Cold Region Hydrology in a Changing Climate (Proceedings of symposium H02 held during IUGG2011 in Melbourne, Australia, July 2011) (IAHS Publ. 346, 2011).

Siberian Lena River heat flow regime and change

BAOZHONG LIU[1] **& DAQING YANG**[2]

1 *Water and Environmental Research Center, University of Alaska Fairbanks, Fairbanks, Alaska 99775, USA*
2 *National Hydrology Research Center (NHRC), 11 Innovation Boulevard, Saskatoon S7N 3H5, Canada*
daqing.yang@ec.gc.ca

Abstract Heat flow, as a synthetic measure of discharge and water temperature, is useful to define the characteristics of a watershed's response to climate change. In this research, based on monthly discharge and water temperature data collected during 1950–1990, we defined the heat flow regime and quantified its change over the Lena watershed. Results show that near the Lena basin outlet, stream temperature is the dominant factor for the seasonal maximum heat flow in July. Trend analysis shows that the Lena River heat flow in June increased by 888 HU (41%) during 1950–1990 due to the stream temperature increase. This result may indicate a greater thermal impact of the Lena River on the local ecology over the Lena delta and on the land-fast sea-ice of the Laptev Sea.

Key words Lena River, Siberia; heat flow regime and change

1 INTRODUCTION

River discharge and water temperature are two major measures for characterizing a watershed undergoing climate change in terms of mass and energy, respectively. The water cycle that involves the ground, surface and atmosphere is essentially driven by energy. Thus, there is a need to combine mass and energy to investigate watershed response to climate change. Heat flow is not a new hydrological term; Mackay & Mackay (1975) mathematically defined it as a function of discharge and water temperature, and furthermore, they defined the mean open season river heat flow regimes at the Fort Providence and Fort Norman in the Mackenzie River basin. Elshin (1981) calculated the heat runoff (heat flow) for rivers in the European part of the former USSR.

Studies showed that Lena River runoff has experienced significant changes, i.e. an increase in winter, spring, and summer seasons, and a decrease in the autumn season, in the past few decades due to climate change and human activities (Yang *et al.*, 2002; Ye *et al.*, 2003). In addition, Yang *et al.* (2005) reported that the Siberian Lena watershed has experienced a basin-wide stream temperature rise in the early warm season during 1950–1992. From a perspective of the Earth system in which the hydrological cycle involves processes in and between the atmosphere, ground surface, and underground, the streamflow and water temperature changes demonstrate the responses of the permafrost-underlain Siberian Lena watershed to climatic fluctuations in terms of mass and energy. Thus, the heat flow regime and change are of great significance for understanding hydrological responses to climate change over the northern regions.

In this study, based on long-term (1950–1990) Lena River discharge and stream temperature data, we define the heat flow seasonality, interannual variability, and examine the long-term changes of the heat flow over the Lena basin as a whole. The purpose of this research is to present a new perspective regarding how large Arctic watersheds respond to climate change.

2 METHODS, DATA AND BASIN DESCRIPTION

The total heat flow in a given month is calculated for the open water season (May to October) using the following equation (Elshin, 1981):

$$H = kQTn \qquad (k = c_1 c_2 c_3 = 0.3615) \tag{1}$$

where, H is the monthly total heat transported by a river in a given month (10^6 MJ); k is a constant, 0.3615 (10^6 MJ·s/(m^3 day °C)); Q is discharge (m^3/s); T is stream temperature (°C); and n is number of open water days in a given month; c_1 is specific heat of water, 4.184 J/(g °C); c_2 is a conversion coefficient for discharge, 10^6 g/m^3; c_3 is conversion coefficient for time, 88 400 s/day.

As the magnitude of the heat flow is very large for some months, we define 10^9 MJ/month as a heat unit (HU). The heat flow in the cold season (November to April) is negligible because the stream temperature is usually very close to 0°C when the river is ice-covered. In the calculation of heat flow, the number of open water days (n) for June to September is 30 or 31, and for May and October is 10 and 20, respectively. This is a conservative means to avoid potential overestimation of the heat flow calculation in May and October, because the river usually opens in mid May and freezes in late October.

