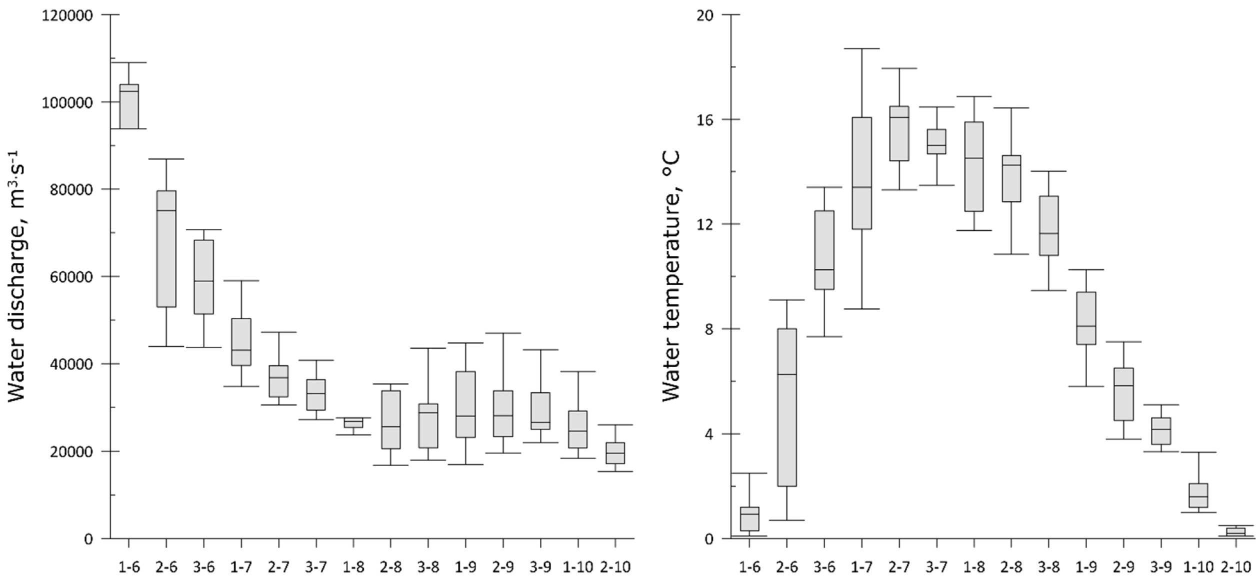

Fig. 2 Water discharge and stream temperature of the Lena R. at Kyusyur by 10-day periods. On *x*-axis, 10-day period numbers and months, separated by a hyphen. Boxplots mark median, 25% and 75% quartiles, and whiskers match interquartile range x 1.5

Stream temperature reaches its maximum values, between 14°C and 16°C on average, by early to mid-July, then remains at this plateau until mid-August, and gradually decreases to 0.2°C by mid-October (Fig. 2, right). Mean highest daily T_w is 18.5 ± 1.5°C and is observed in July. Multiple publications claim upward trends in T_w in recent decades (Yang *et al* 2005; Liu & Yang 2011; Georgiadi *et al* 2017; Magritsky *et al* 2017); our results support these conclusions.

In numerous preceding publications, heat flux of the Lena R. at Kyusyur GS is assessed using published 10-day averages (1935-2012; Georgiadi *et al.* 2017; Lammers *et al.* 2007; Magritsky *et al.* 2017). Here, the daily T_w dataset is used in calculations along with 10-day averages; Eq. 1 was used in calculations. Data analysis reveals no averaging bias related to the use of 10-day average T_w in lieu of daily values, the two estimates being identical at 16.4 ± 2.7 EJ·a^{-1}. This is substantially higher than previous estimates, and is close to 16.04 EJ·a^{-1} estimate for 1980-2012, published by Magritsky (2016).

The Lena R. water temperature distribution

Besides averaging bias, the T_w data from Kyusyur GS are reported to be negatively biased, affected by a cold jet in the near-bank zone (Reinberg 1938). Our field data from the 2018 campaign confirm this report.

Water temperature distribution at the Kyusyur GS cross-section is found to be mostly uniform in both vertical (surface to bottom) and lateral (bank to bank) directions. Vertical temperature distribution is uniform at least in the first 7 to 10 m of the water column, evidencing strong turbulent mixing in the cross-section, reserve observation points adjacent to riverbanks (Table 1, Fig. 3). At Transect 1, near the left bank, water temperature decreases with depth by only 0.18°C within 10 m, while at Transect 7, along the right bank, several distinct water masses are observed, the one at 4 m depth having properties resembling those of the surface waters (Fig. 3, right).

Table 1

Water temperature of the Lena R. at transects in the Kyusyur GS cross-section (see Fig. 3 for spatial reference; observations made 15 August 2018)

Transect	**Depth *d*, m**	**Surface T_w, °C**	**T_w at depth *d*, °C**	**Mean T_w, °C**
1	10	17.75	17.57	17.6
2	7	17.76	17.76	17.76
3	7	17.84	17.82	17.83
4	7	17.9	17.9	17.9
5	8	18.0	17.98	18.0
6	9	17.9	17.88	17.9
7	9	17.2	17.1	17.15

In lateral direction, lower temperature values were observed near the banks of the Lena R. Midstream water temperature was around 17.9 to 18.0°C, but it was by 0.4°C lower at Transect 1, and by 0.85°C lower at Transect 7 (Table 1). Thermal impact of minor tributaries, heat exchange with channel bottom, cooling influence of permafrost or stream circulation patterns may be deemed responsible for these anomalies.

