

Revising contemporary heat flux estimates for the Lena River, Northern Eurasia

N. I. Tananaev, A. G. Georgiadi and V. V. Fofonova

ABSTRACT

The Lena River (Lena R.) 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 the 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 T_w negative peaks mostly coincide with flood peaks on the Yeremeyka River, 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, approximately 500 km upstream Kyusyur. Heat flux is controlled by stream temperature in June, during the freshet period, while from late July to mid-September, water runoff is a dominant factor.

Key words | heat flux, Lena River, permafrost hydrology, Russian Arctic, stream temperature

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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 the 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 a hydrologic and thermal regime under a contemporary climate change (van Vliet *et al.* 2013; Park *et al.* 2017). Recently, numerous studies have been focusing on a 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 River (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 the 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 the averaging bias. Moreover, multiple concerns were expressed since the 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 approximately 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 $16.59 \text{ EJ}\cdot\text{a}^{-1}$ to account for potential negative bias in the Kyusyur GS T_w data, but this $1.0 \text{ EJ}\cdot\text{a}^{-1}$ 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 the 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 re-evaluated based on daily T_w values and several thermal regime scenarios, and is constrained from the top with the heat flux estimate at Zhigansk GS, approximately 500 km upstream Kyusyur.

Study site

The Lena R., with the basin area at the outlet approximately $2.43 \times 10^6 \text{ km}^2$, 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 (Figure 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).

Long-term hydrological monitoring at the Lena R. outlet is performed at Kyusyur, a gauging station operated by the Russian Hydrometeorological Agency (Roshydromet) from 1935 to the present (Figure 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 (Figure 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 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 the Tiksi Branch of Yakutian Hydrometeorological Centre, the 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; and (c) revise contemporary heat flux estimates.

On the Roshydromet network, T_w is measured twice daily at 8 am and 8 pm, 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 5 min and 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

