Stream temperature changes over Lena River Basin in Siberia

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[1] This study analyzes long-term (1950–1992) stream temperature records over the Lena watershed, in order to understand water temperature regimes and changes induced by reservoir regulations, and by natural variations. Water temperature regimes are similar over the Aldan and Upper Lena regions. Stream temperatures at the Lena basin outlet are up to 8°C lower than the southern subbasins. Reservoir regulations strongly influence regional water temperature regime and change particularly in the regulated subbasins. Because of dam impact, stream temperatures increased (decreased) in the Vilui valley during the early (middle) open water season. Trend analyses show consistent warming across the entire Lena River basin in the early open water season, and mixed results in summer for the unregulated subbasins. For the regulated Vilui tributary, stream temperatures significantly increased in the early and late parts of the warm season due to combined effects of natural changes and reservoir regulations. **Citation:** Yang, D., B. Liu, and B. Ye (2005), Stream temperature changes over Lena River Basin in Siberia, *Geophys. Res. Lett.*, *32*, L05401, doi:10.1029/2004GL021568.

1. Introduction

[2] Stream temperature is an important climatic and hydrologic variable, as it directly reflects river thermal characteristics. River thermal conditions affect biological processes. In the high latitude regions, stream temperatures significantly impact the freeze-up/break-up processes, thickness of river ice cover, and thermal erosions along the riverbanks. *Marsh and Prowse* [1987] studied the influence of stream heat on overlying ice cover of the Liard River, and discovered large spatial and temporal variations in water temperatures and heat fluxes. *MacKay and MacKay* [1975], based on long-term field observations of water temperatures at three locations in the Mackenzie River, defined the basis thermal regimes, and quantified the river heat transport. *Costard et al.* [2003] reported that water temperature and discharge are the major factors controlling thermal erosions of the frozen riverbanks in the Siberian Lena basin, and relatively water temperature is more important than streamflow.

[3] Stream temperatures usually follow air temperature closely on a seasonal time scale [*Sinokrot and Stefan*, 1993]. Due to climate change and human impact, stream temperatures have increased over US, Austrian, and Australian rivers. These elevated water temperatures have become an important concern in watersheds where aquatic species such as salmonids are present [*Lowney*, 2000]. In addition to climate factors, human activities particularly construction of large reservoirs, also affect river discharge and stream temperature over space and time. *Lowney* [2000] investigated the impact of reservoir operations on diurnal stream temperatures variation in the upper Sacramento River, and reported unusual spatial patterns in daily maximum and minimum magnitudes. *Preece and Jones* [2002] recently examined the modifications in stream temperature caused by the release of hypolimnetic water from thermally stratified reservoirs, and found that the effect was greatest immediately downstream of the dam, where annual daily maximum temperature was approximately 5.0°C lower and occurred three weeks later than the pre-dam condition.

[4] Examinations of stream temperature changes and variations are important to understand climate-hydrology linkage and to quantify heat flux from the northern rivers into the ocean system. The main objectives of this research are to investigate the long-term variations and changes in stream temperature over the Lena River basin, and to assess the impacts of large reservoirs on river thermal dynamics. The results of this study are useful in understanding hydrologic response to climatic changes and variations in the Siberian regions. They are also important to studies of thermal impacts of large north-flowing rivers on high-latitude ecology and ocean systems.

2. Basin Description, Data Sets, and Method of Analyses

[5] The Lena River originates from the Baikal Mountains in the south central Siberian Plateau and flows northeast and north, entering into the Arctic Ocean via the Laptev Sea (Figure 1). Its drainage area is about 2,430,000 km^2, mainly covered by forest and underlain by permafrost. The Lena River contributes 524 km^3 of freshwater per year, or about 15% of the total freshwater flow into the Arctic Ocean [*Yang et al.*, 2002; *Ye et al.*, 2003]. Relative to other large rivers, the Lena basin has less human activities and much less economic development [*Dynesius and Nilsson*, 1994]. There is only one large reservoir in the Vilui subbasin. A large dam (75 m high and 600 m long, and maximum reservoir capacity 35.9 km^3) and a power plant were completed in 1967 near the Chernyshevskyi (112°15′W, 62°45′N). This reservoir is used primarily for electric power generation - holding water in spring and summer seasons to reduce snowmelt and rainfall floods, and releasing water from near the bottom of the reservoir to meet the higher demand for power in winter [*Ye et al.*, 2003].