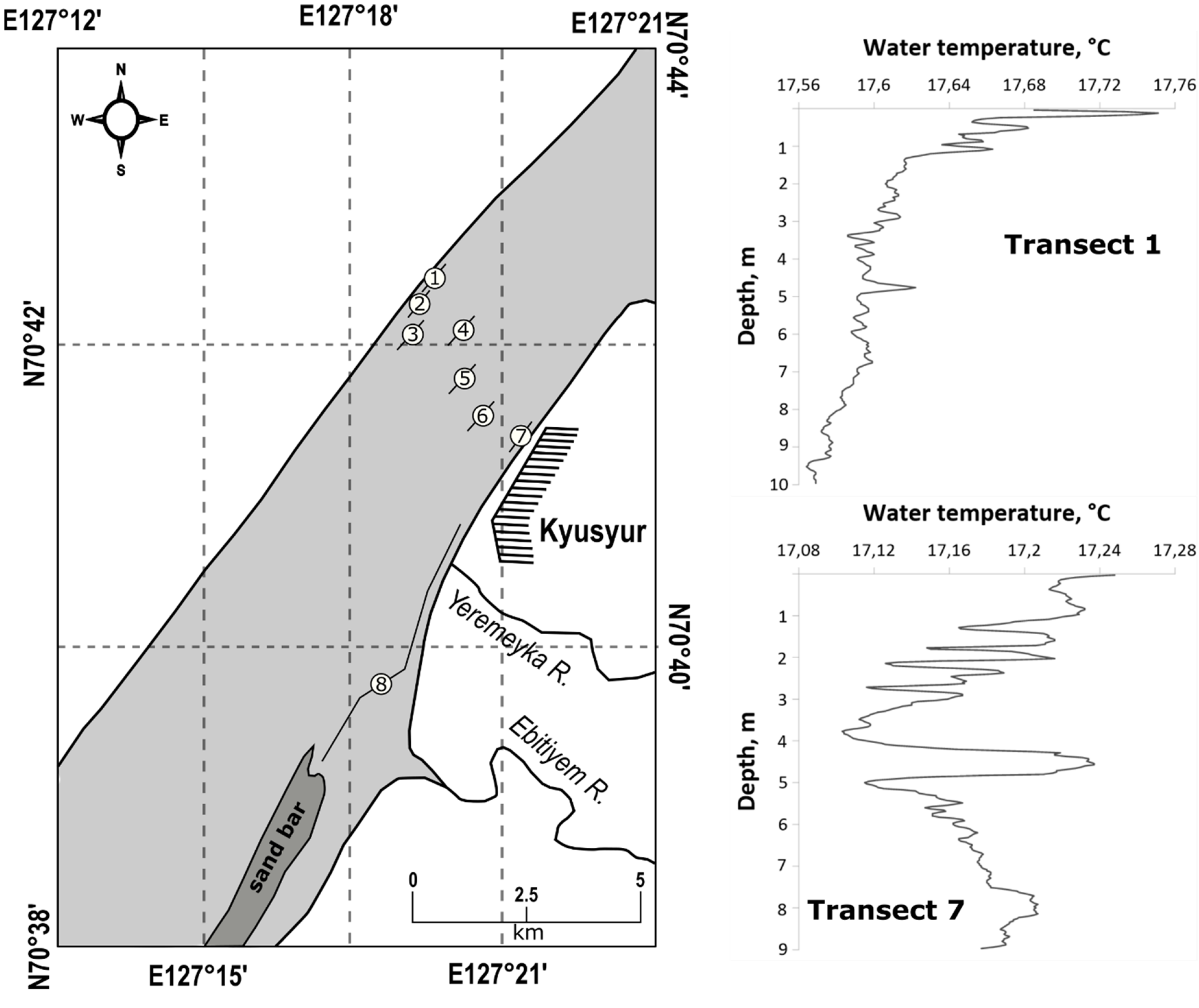

Fig. 3 Water temperature observation points near Kyusyur GS (left), vertical temperature profiles at near-bank transects (right)

Numerous minor mountainous tributaries drain to the Lena R. along the right bank of the river (see Fig. 1, right). Their potential impact on the Lena R. thermal regime and their role in producing this relatively cold jet along the right bank of the river have been demonstrated previously (Fofonova *et al.*, 2017), though other explanations cannot be ruled out straight away and are discussed further in the text. A transect was then planned to track longitudinal gradient in water temperature around the mouth zone of such tributaries. The closest tributary upstream from Kyusyur is the Yeremeyka R. (Fig. 3, left), but it had completely dried out at the time of our fieldwork. Observations were then performed at the mouth of a larger river, the Ebitiyem R., from a moving boat with a sensor submerged at *ca.* 0.5 m depth. Data from this longitudinal transect between the Ebitiyem R. mouth to the Lena R. right bank, confirm that thermal imprint of this tributary is significant and persists at least as far as the gauging station area (Fig. 4).

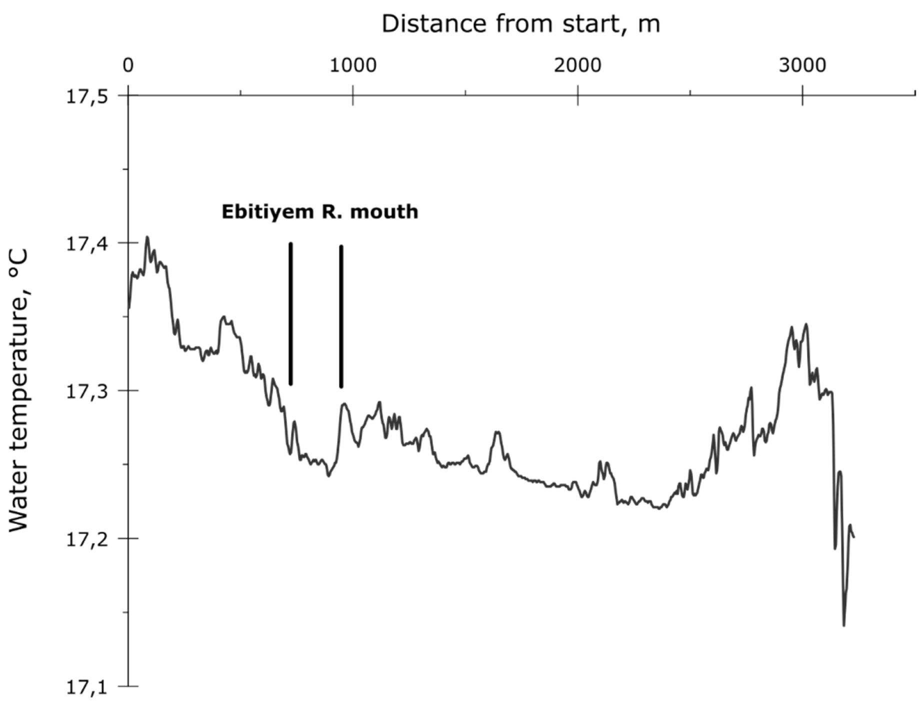

Fig. 4 The Lena R. surface water temperature along the Transect 8, see Fig. 3, right, for reference

Upstream the tributary mouth, water was already cooler than at midstream, ca. 17.4°C, and a further decrease down to 17.2°C is corresponding to the tributary inflow. This pattern continues toward the gauging station, where water temperature drops further to

17.1°C (Fig. 4). A 1.5°C decrease in water temperature toward the end of the transect was observed where the survey boat approached the right bank and was about 100 m from the shoreline.