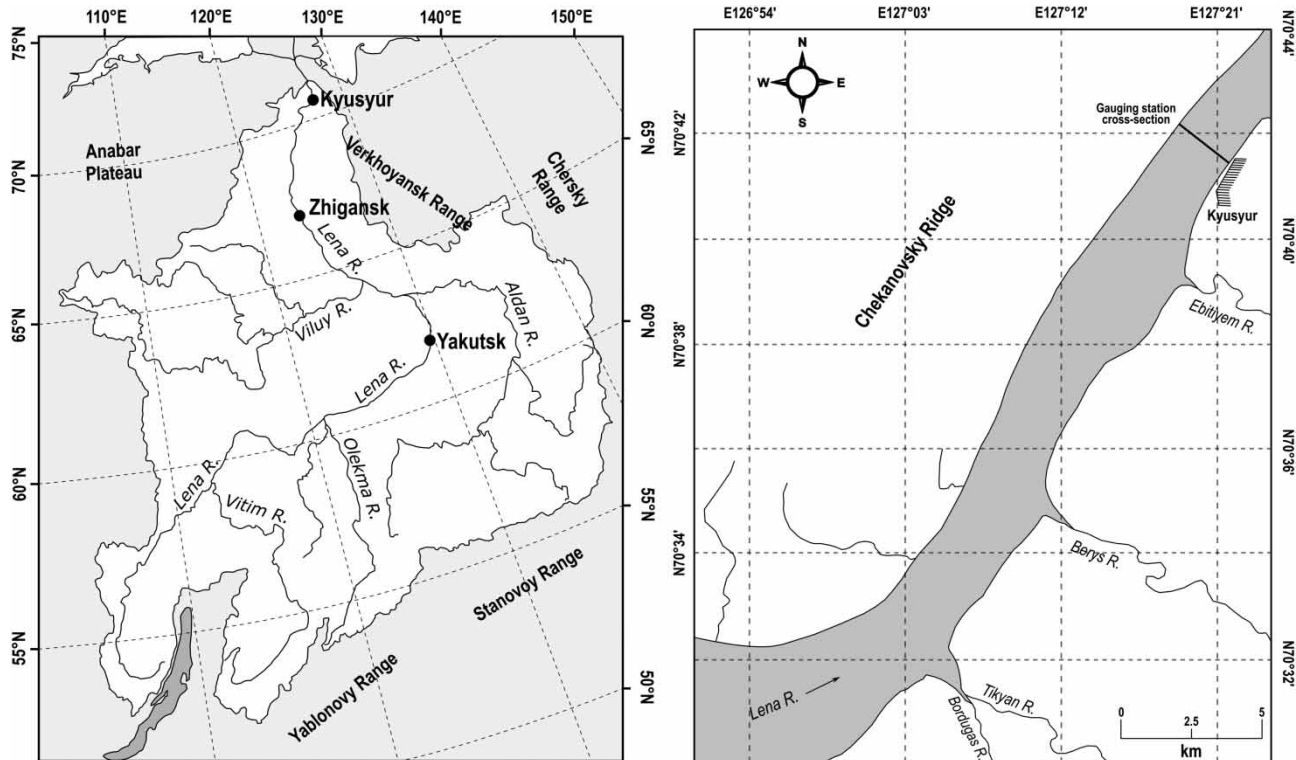


Figure 1 | The Lena R. basin (left) and Kyusyur GS location within the Lena R. valley (right).

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, approximately 500 km upstream of 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 River (Yeremeyka R.) at Kyusyur, provided by the 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 8 am and 8 pm 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 the specific heat of water and is generally a variable with temperature but kept constant at $4,186 \text{ J} \cdot \text{kg}^{-1} \cdot \text{K}^{-1}$ throughout this study; ρ is water density of about $1,000 \text{ kg} \cdot \text{m}^{-3}$; Q is water discharge, $\text{m}^3 \cdot \text{s}^{-1}$; T_w is stream temperature, °C; n is the number of days in the calculation interval; $t = 86,400 \text{ s}$ 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 R. 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 River (Ebitiyem R) mouth to the Lena R. right bank (Figure 1, right).

RESULTS

The Lena R. 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 m³·s⁻¹ (Figure 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.

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 (Figure 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; Lammers et al. 2007; Georgiadi et al. 2017; Magritsky et al. 2017). Here, the daily T_w dataset is used in calculations along with 10-day averages; Equation (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 $16.4 ± 2.7 \text{ EJ} \cdot \text{a}^{-1}$. This is substantially higher than previous estimates and is close to the 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