Discharge data are available from the R-ArcticNet (v. 2.0) (a database of pan-Arctic river discharge, www.r-arcticnet.sr.unh.edu/main.html). Yang *et al.* (2005) have reported the source, method of observation, and quality of stream temperature data. The raw stream temperature data were measured three times a month (10th, 20th, and 30th). To derive the monthly mean stream temperature, we averaged different combinations of the water temperature measurements, for instance, averaging the 10th, 20th, and 30th day records in a month, averaging the 30th day of the previous month and the other three records in the month, or just averaging the 10th and 20th days. Finally, we selected the last method to estimate the monthly mean stream temperature. The estimate made by this approach is closer to the value in mid month, which is representative and conservative. This approach can be consistently applied to each month, including May and October. In data processing, when one of the 10th and 20th measurements is missing, we use a long-term mean value to fill the gap. If both records are missing, the monthly mean stream temperature in that year will be taken as a missing record.

The Lena River is one of the largest rivers in the Arctic. It originates from the Baikal Mountains in the south central Siberian Plateau and flows northeast and north, emptying into the Arctic Ocean via the Laptev Sea (Fig. 1). The drainage area of the Lena basin is about 2 430 000 km^2, approximately 78–93% of which is underlain by permafrost (Zhang *et al.*, 1999). The Lena River contributes 524 km^3 of freshwater per year, or about 15% of the total freshwater into the Arctic Ocean (Prowse & Flegg, 2000; Shiklomanov *et al.*, 2000). The drainage is covered mainly by forest (84%), shrub (9%), grassland (3%), cropland (2%), and wetland (1%) (Revenga *et al.*, 1998). The basin's total population is about 2.3 million people, with one city (Yakutsk) having a population of more than 270 000. Compared with other large Siberian rivers, such as the

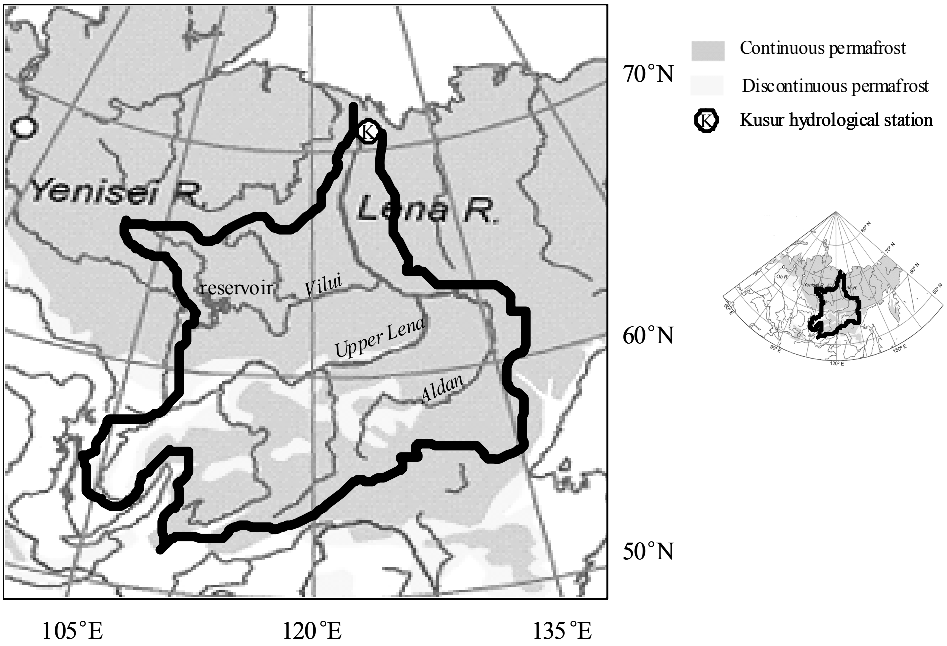

Fig. 1 The Lena watershed in Siberia. Also shown are permafrost distribution, major tributaries, basin boundaries, and the Kusur hydrologic station near the basin outlet.

Ob and Yenisei, the Lena basin has less human activity and much less economic development (Dynesius & Nilsson, 1994). There is only one large reservoir (capacity greater than 25 km^3), in west Lena basin, which was built during the late 1960s.

This study examines the response of the Lena basin as a whole to the climate change, thus data near the basin outlet are used (Fig. 1). Technically, we use the long-term mean and standard deviation to define the regime and interannual variation, and carry out trend analysis to identify a total change ("trend" in this paper) during a period by linear regression (Ye *et al.*, 2003). The standard *t*-test is used to indicate the statistical significance (or confidence level) of trend. In terms of confidence level, in this study we regard over 90% confidence as "significant", 60–89% as "considerable", and lower than 59% as "weak". Percentage of change (total trend to long-term mean) is also used to indicate the degree of change.