Field results prove the incoherence of the T_w data reported by Kyusyur GS, with the temperature difference between midstream and near-bank, ΔT_w, reaching 0.85°C. Discharge-weighted cross-sectional average T_w is not expected to be significantly lower than midstream, since 'colder' channel sections adjacent to riverbanks are relatively shallow and have lower velocity. Detailed seasonal surveys are to be performed to relate observations at Kyusyur GS to cross-section average T_w.

Scenario-based Lena R. heat flux reassessment

The Lena R. heat flux for the 2002-2011 period was reassessed upon collecting field evidences that the T_w values observed at Kyusyur GS are misrepresentative for the cross-section average. A correction factor ΔT_w, either constant or time-dependent, was introduced in the observed data. Its value cannot be derived from a single field survey, hence modeling results presented in (Fofonova *et al.*, 2017) were used in scenario building. These referenced results were output from a numerical experiment, performed using a Computational Fluid Dynamics module in COMSOL Multiphysics®, a modeling software platform for finite-element analysis.

Two simple hypothetical scenarios were developed, for constant or time-dependent ΔT_w. For all scenarios, $\Delta T_w = 0$°C for May, June and October.

<u>Scenario 1</u>: $\Delta T_w = +0.8$°C for July, August and September. This ΔT_w value is a simulated mean difference between cross-section average T_w and near-bank T_w observed at Kyusyur GS (Fofonova *et al.*, 2017, Fig. 9a), and is surprisingly close to our field results. This

correction increases the Lena R. heat flux to 17.3 ± 2.8 $EJ \cdot a^{-1}$ (2002-2011) *i.e.* by 5% compared to uncorrected value.

Scenario 2: is based on the previous scenario, but accounts for extreme temperature gradients that could be observed throughout the open-water period. Simulated daily ΔT_w values were up to +3.0°C in July 2011 and August 2007, and up to +5°C in September 2003 on certain days (Fofonova *et al.* 2017). Highest monthly average ΔT_w values were +2.0°C in July and August, and +3.0°C in September.

Monthly ΔT_w variation scenarios were formulated as follows, allowing temperature anomalies in one of three months (Cases 2-4), two (Cases 5-7) or in all three months (Case 8):

(1) July-September, ΔT_w = +0.8°C, same as Scenario 1;

(2) July, ΔT_w = +2.0°C; August-September, ΔT_w = +0.8°C;

(3) July & September, ΔT_w = +0.8°C; August, ΔT_w = +2.0°C;

(4) July & August, ΔT_w = +0.8°C; September, ΔT_w = +3.0°C;

(5) July & August, ΔT_w = +2.0°C; September, ΔT_w = +0.8°C;

(6) July, ΔT_w = +2.0°C; August, ΔT_w = +0.8°C; September, ΔT_w = +3.0°C;

(7) July, ΔT_w = +0.8°C; August, ΔT_w = +2.0°C; September, ΔT_w = +3.0°C;

(8) July & August, ΔT_w = +2.0°C; September, ΔT_w = +3.0°C.

These distributions have differing frequencies of occurrence, or return periods, which are unknown for general population. Sample frequencies, calculated based on modeling results from Fofonova et al. (2017), were used in further analysis. Cases 2-4 each occur once in 10 years, as they were each observed once during the decadal modeling interval. Cases 5-7 occur once in 100 years, and Case 8 once in 1000 years, as per joint probability calculation rules. Case 1 takes what is left, or 889 years out of 1000. Heat fluxes were calculated for each year of record and for each case, then this dataset was bootstrapped with number of permutations $n = 10000$ accounting for frequencies of occurrence. Revised contemporary mean annual Lena R. heat flux is estimated at 17.6 ± 2.8 EJ·a^{-1} (2002-2011; Fig. 5), corrected for ΔT_w extremes and accounting for their return periods.