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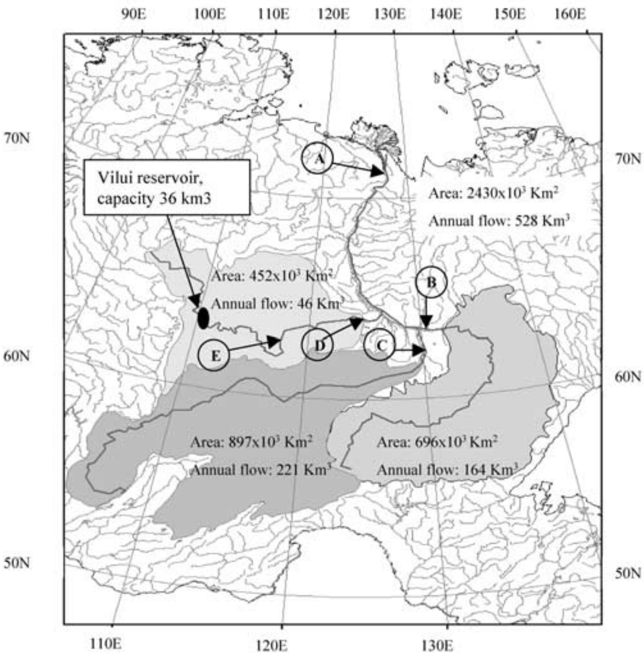

Figure 1. The Lena River watershed and locations (letters) of hydrological stations used for this study. Also shown are reservoir location/information, subbasin boundaries, areas, and mean annual flows.

[6] In the former USSR, stream temperatures were observed at the regional hydrologic stations three times a month (10th, 20th, and 30th day), and measurements were taken twice (at 8:00 A.M. and 8:00 P.M.) on each observation day [*State Hydrologic Institute*, 1961]. The observations were made near the river bank with flowing water deeper than 0.3–0.5 m. For small rivers and rivers with offshore bars, measurements were taken at a location along the deepest channel. Stream temperature observations usually start at the beginning of spring while the rivers are ice-covered and water temperatures are close to 0°C, and observations stop in fall season 3–5 days after the rivers freeze up. During observations, a thermometer (installed inside a cup) was placed at 0.3–0.5m below the water surface for 5–8 minutes, and the cup was retrieved carefully for a quick recording of temperatures. Local conditions, such as topographic and vegetation effects, and groundwater recharge, influence temperature observations in small streams [*Brown*, 1969]. For large rivers, lateral and vertical mixing of water is often very strong particularly during the high discharge periods, and groundwater advection is relatively insignificant [*Brown*, 1969]. Water temperature data collected at the regional networks have been considered as reliable indicators of large river thermal conditions [*MacKay and MacKay*, 1975; *Elshin*, 1981].

[7] In this brief report, we analyze long-term (1950–1992) stream temperature data for the major sub-basins and at Lena river outlet. Relevant station information, such as basin area, yearly flow and dam, is provided in Figure 1. We calculated and compared long-term means of stream temperature between the pre- and post-dam periods so as to quantify reservoir impact on stream thermal regimes. We also carried out trend analysis and statistical significance test to define the long-term changes (total trend during the period) in stream temperatures by a linear regression. The standard *t*-test was used to determine the statistical significance of the trends. The results of trend and regime analyses were compared among the sub-basins to determine and understand the regional differences in stream thermal characteristics.

3. Stream Temperature Regime and Change

[8] We describe stream temperature seasonality and variation, and identify different characteristics of water temperature changes among the sub-basins/regions, i.e. the Aldan, Upper Lena, Vilui valley and at the Lena basin outlet.

3.1. Aldan Tributary

[9] Long-term mean stream temperatures during open water season near the Aldan's outlet (station B in Figure 1) show a period of rising temperature (from 0 to 15°C) from May 20 to June 30, a relatively stable high temperature period (about 17°C) from July 10 to August 10, and a period of falling temperature (from 16 to 0°C) from August 20 to October 20, with the maximum stream temperature of 18°C on July 20 (Figure 2a). The inter-annual variation of stream temperatures is stable over the open water season. Although the long-term mean stream temperatures vary widely from 3°C to 18°C over the season, their standard deviations are between 1.8°C and 2.0°C during the open water season, except for May 20, October 10 and 20 with the standard deviations of 0.3°C, 1.1°C, and 0.5°C, respectively (Figure 2b).