3 DATA ANALYSES AND RESULTS

3.1 Discharge

The seasonal cycle of monthly discharge near the Lena basin outlet (station K in Fig. 1) is presented in Fig. 2(a). It generally shows a low-flow (1378–3522 m^3/s) period during November to April and a high-flow (6392–74 657 m^3/s) season from June to October, with maximum discharge usually occurring in June due to snowmelt floods. Generally, watersheds with a high percentage of permafrost coverage have low subsurface storage capacity and thus a low winter baseflow, and a high summer peak flow (Kane, 1997). In the Lena River basin, which is mostly underlain by continuous permafrost (78–93%), the peak flow in June is about 54 times the lowest discharge in April and about 12 times the May runoff. The streamflow in July sharply drops to 55% of the June peak flow. Streamflow drops slowly to about 13 586 m^3/s in October due to less rainfall. The runoff in November and December (3522 and 3008 m^3/s, respectively) is relatively larger than that in January to April (1378–2814 m^3/s). The interannual variation of monthly runoff near the Lena River outlet is generally small in the cold season (standard deviation around 428–829 m^3/s), and large (standard deviation between 3314 and 10 390 m^3/s) in the warm season.

Trend analysis of monthly discharge records near the Lena basin outlet reveals a discharge increase during most months (Fig. 2(a)). Discharge increases over the period 1950–1990 are found of between 747 and 1009 m^3/s (21–73%) during November to April. These positive changes are statistically significant at a 92–99% confidence level. Strong streamflow increase near the Lena River outlet is found to be about 9280 m^3/s (145%) in May, which is statistically significant at the 99% confidence level. A weak discharge decrease is found of about 4600 m^3/s in June, but is statistically insignificant (59% confidence level). The negative trend in June is a reasonable consequence of the strong runoff increase in May due to earlier snow cover melt. Weak discharge increases are found, about 2078 m^3/s (5%) in July, about 1825 m^3/s (7%) in August, and about 484 m^3/s (2%) in September. These positive changes are statistically insignificant (below 39% confidence level). The streamflow decrease is found to be very weak in October (about –137 m^3/s, 1%), and statistically insignificant (6% confidence level). As the result of the monthly streamflow changes, yearly mean discharge shows a considerable (75% confidence level) upward trend, 1266 m^3/s (or 8%) over the period 1950–1990.

3.2 Stream temperature

The seasonal cycle of monthly stream temperature near the Lena basin outlet (Fig. 1) shows an extended ice-covered period from November to May, and an open water period from June to October (2.7–13.5°C), with higher stream temperature in both July and August (Fig. 2(b)). According to the original stream temperature measurements as taken every ten days, stream temperature records on 30 May near the Lena basin outlet are not available during 1950–1966, while mostly available during 1967–1990. The available stream temperature measurements for 30 May are usually very low (around 0.1°C), thus we count May as part of the ice-covered period.