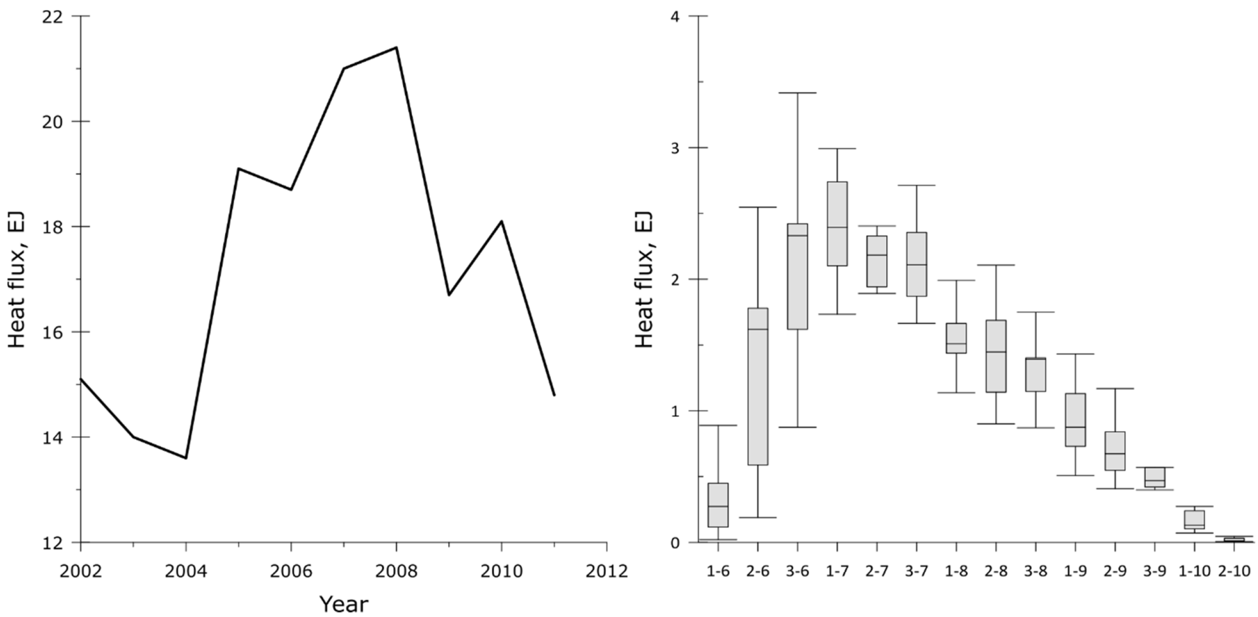

Fig. 5 Revised annual Lena R. heat flux, 2002-2011, and its distribution across 10-day periods. On *x*-axis, 10-day period numbers and months, separated by a hyphen. Boxplot marks median, 25% and 75% quartiles, and whiskers match interquartile range x 1.5

The Lena R. heat flux appears to vary highly across years (Fig. 5). At a monthly scale, late June fluxes are highly variable and could mark annual maximum; on average, however, the latter is observed in July, when the freshet is still at its falling limb and highest T_w are observed.

Discussion

Constraining Lena R. heat flux estimate

The revised estimate is based on modeling results, assuming a virtually constant ΔT_w value. Its lower bound constraint can be easily estimated at 16.4 $EJ \cdot a^{-1}$, *i.e.* estimated heat flux before temperature corrections. The upper bound constraint is hard to assess based on data from Kyusyur GS, since the true ΔT_w and its temporal variation are unknown. The ArcticGRO T_w dataset collected in Zhigansk GS, about 500 km upstream from Kyusyur, is used to evaluate the upper bound constraint. Water discharge data from Kyusyur GS are used in calculations, since the gauging station in Zhigansk had never observed this parameter. A certain positive bias may originate from this substitute, since the distance between the two gauging stations is significant, and water discharge in Zhigansk is expected to be somewhat less than in Kyusyur. However, no major tributaries flow into the Lena R. between the gauging stations in question. The potential increase in discharge is negligible compared to the Lena R. discharge, though hard to quantify, since no gauging stations observe the discharge of minor tributaries between Zhigansk and Kyusyur. Secondly, as we look for the upper bound constraint, this positive bias raising the upper bound might not be critical for evaluation purposes.

In total, ArcticGRO database contains 38 T_w observations from 2003 to 2018, covering the open water period from mid-May to early October. These observations were averaged across months (Fig. 6). These are rough estimates since T_w measurements are unevenly distributed throughout months, but they are based on the only data which are openly available. Corresponding mean monthly water discharge values at Kyusyur GS for 2002-2011 period were used in calculations.

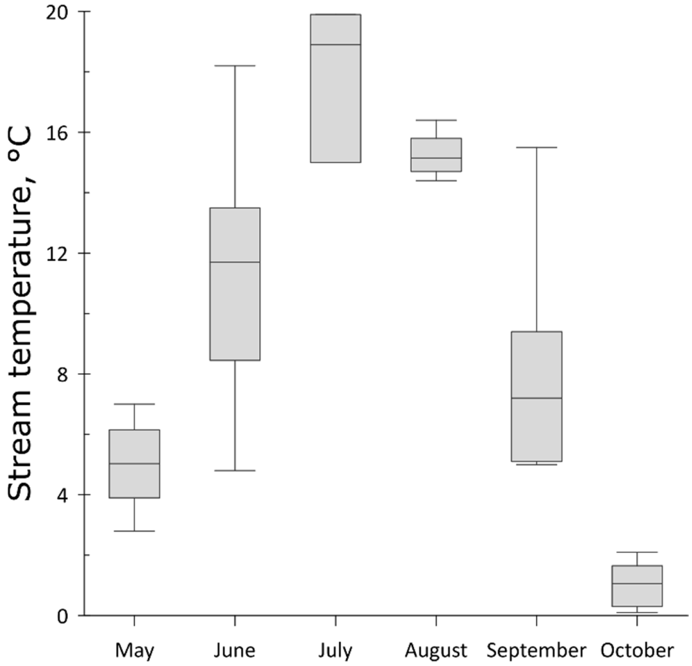

Fig. 6 Mean monthly stream temperature, the Lena R. at Zhigansk GS, ArcticGRO data (Holmes *et al.* 2018)

Mean annual heat flux at Zhigansk GS equals 26.9 EJ·a^{-1} (2003 to 2011) and can serve as an extreme upper bound to constrain the heat flux observed at Kyusyur GS, supposing that total heat turnover in the stream is maintained at zero level as water travels from Zhigansk to Kyusyur.

Hydrological controls over the Lena R. heat flux

Riverine heat flux is controlled by water discharge and stream temperature, both highly variable. In a long-term perspective, the heat flux variation of the Lena R. is mostly related to changes in water runoff (Fig. 7). The following linear equation describes this relation ($r = 0.84$, $p < 0.01$):

$$HF = 0.0315 \cdot W_Q - 1.28, \quad (2)$$

where HF – annual heat flux/runoff, EJ; W_Q – annual runoff, km^3.