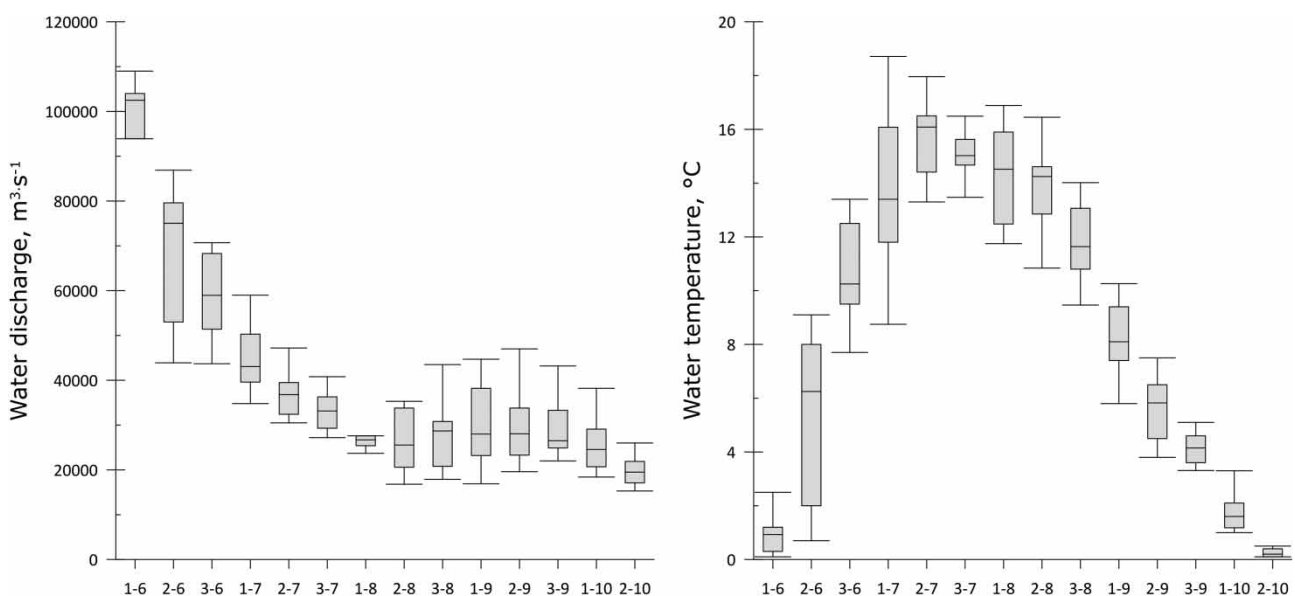


Figure 2 | Water discharge and stream temperature of the Lena R. at Kyusyur by 10-day periods. On the x-axis, 10-day period numbers and months, separated by a hyphen. Boxplots mark median, 25% and 75% quartiles, and whiskers match interquartile range $\times 1.5$.

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 7–10 m of the water column, evidencing strong turbulent mixing in the cross-section, except observation points adjacent to riverbanks (Table 1, Figure 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 (Figure 3, right).

In the lateral direction, lower temperature values were observed near the banks of the Lena R. Midstream water temperature were around 17.9–18.0 °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 the channel bottom and cooling influence of permafrost or stream circulation patterns may be deemed responsible for these anomalies.

Numerous minor mountainous tributaries drain to the Lena R. along the right bank of the river (see Figure 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 the longitudinal gradient in water temperature around the mouth zone of such tributaries. The closest tributary upstream

from Kyusyur is the Yeremeyka R. (Figure 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 approximately 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 (Figure 4).

Upstream of the tributary mouth, water was already cooler than at midstream, approximately 17.4 °C, and a further decrease down to 17.2 °C corresponds to the tributary inflow. This pattern continues toward the gauging station where water temperature drops further to 17.1 °C (Figure 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 the midstream and the near-bank, ΔT_w , reaching 0.85 °C. Discharge-weighted, cross-sectional average T_w is not expected to be significantly lower than the midstream, since ‘colder’ channel sections adjacent to riverbanks are relatively shallow and have lower velocity. Detailed seasonal surveys are 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 evidence 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.

Table 1 | Water temperature of the Lena R. at transects in the Kyusyur GS cross-section (see Figure 3 for spatial reference; observation date: 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