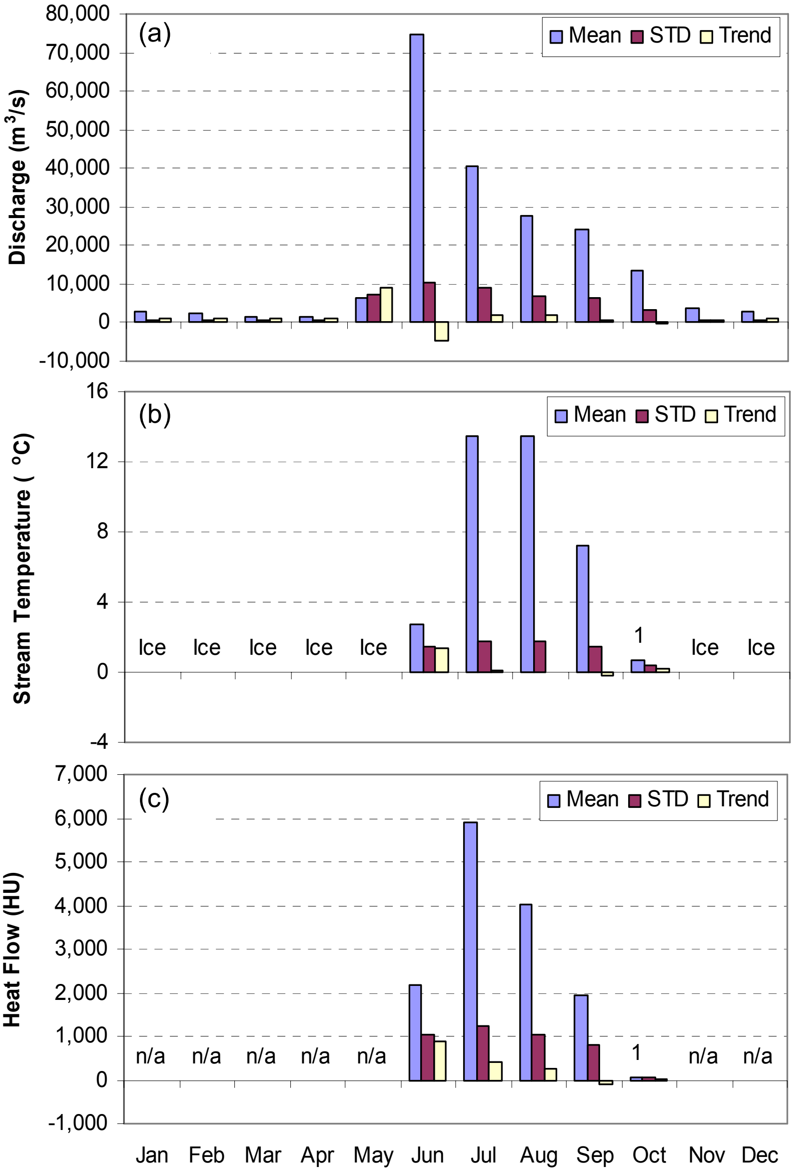

Fig. 2 Long-term (1950–1990) mean, standard deviation, and total trend of monthly discharge (a), stream temperature (b), and heat flow (c) near Lena basin outlet. Number of missing records indicated above bars, 1 HU = 10^9 MJ/month.

Water temperature measurements indicate that the Lena basin outlet becomes frozen in late October. The long-term (1950–1990) mean monthly stream temperature in June is 2.7°C. It increases sharply to 13.5°C in June and remains higher (around 13.5°C) in August. Monthly stream temperature drops sharply to 7.3°C in September, and continuously decreases to 0.7°C in October when the Lena River outlet gradually becomes frozen. The interannual variation of monthly stream temperature near the Lena basin outlet is generally large from June to September (standard deviation 1.4–1.8°C) and small in October (0.4°C).

Trend analysis of the monthly stream temperature over the period 1950–1990 reveals the strongest water temperature increase in June, 2.3°C, which is statistically significant at 93% confidence level. The stream temperature increases are found to be very weak in July and August (less than 0.1°C), and statistically insignificant (below 5% confidence level). A weak stream temperature decrease/increase is detected in September (–0.2°C)/October (0.2°C), both statistically insignificant (23% and 49% confidence levels, respectively).

3.3 Heat flow

According to the stream temperature measurements as taken every ten days over the period 1950–1990, the zero-heat transportation period near the Lena basin outlet is defined from November to May when the final part of Lena River is generally ice-covered. The heat transportation near the Lena basin outlet is active in the open water season, roughly from June to October (Fig. 2(c)). The heat transport in June near the Lena River outlet is large (2181 HU) due mainly to the large monthly discharge, although the monthly stream temperature is quite low (2.7°C) in this month. Heat flow increases sharply to the seasonal maximum in July (5888 HU). This indicates that the maximum July monthly stream temperature overwhelms the maximum June monthly discharge. The heat transport near the Lena River outlet in August drops to 4016 HU, due mainly to the decrease of monthly discharge in August. The heat flow decreases continuously to 1154 HU in September mainly due to the decrease of monthly stream temperature in this month. The heat transport in October before the upper Lena becomes frozen is about 71 HU. The annual total heat flow near the Lena River's outlet is 14 028 HU. The interannual variation of heat flow near the Lena basin outlet is generally large from June to September (standard deviation 787–1236 HU) and small in October (56 HU).