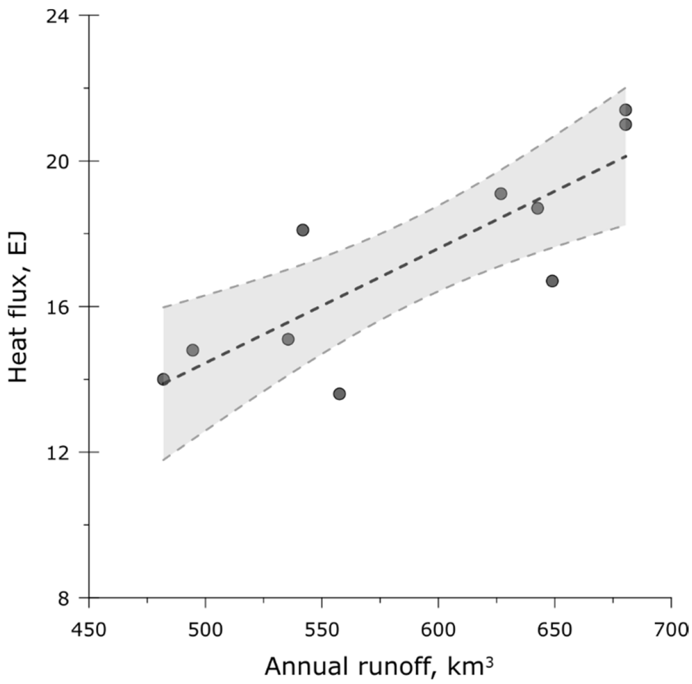

Fig. 7 The Lena R. annual heat flux related to annual runoff at Kyusyur GS, 2002-2011

However, at sub-annual scale, water discharge and stream temperature seem to mostly act as two independent controls over heat flux. For most of the year, these two parameters are mutually independent at a 10-day scale at R^2 below 0.2, with a slight tendency toward lower T_w values at higher discharges (Fig. 8). Notable exceptions include early and mid-July, when T_w is decreasing with higher Q (R^2 = 0.35…0.72) and October, when this same relation is positive with R^2 = 0.75.

Falling limb of a freshet generally continues to mid-July, and high discharge at this time corresponds to the overlapping rain events. The latter originate from the mountainous southern part of the basin, where permafrost groundwater and numerous icings may influence stream temperature. However, their thermal impact is expected to be negligible, as this water should accumulate heat during its 2000 km descent to Kyusyur. Hence closer sources are to be thought of. The Vilyui R. is regulated by a large hydropower station, discharging colder waters, but its water temperature returns to equilibrium values by the river mouth (Magritsky, 2016). The retarded freshet or juxtaposed rain floods on the Aldan River (Fig. 1, left) could be responsible for this temperature decline. Most of its basin is mountainous, where icings are abundantly present, and flash floods are common on its right tributaries upstream the Lena-Aldan confluence.

In October, higher runoff is also related to rain events, but at this time, the most distant sources of warmer water are at play. Longer travel time assures higher heat accumulation may be partly related to heat release from the alluvial channel and floodplain. The Lena R. channel between Yakutsk and Zhigansk accommodates enormous sand bars, that are drained and exposed to sunlight at low levels. Their prolonged inundation toward the end of autumn might serve an important heat source, as previously suggested by Fofonova *et al* (2017), though never assessed directly.

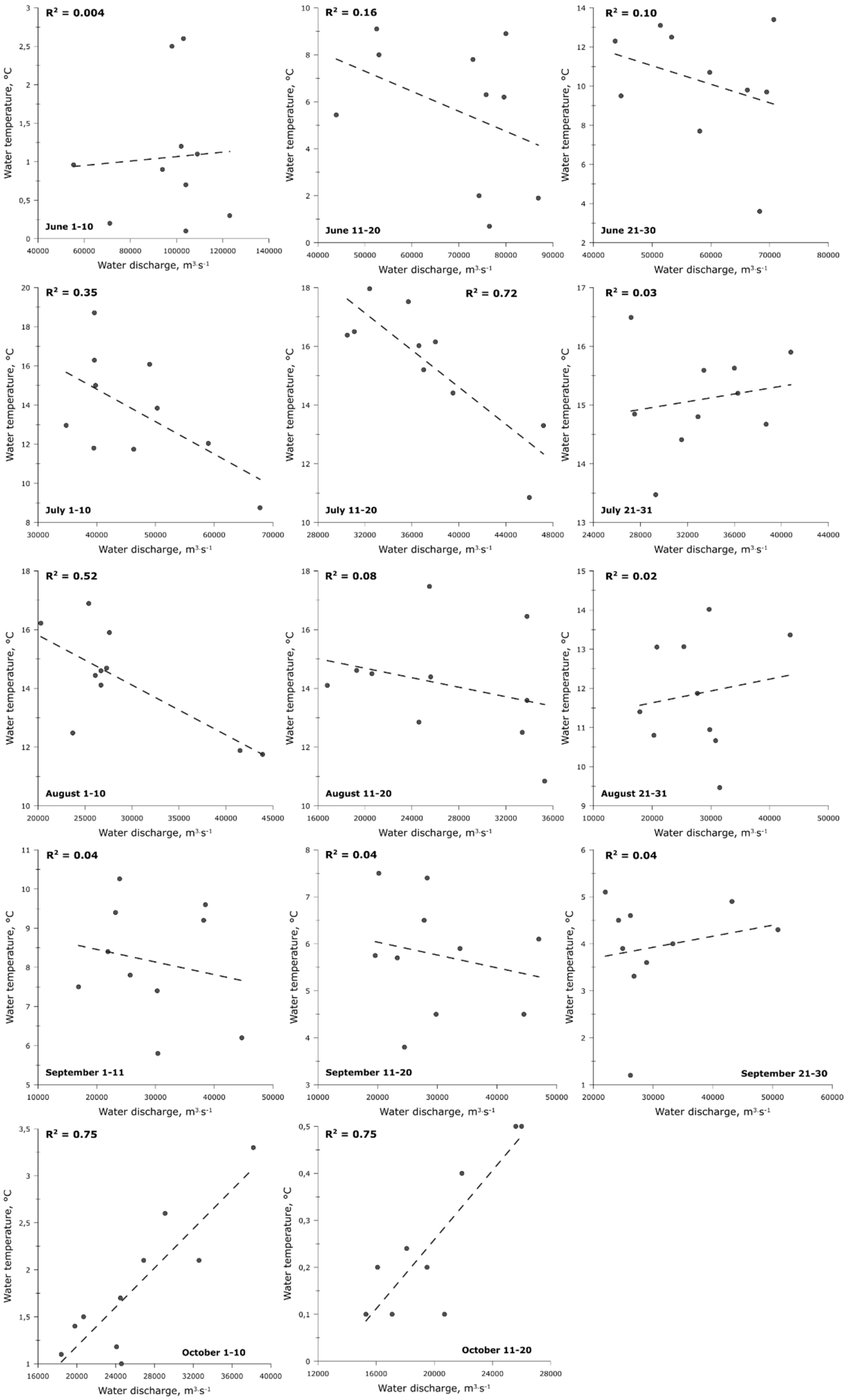

Fig. 8 The Lena R. water discharge related to 10-day average T_w, Kyusyur GS (2002-2011)

When water discharge and temperature are correlated, both are controlling heat flux. When no relation is observed, both fluctuate chaotically and none has a unique control on heat flux. However, two distinct periods with both Q-controlled and T_w-controlled heat flux emerge in our analysis. Temperature-controlled heat flux is observed throughout June, while most of the open-water period the Lena R. heat flux is discharge-controlled (Table 2).