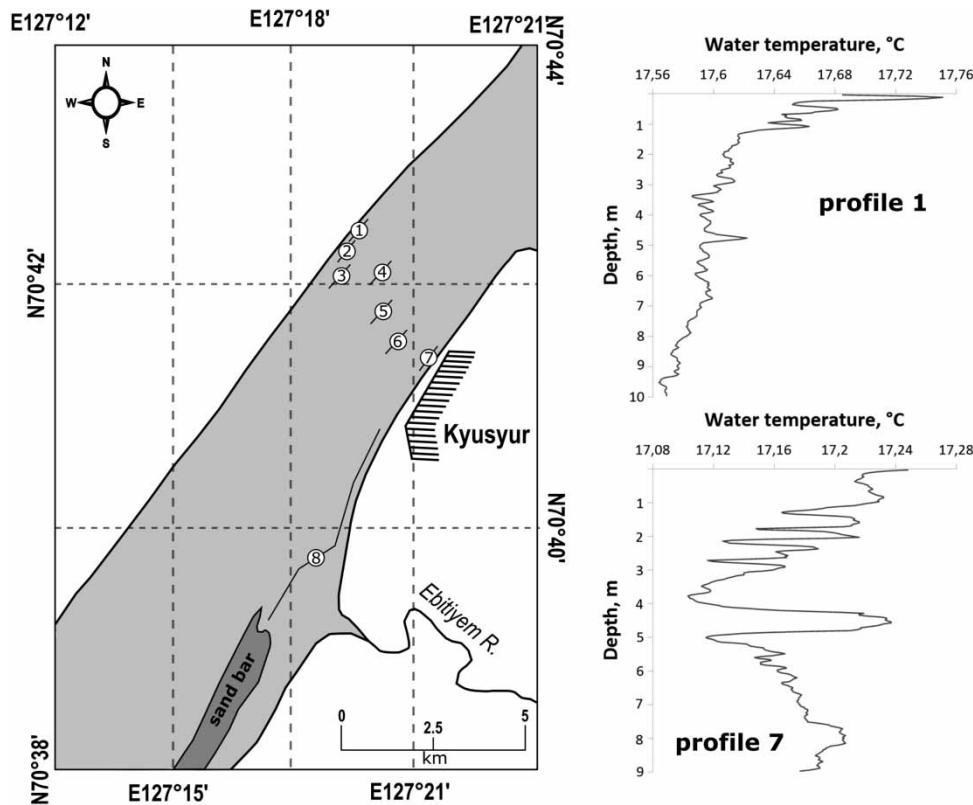


Figure 3 | Water temperature observation points near Kyusyur GS (left), vertical temperature profiles at near-bank transects (right).

Scenario 1: $\Delta T_w = +0.8^\circ\text{C}$ 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, Figure 9(a))

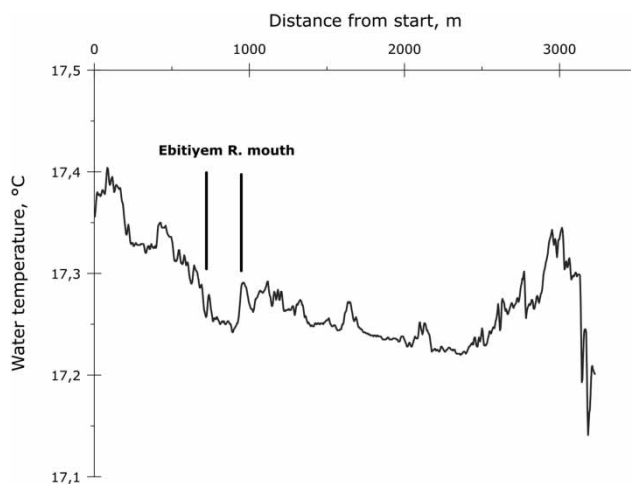


Figure 4 | The Lena R. surface water temperature along the Transect 8. See Figure 3, right, for reference.

and is surprisingly close to our field results. This correction increases the Lena R. heat flux to $17.3 \pm 2.8 \text{ EJ}\cdot\text{a}^{-1}$ (2002–2011), i.e. by 5% compared to an uncorrected value.

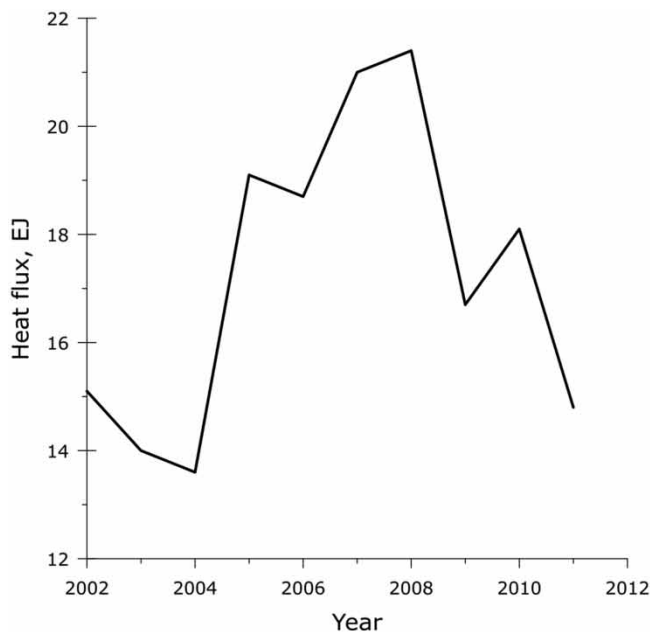
Scenario 2: It is based on the previous scenario, but accounts for extreme temperature gradients that could be observed throughout the open-water period. Simulated daily ΔT_w values were up to $+3.0^\circ\text{C}$ in July 2011 and August 2007 and up to $+5^\circ\text{C}$ in September 2003 on certain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