Trend analysis over the period 1950–1990 reveals heat flow increases during June to August and October, and decrease only in September (Fig. 2(c)). The largest heat flow increase, 888 HU (41%), is found in June, and is statistically significant at the 90% confidence level. This strong heat flow increase is due mainly to the strong upward trend of stream temperature in June, as the discharge trend is downward in this month. The positive changes are found to be 415 HU (7%) in July and 269 HU (7%) in August, both statistically insignificant (47 and 37% confidence levels, respectively). These positive changes are mainly due to runoff increases in these two months as the temperature changes are very weak. A weak heat flow decrease of about –86 HU (4%) is detected in September, but is statistically insignificant (16% confidence level). This weak decrease is mainly due to the weak downward trend of stream temperature as the discharge trend is weakly upward in this month. The heat flow in October has slightly increased (7 HU, 10%), statistically insignificant (19% confidence level), which is due mainly to the slight stream temperature increase in this month. As the result of monthly heat flow changes, the annual total heat transport near the Lena River outlet shows a considerable increase (1521 HU) over the period 1950–1990, although statistically it is less significant (68% confidence level).

4 SUMMARY

The heat flow regime over the Lena watershed is estimated in this research. Results show that the heat flow near the Lena River's outlet has considerably increased during 1950–1990. The strongest heat flow increase (41%) is detected in June and attributed to the stream temperature increase in this month. This heat flow increase may have a great impact on the land-fast sea-ice dynamics of the Laptev Sea (Bareiss *et al.*, 1999; Alexandrov *et al.*, 2000). There is a need to evaluate the impact of the June heat flow increase on the lives of both birds and aquatic species in the Lena delta. Weak heat flow increases are also detected in July and August, and attributed to the increased runoff. This may indicate increased sediment in the Lena River due to the strong thermal erosion on the riverbed and banks.

Acknowledgement This study was supported by the US NSF (Award no. ARC- 0612334).

REFERENCES

Alexandrov, V. Y., Martin, T., Kolatschek, J., Eicken, H. & Kreyscher, M. (2000) Sea ice circulation in the Laptev Sea and ice export to the Arctic Ocean: results from satellite remote sensing and numerical modeling. *J. Geophys. Res.* **105** (C), 17143–17159.

Bareiss, J., Eicken, H., Helbig, A. & Martin, T. (1999) Impact of river discharge and regional climatology on the decay of sea ice in the Laptev Sea during spring and early summer. *Arctic, Antarctic & Alpine Res*. **31**, 214–229.

Dynesius, M. & Nilsson, C. (1994) Fragmentation and flow regulation of river systems in the northern third of the world. *Science* **266**, 753–762.

Elshin, Y. (1981) River heat runoff in the European part of Russia. *Meteorology and Hydrology* **9**, 85–93.

Kane, D. L. (1974) A review of dam construction techniques in permafrost regions. *Northern Engineer* **6**, 25–29.

Mackay, J. R. & Mackay, D. K. (1975) Heat energy of the Mackenzie River. In: *Further Hydrologic Studies in the Mackenzie Valley, Canada* (Environmental-Social Committee Northern Pipelines. Task Force on Northern Oil Development report, Report 74-35), 1–23. Ottawa, Information Canada.

Prowse, T. D. & Flegg, P. O. (2000) Arctic river flow: A review of contributing areas. In: *The Freshwater Budget of the Arctic Ocean* (ed. by E. L. Lewis, E. P. Jones, P. Lemke, T. E. Prowse & P. Wadhams) (Proc. NATO Advanced Research Workshop, Tallin, Estonia, 27 April–1 May 1998), 269–280. Kluwer Acad., Norwell, Massachusetts, USA.

Revenga, C., Murray, S., Abramovitz, J. & Hammond, A. (1998) *Watersheds of the World: Ecological Value and Vulnerability*. World Resour. Inst. and World Watch Inst., Washington, DC, USA.

Shiklomanov, I. A., Shiklomanov, A. I., Lammers, R. B., Peterson, B. J. & Vörösmarty, C. J. (2000) The dynamics of river water inflow to the Arctic Ocean. In: *The Freshwater Budget of the Arctic Ocean* (ed. by E. L. Lewis, E. P. Jones, P. Lemke, T. E. Prowse & P. Wadhams) (Proc. NATO Advanced Research Workshop, Tallin, Estonia, 27 April–1 May 1998), 281–296. Kluwer Acad., Norwell, Massachusetts, USA.

Yang, D., Kane, D., Hinzman, L., Zhang, X., Zhang, T. & Ye, H. (2002) Siberian Lena River hydrologic Regime and recent change. *J. Geophys. Res.* D **107**, 4694, doi:10.1029/2002JD002542.

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

Ye, B., Yang, D. & Kane, D. (2003) Changes in Lena River streamflow hydrology: human impacts vs. natural variations. *Water Resour. Res.* **39**, 1200, doi:10:1029/2003WR001991.

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