Table 2

Discharge- vs water temperature-controlled heat flux periods, the Lena R. at Kyusyur

Period	**R^2, Q vs HF**	**R^2, T_w vs HF**	**Pattern**
June 1-10	0.04	**0.98**	T_w-controlled
June 11-20	$3 \cdot 10^{-5}$	**0.83**	T_w-controlled
June 21-30	0.07	**0.68**	T_w-controlled
July 1-10	0.15	0.24	
July 11-20	0.12	0.04	
July 21-31	**0.91**	0.22	Q-controlled
August 1-10	**0.80**	0.12	Q-controlled
August 11-20	**0.69**	0.08	Q-controlled
August 21-31	**0.85**	0.27	Q-controlled
September 1-10	**0.66**	0.16	Q-controlled
September 11-20	**0.72**	0.11	Q-controlled
September 21-30	**0.77**	**0.41**	
October 1-10	**0.86**	**0.96**	
October 11-20	**0.87**	**0.96**	

Values in **bold** are significant at $p < 0.01$

This apparent seasonality stems from this large river hydrology. During the freshet, water discharge is enormously high, occasionally exceeding 150 000 $m^3 \cdot s^{-1}$, and even slightly warmer water will produce disproportionally high HF response compared to other periods. From the end of July to late September, the variation in T_w decreases since the major heat source across the basin is solar radiation (see Fig. 2, right), and the amount of water takes over the total heat flux value for these periods.

This pattern has long-standing implications from the climate change perspective. We can assume that climate change effects on the Lena R. heat flux would be less significant if they will be related to: (a) water discharge increase in June, *e.g.* higher snow water equivalent during winter or higher rainfall around the freshet peak; (b) water temperature increase in August-September, *e.g.* persistent high pressure over central Yakutia or less impact from cooler mountainous rivers. In contrast, (c) an increase in June water temperature, associated with earlier onset of summer, or (d) rainfall runoff increase throughout July and August, caused by heavy rains in the Vitim and Olyokma R. basins, will lead to pronounced heat flux increase in Kyusyur and in the Lena Delta region. In all cases, runoff/temperature increase in October will lead to higher heat flux.

Cold water origin in the Lena R. channel

Thermal impact of minor tributaries, heat exchange with channel bottom, cooling influence of permafrost or stream circulation patterns may be deemed responsible for an observed negative temperature anomaly at the Kyusyur GS. Heat exchange with channel bottom is expected to be negligible, compared to total heat export of the Lena R., because of the presence of a talik, or an extensive non-frozen zone below the channel. Thermal regime of this talik zone is controlled by convective heat transfer of riverine waters

(Wankiewicz 1984), therefore only minor thermal influence on the near-bottom stream temperature is expected.

Permafrost is present in riverbanks as both frozen soil, ice wedges and massive ground ice, and its melting can potentially affect the stream temperature. During the low-flow period, permafrost meltwater drains to the main Lena R. channel as small springlets, potentially contributing to water temperature decrease. However, this influence might not extend more then by several meters from the shoreline because of modest volumetric contribution of these springlets to the total summer runoff.

The thermal effect of steady open-channel circulation near Kyusyur GS cannot be completely ruled out, but even if present, its influence is mostly indirect. The straight channel segment adjacent to Kyusyur GS (see Fig. 1, right) is an outer part of a Lena R. channel bend. A steady outer-bank circulation cell is expected to be present in the flow (Blanckaert & de Vriend 2004), inhibiting lateral mixing. Therefore, contrasting stream properties in the alongshore river section, including stream temperatures, are in part secured by this circulation cell. Lateral input from tributaries is expected to be 'locked' in this cell as long as this circulation pattern persists.

Previous modeling results (Fofonova *et al.* 2017) and our field observations strongly support the origin of the cold water jet along the right bank of the Lena R. from numerous minor right-bank tributaries (Fig. 1, right). While flow may cease during summer on smaller creeks, like the Yeremeyka R. with basin area of 9.7 km^2, the larger tributaries maintain their flow throughout the rain-free period. The thermal impact of these minor tributaries, already significant under low-flow conditions, may increase drastically during heavy rains in their basins. This effect was traced in the T_w data observed at Kyusyur GS, using daily discharge data from the Yeremeyka R. at Kyusyur, a gauging station at the outlet of a minor Lena R. tributary (see Fig. 3, left). In most cases, the T_w in Kyusyur drops significantly at the time of the flood peak at the Yeremeyka R., which in this analysis represents all minor right tributaries (Table 3). This effect is present at various Lena R. discharges, up to 78100 $m^3 \cdot s^{-1}$. It is less pronounced in September, and can exceed 2.5°C in July (Table 3). These data strongly support the origin of the cold near-bank water from numerous minor right-hand tributaries of the Lena R.