Monthly ΔT_w variation scenarios were formulated as follows: allowing temperature anomalies in 1 of 3 months (Cases 2–4), 2 (Cases 5–7) or in all 3 months (Case 8):

1. July–September, $\Delta T_w = +0.8^\circ\text{C}$, same as Scenario 1;
2. July, $\Delta T_w = +2.0^\circ\text{C}$; August–September, $\Delta T_w = +0.8^\circ\text{C}$;
3. July and September, $\Delta T_w = +0.8^\circ\text{C}$; August, $\Delta T_w = +2.0^\circ\text{C}$;
4. July and August, $\Delta T_w = +0.8^\circ\text{C}$; September, $\Delta T_w = +3.0^\circ\text{C}$;

5. July and August, $\Delta T_w = +2.0$ °C; September, $\Delta T_w = +0.8$ °C;
6. July, $\Delta T_w = +2.0$ °C; August, $\Delta T_w = +0.8$ °C; September, $\Delta T_w = +3.0$ °C;
7. July, $\Delta T_w = +0.8$ °C; August, $\Delta T_w = +2.0$ °C; September, $\Delta T_w = +3.0$ °C;
8. July and August, $\Delta T_w = +2.0$ °C; September, $\Delta T_w = +3.0$ °C.

These distributions have differing frequencies of occurrence, or return periods, which are unknown for the 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 1,000 years, as per joint probability calculation rules. Case 1 takes what is left, or 889 years out of 1,000. Heat fluxes were calculated for each year of record and for each case, then this dataset was bootstrapped with the number of permutations $n = 10,000$ accounting for frequencies of occurrence. Revised contemporary mean annual Lena R. heat flux is estimated at $17.6 \pm 2.8 \text{ EJ}\cdot\text{a}^{-1}$ (2002–2011; Figure 5), corrected for ΔT_w extremes and accounted for their return periods.



The Lena R. heat flux appears to vary highly across years (Figure 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 values 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 $16.4 \text{ EJ}\cdot\text{a}^{-1}$, 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

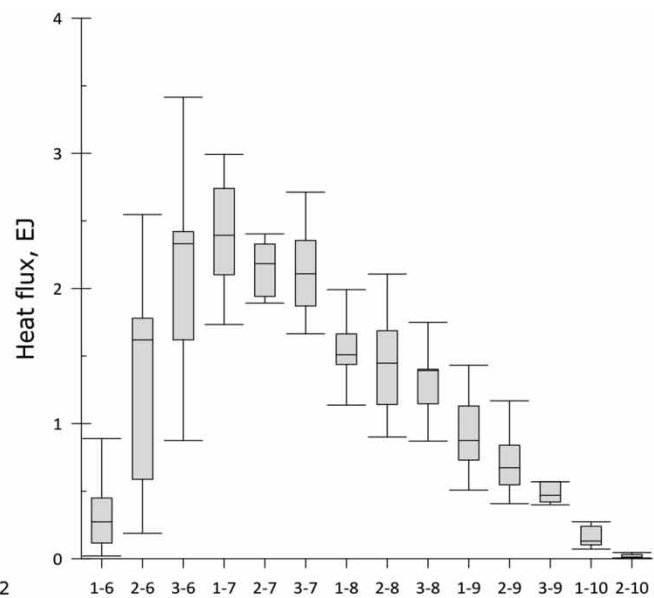


Figure 5 | Revised annual Lena R. heat flux, 2002–2011, and its distribution across 10-day periods. On x-axis, 10-day period numbers and months, separated by a hyphen. Boxplot marks median, 25% and 75% quartiles, and whiskers match interquartile range $\times 1.5$.

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 (Figure 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 the 2002–2011 period were used in calculations.

Mean annual heat flux at Zhigansk GS equals $26.9 \text{ EJ}\cdot\text{a}^{-1}$ (2003–2011) 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 the zero level as water travels from Zhigansk to Kyusyur.

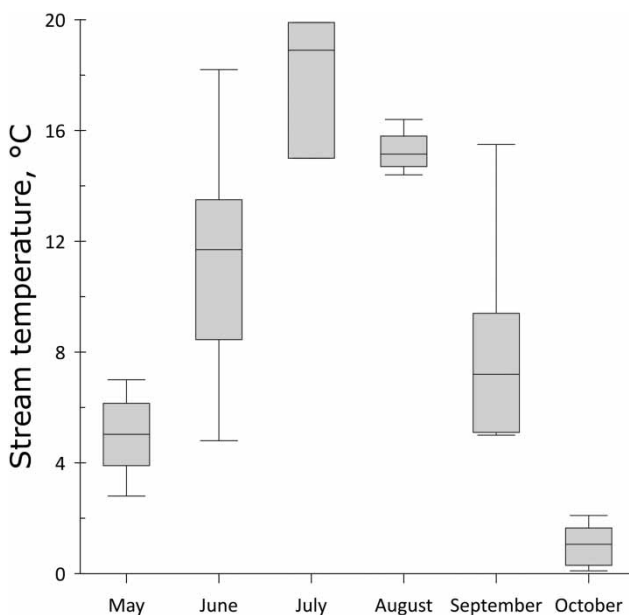


Figure 6 | Mean monthly stream temperature, the Lena R. at Zhigansk GS, ArcticGRO data (Holmes et al. 2018).

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 (Figure 7). The following linear equation describes this relation ($r = 0.84$, $p < 0.01$):

$$\text{HF} = 0.0315 \cdot W_Q - 1.28 \quad (2)$$

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

However, at the 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 (Figure 8). Notable exceptions include early and mid-July, when T_w is decreasing with a higher Q value ($R^2 = 0.35 \dots 0.72$) 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

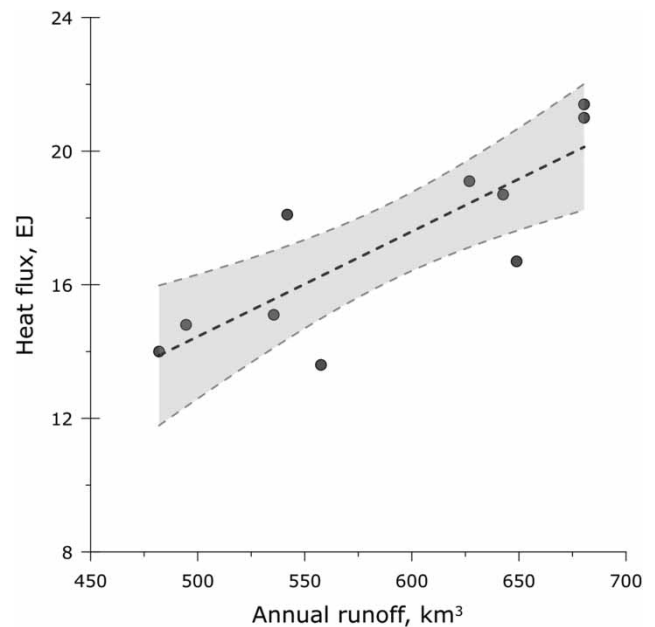


Figure 7 | The Lena R. annual heat flux related to annual runoff at Kyusyur GS, 2002–2011.