Table 3

Thermal effect of the rain flood peaks on the right-bank tributaries, represented by the Yeremeyka R., on the Lena R. T_w at Kyusyur GS, 2002-2011

Year	**Flood peak, Yeremeyka R.**		**Minimum T_w at Kyusyur**			
	Date	**Q, $m^3 \cdot s^{-1}$**	**Date**	**Q, $m^3 \cdot s^{-1}$**	**Min T_w, °C**	**Off-min T_w, °C (*)**
2002	29.07	2.34	31.07	35400	10.9	11.7
2003	29.07	1.26	30.07	32200	10.9	14.3
	08.09	3.14	09.09	25600	3.9	5.2
2004	30.08	1.22	01.09	30100	7.8	8.0
2005	30.08	1.09	01.09	46200	6.5	7.0
	19.09	0.66	22.09	35200	3.8	3.9
2006	24.07	1.58	24.07	34200	11.5	12.3
	06.08	1.25	06.08	26100	15.5	16.3
	18.09	0.74	–	–	–	–
2007	18.06	1.29	19.06	78100	8.3	9.8
	11.07	1.58	11.07	44400	8.6	11.6
	01.08	2.71	04.08	42300	10.7	11.8
2008	28.08	0.49	–	–	–	–
2009	04.09	0.74	04.09	30800	4.5	5.1
	09.09	0.74	09.09	31200	4.8	5.6

2010	28.06	0.73	–	–	–	–
	27.07	1.51	28.07	40200	14.9	15.2
	01.09	0.45	02.09	22500	10.6	10.8
2011	09.07	0.72	09.07	30000	12.3	13.4
	17.07	1.14	–	–	–	–
	27.07	0.68	29.07	25200	14.8	15.3

(*) Calculated as average T_w of the two days adjacent to the minimum T_w date in Kyusyur GS

The potential sources of this cold storm- and baseflow are numerous, snow and icings meltwater, and groundwater flow among the most important.

Snow cover in this High Arctic region normally decays by mid-June, but remnant snow patches may persist until late July and even to mid-August in shadowed valleys, adjacent to north-facing valley slopes and in the mountainous areas of the Verkhoyansk Range. Thermal impact of melting snow on water temperature during summer months is probably negligible, since meltwater from these snow patches is not directly connected to streamflow and has to travel through the floodplain, mostly in the active layer, to reach the nearby streams.

Icings are common permafrost hydrology features (Pinneker, 1990; Yoshikawa *et al.*, 2007). Normally, medium and large icings of the Verkhoyansk region completely decay by late August, and only the largest ones are capable of surviving one or more summers. Their contribution to river runoff may reach significant proportions, up to 12% of total basin discharge (Clark, Lauriol, 1997), particularly important during baseflow period, but also during heavy rainfall, when the flood wave leads to ice deterioration and decay. Cold icing water is directly connected to streams and may play a significant role in water cooling. Several typical icing fields in the Tikyan R. basin are detectable using satellite imagery.

Groundwater flow has minor influence on river runoff in the continuous permafrost regions, but the presence of icings confirms groundwater discharge in the valleys of minor Lena R. tributaries. Regional observations on groundwater temperature are absent, but most springs are reported to have water temperatures close to 0°C under similar conditions in northeastern Alaska (Kane *et al.*, 2013).

Implications for other Russian Arctic gauging stations

Our results show that local hydrology may interfere severely with the accuracy of routine stream temperature observations. To this end, data from the major Russian Arctic river outlets should be analysed for relevance. At the Yenisey R. outlet, stream temperature is observed at Igarka GS. This gauging station is situated on the right bank of the Igarskaya Branch, a large side channel receiving numerous tributaries upstream the GS cross-section. The Ob R. outlet is at Salekhard GS, where the gauging station is situated on the right bank of a secondary branch in a highly braded section. In theory, the data from these stations can also be biased and misrepresent the cross-section average T_w. If this is the case, then the total heat flux from the Russian Arctic rivers is undervalued, affecting the quality of ocean circulation model outputs.

Conclusions

This study confirms, with both published and field data, that stream temperature observations at Kyusyur GS are misrepresentative neither for midstream nor the cross-sectional average temperatures.

During our field survey, the water temperature at the observation point of Kyusyur GS, *ca.* 3 m from the river bank, was found to be by 0.85°C lower than midstream temperature, which is surprisingly close to previous modeling results (Fofonova *et al.*, 2017). Field data evidence the existence of a relatively cold-water jet extending at least 150 m from the right Lena R. bank toward midstream.

We conclude therefore that existing heat flux calculations for the Lena R. at Kyusyur are negatively biased. The thermal impact of numerous minor upstream tributaries is shown to be a major reason for this misrepresentation, and to increase during rain floods on these tributaries.

Revised Lena R. heat flux estimate, corrected for this negative bias, is 17.6 ± 2.8 $EJ \cdot a^{-1}$. From the upper bound, our estimate is constrained at 26.9 $EJ \cdot a^{-1}$, obtained using monthly-averaged T_w data from Zhigansk GS, ca. 500 km upstream Kyusyur. During most of the year, water discharge is controlling heat flux value, but in June, the latter is totally controlled by stream temperature.

Acknowledgements

This study is partially funded by Russian Fund for Basic Research, Project 17-05-00948 (hydrological analysis and heat flux calculations), Project 18-05-60240-ARCTIC (field investigations). The authors are grateful to Afanasiy Popov (technician, Kyusyur GS, Roshydromet) and other locals for the assistance in the 2018 fieldwork.

Author contributions. Conceptualization, methodology, investigation, formal analysis, writing – original draft, N.T.; Funding acquisition, conceptualization, investigation, A.G.; Resources, V.F.; Data curation, N.T. and V.F. All authors contributed to discussions, review and editing of the original draft.

References

Blanckaert K. & de Vriend H.J. (2004) Secondary flow in sharp open-channel bends, *J. Fluid Mech.* **498**, 353–380.

Clark I.D., Lauriol B. (1997) Aufeis of the Firth River basin, Northern Yukon, Canada: Insights into permafrost hydrogeology and karst, *Arctic and Alpine Res.* **29(2)**, 240–252.

Dmitrenko I.A., Kirillov S.A., Tremblay L.B., Bauch D. & Willmes S. (2009) Sea-ice production over the Laptev Sea shelf inferred from historical summer-to-winter hydrographic observations of 1960s-1990s, *Geophys. Res. Lett.* **36**, L13605, doi: 10.1029/2009GL038775.