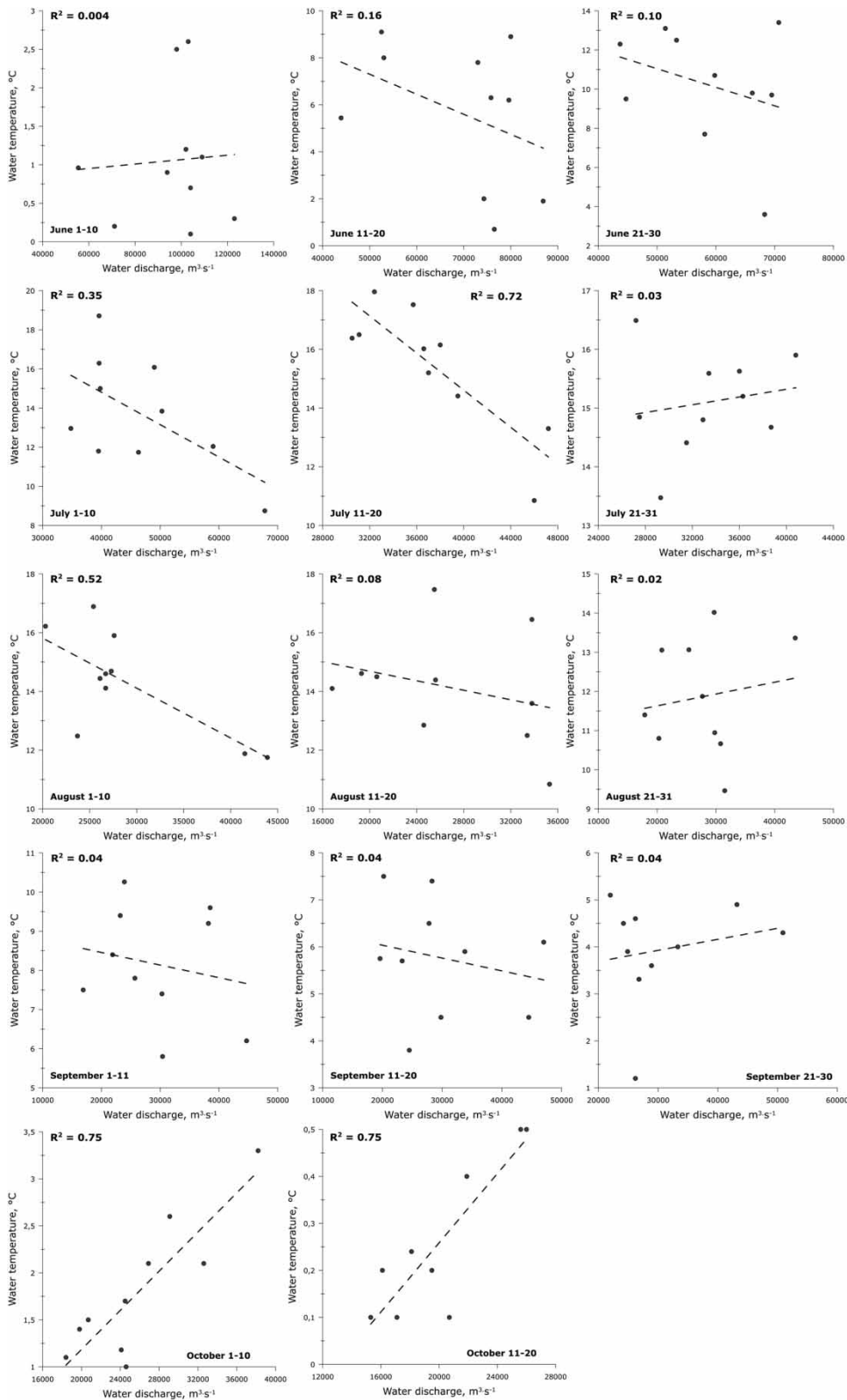


Figure 8 | The Lena R. water discharge related to 10-day average T_w , Kyusyur GS (2002–2011).

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 2,000 km descent to Kyusyur. Hence, closer sources are to be thought of. The Vilyui River 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 (Figure 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 of 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 that 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 as an important heat source, as previously suggested by Fofonova et al. (2017), though never assessed directly.

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).

This apparent seasonality stems from this large river hydrology. During the freshet, water discharge is enormously high, occasionally exceeding $150,000 \text{ m}^3 \text{ s}^{-1}$, and even slightly warmer water will produce a disproportionately 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 Figure 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

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	3×10^{-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 $p < 0.01$.

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 water temperature in June, associated with the earlier onset of summer, or (d) rainfall runoff increase throughout July and August, caused by heavy rains in the Vitim and Olyokma River basins, will lead to a pronounced heat flux increase in Kyusyur and in the Lena Delta region. In all cases, a 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 the 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 the channel bottom is expected to be negligible, compared to the total heat export of the Lena R., because of the presence of a talik or an extensive non-frozen zone below the channel. The thermal regime of this talik zone is controlled by the 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 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 a water temperature decrease. However, this influence might not extend more than 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 Figure 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 (Figure 1, right). While flow may cease during summer on smaller creeks, like the Yeremeyka R. with the basin area of 9.7 km², 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 Figure 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 78,100 m³·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.

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

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 ·s ⁻¹	Date	Q , m ³ ·s ⁻¹	Minimum T_w , °C	Off-min T_w , °C ^a
2002	29.07	2.34	31.07	35,400	10.9	11.7
2003	29.07	1.26	30.07	32,200	10.9	14.3
	08.09	3.14	09.09	25,600	3.9	5.2
2004	30.08	1.22	01.09	30,100	7.8	8.0
2005	30.08	1.09	01.09	46,200	6.5	7.0
	19.09	0.66	22.09	35,200	3.8	3.9
2006	24.07	1.58	24.07	34,200	11.5	12.3
	06.08	1.25	06.08	26,100	15.5	16.3
	18.09	0.74	–	–	–	–
2007	18.06	1.29	19.06	78,100	8.3	9.8
	11.07	1.58	11.07	44,400	8.6	11.6
	01.08	2.71	04.08	42,300	10.7	11.8
2008	28.08	0.49	–	–	–	–
2009	04.09	0.74	04.09	30,800	4.5	5.1
	09.09	0.74	09.09	31,200	4.8	5.6
2010	28.06	0.73	–	–	–	–
	27.07	1.51	28.07	40,200	14.9	15.2
	01.09	0.45	02.09	22,500	10.6	10.8
2011	09.07	0.72	09.07	30,000	12.3	13.4
	17.07	1.14	–	–	–	–
	27.07	0.68	29.07	25,200	14.8	15.3

^aCalculated as average T_w of the 2 days adjacent to the minimum T_w date in Kyusyur GS.

important during the 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 analyzed 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, approximately 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 indicate

the existence of a relatively cold water jet extending at least 150 m from the right Lena R. bank toward the 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 $17.6 \pm 2.8 \text{ EJ}\cdot\text{a}^{-1}$. From the upper bound, our estimate is constrained at $26.9 \text{ EJ}\cdot\text{a}^{-1}$, obtained using monthly averaged T_w data from Zhigansk GS, approximately 500 km upstream Kyusyur. During most of the year, water discharge is controlling a heat flux value, but in June, the latter is totally controlled by stream temperature.

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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 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., Preußer, 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. *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. Available from: <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* (D. A. Huntley, G. J. L. Leeks & D. Walling, eds). IWA Publishing, 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). *Hydrogeol. 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. *Cold Region Hydrology in a Changing Climate*. In: *Proceedings of Symposium H02 Held during IUGG2011*, July, Melbourne, Australia. IAHS Publ. 346, pp. 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. S. 2019 ‘rcompanion’: Functions to Support Extension Education Program Evaluation, ver. 2.1.7, <https://cran.r-project.org/package=rcompanion> (published 8 April 2019).
- 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, Y. V. 1990 Groundwater monitoring and management in permafrost areas. In: *Groundwater Monitoring and Management, Proceedings of the Dresden Symposium*, March. IAHS Publication No. 173, pp. 39–44.
- Reinberg, A. M. 1938 Hydrology of Soviet Arctic Rivers: hydrology information about Lena, Ebitiem, Indigirka, Hatanga, Yenisei and Kolyma Rivers. *Proc. Arctic Antarctic Res. Inst.* **105**, 51–72 (in Russian).
- RStudio 2019 *Integrated Development Environment for R (Version 1.1.447)*. Computer Software, Boston, VA, USA.
- 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.
- Tananaev, N., Makarieva, O. & Lebedeva, L. 2016 Trends in annual and extreme flows in the Lena River basin, Northern Eurasia. *Geophys. Res. Lett.* **43**, 10764–10772. doi: 10.1002/2016GL070796.
- 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. *Water 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 Sci.* **8** (3), 232–241. doi:10.1016/j.polar.2014.05.001.
- Yang, D., Shi, X. & 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.