Fofonova V., Zhilyaev I., Kraineva M., Iakshina D., Tananaev N., Volkova N., Sander L., Papenmeier S., Michaelis R. & Wiltshire K.H. (2017) Features of the water temperature long-term observations on the Lena River at basin outlet, *Polarforschung* **87(2)**, 135-150.

Francis J.A., White D.M., Cassano J.J., Gutovski Jr. W.J., Hinzman L.D., Holland M.M., Steele M.A. & Vörösmarty C.J. (2009) An arctic hydrologic system in transition: Feedbacks and impacts on terrestrial, marine, and human life, *J. Geophys. Res.* **114**, L04019, doi: 10.1029/2008JG000902.

Georgiadi A.G., Kashutina E.A. & Milyukova I.P. (2017) Long-term changes of water flow, water temperature and heat flux of the largest Siberian rivers, *Polarforschung* **87(2)**, 167-176.

Golubeva E., Platov G., Malakhova V., Iakshina D. & Kraineva M. (2015) Modeling the impact of the Lena River on the Laptev Sea summer hydrography and submarine permafrost state, *Bull. Nov. Comp. Center* **15**, 13-22.

Gutjahr O., Heinemann G., Preuβer A., Willmes S. & Drüe C. (2016) Quantification of ice production in Laptev Sea polynyas and its sensitivity to thin-ice parameterizations in a regional climate model, *The Cryosphere* **10**, 2999–3019.

Holmes R.M., McClelland J.W., Tank S.E., Spencer R.G.M. & Shiklomanov A.I. (2018) Arctic Great Rivers Observatory. Water Quality Dataset. Version 20181010. https://www.arcticgreatrivers.org/data

Huntley D.A., Leeks G.J.L. & Walling D. (2009) From rivers to coastal seas: the background and context of the land-ocean interaction study. In: Land-Ocean Interaction (Huntley D.A., Leeks G.J.L., Walling D., eds), IWA Publ. House, London, UK, pp. 1-8.

Kane D.L., Yoshikawa K. & McNamara J.P. (2013) Regional groundwater flow in an area mapped as continuous permafrost, NE Alaska (USA), *Hydrogeology J.*, **21(1)**, 41-52.

Kirillov S.A. (2006) Spatial variation in sea-ice formation-onset in the Laptev Sea as a consequence of the vertical heat fluxes caused by internal waves overturning, *Polarforschung* **76(3)**, 119-123.

Lammers R.B., Pundsack J.W. & Shiklomanov A. (2007) Variability in river temperature, discharge and energy flux from the Russian pan-Arctic landmass, *J. Geophys. Res.* **112**, G04S59, doi: 10.1029/2006JG000370.

Liu B., Yang D. (2011) Siberian Lena River heat flow regime and change, IAHS Publ. 346, 71-76.

Magritsky D.V. (2016) Factors and trends of the long-term fluctuations of water, sediment and heat runoff in the lower reaches of the Lena River and the Vilyui River, *Bull. Moscow State University, Series 5 Geography*, **No. 6**, 85–94 (in Russian).

Magritsky D., Alexeevsky N., Aybulatov D., Fofonova V. & Gorelkin A. (2017) Features and evaluations of spatial and temporal changes of water runoff, sediment yield and heat flux in the Lena River delta, *Polarforschung* **87(2)**, 89-110.

Mangiafico S. (2019) 'rcompanion': Functions to support extension education program evaluation.

Nummelin A., Ilicak M., Li C. & Smedsrud S.H. (2016) Consequences of future increased Arctic runoff on Arctic Ocean stratification, circulation and sea ice cover, *J. Geophys. Res.* **121(1)**, 617-637.

Park H., Yoshikawa Y., Yang D. & Oshima K. (2017) Warming water in Arctic terrestrial rivers under climate change, *J. Hydromet.* **18(7)**, 1983-1995.

Pinneker Ye.V. (1990) Groundwater monitoring and management in permafrost areas, IAHS Publ. 173, 39-44.

Reinberg A.M. (1938): Hydrology of Soviet Arctic Rivers: Hydrology information about Lena, Ebitiem, Indigirka, Hatanga, Yenisei and Kolyma Rivers. *Proceed. Arctic Antarctic Res. Institute* **105**, 51-72 (in Russian).

RStudio: Integrated Development Environment for R (version 1.1.447). Computer Software, Boston, VA, USA (Retrieved 1 April 2019).

St. Jacques, J. M., Sauchyn D.J. (2009), Increasing winter baseflow and mean annual streamflow from possible permafrost thawing in the Northwest Territories, Canada, *Geophys. Res. Lett.* **36(1)**, L01401, doi: 10.1029/2008GL035822.

van Vliet M.T.H., Franssen W.H.P., Yearsley J.R., Ludwig F., Haddeland I., Lettenmaier D.P. & Kabat P. (2013) Global river discharge and water temperature under climate change, *Glob Environ Change* **23(2)**, 450-464, doi: 10.1016/j.gloenvcha.2012.11.002.

Wankiewicz A. (1984) Hydrothermal processes beneath Arctic river channels, *Wat. Resour. Res.* **20(10)**, 1417–1426.

Yang D., Liu B. & Ye B. (2005) Stream temperature changes over Lena River Basin in Siberia, *Geophys Res Lett* **32(5)**, L05401, doi: 10.1029/2004GL021568.

Yang D., Marsh P. & Ge S. (2014) Heat flux calculations for Mackenzie and Yukon Rivers, *Polar Science* **8(3)**, 232-241, doi: 10.1016/j.polar.2014.05.001.

Yang, D., X. Shi & Marsh P. (2015), Variability and extreme of Mackenzie River daily discharge during 1973–2011, *Quat. Int.,* **380–381**, 159–168, doi: 10.1016/j.quaint.2014.09.023.

Yoshikawa K.; Hinzman L.D. & Kane D.L. (2007) Springs and aufeis (icing) hydrology in Brooks Range, Alaska, *J. Geophys. Res.* **112**, G04S43, doi:10.1029/2006JG000294.

Zhang T., Barry R.G., Knowles K., Heginbottom G.A. & Brown J. (1999) Statistics and characteristics of permafrost and ground-ice distribution in the Northern Hemisphere, *Polar Geogr.* **23(2)**, 132-154.