[10] Trend analyses over the study period reveal warming and cooling trends before and after July 30 (Figure 2c). Warming rates between 0.4°C and 3.0°C from May 20 to June 30 are statistically significant at 85–98% confidence. Stream temperature also weakly increased by 0.4°C, 0.6°C, and 0.2°C on July 10, July 20, and July 30, respectively, although these changes are less statistically significant (about 12–47% confidence). From August 10 to October 10, cooling trends were found between −1.6°C and −0.6°C. These negative changes were generally statistically significant at 64–90% confidence, and the trends on August 30 and September 10 (−1.4°C and −1.6°C, respectively) are statistically significant at 85% and 90%, respectively. Stream temperatures also very weakly decreased by 0.1°C on October 20. The positive (negative) changes in stream temperatures during early (late) open water season indicate a stream temperature regime shift toward early season.

3.2. The Upper Lena

[11] Mean stream temperatures for the upper Lena region (station C in Figure 1) show a similar regime to the Aldan tributary, i.e., a period of increasing (0–15°C) from May 20 to June 30, a relatively stable high temperature period (about 17–18°C) from July 10 to August 10, and an extended period of decreasing (17–0°C) from August 20 to October 30 (Figure 2a). Unlike the Aldan tributary, the maximum stream temperature (19°C) usually occurs on August 10 in the upper Lena regions, probably due to difference in regional climatic conditions. Larger temperature changes (−0.3°C/day) occur during August 30 to

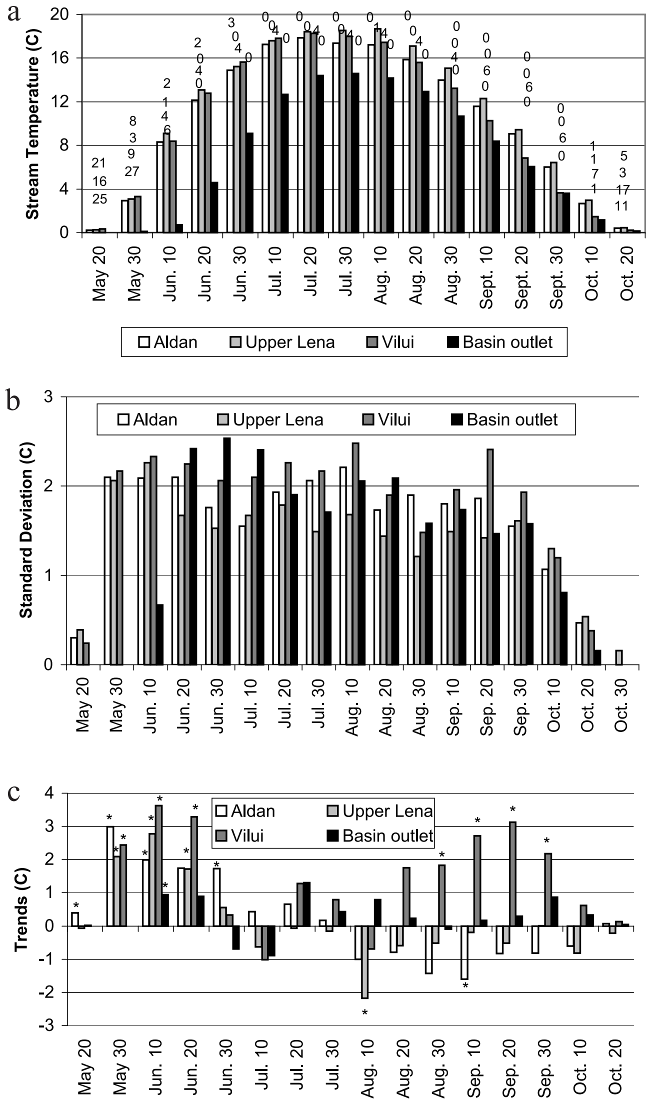

Figure 2. Comparisons of mean stream temperature (a), standard deviation (b), and trends (c), among the sub-basins during 1950–1992. Note numbers of missing data are shown in Figure 2a for each station. ★ in Figure 2c indicates confidence level above 90%. See color version of this figure in the HTML.

September 30 (Figure 2a). The inter-annual variation of stream temperature at this location is stable (standard deviation between 1.2°C and 2.3°C) over the warm season, except for May 20 (0.4°C), October 20 (0.5°C), and October 30 (0.3°C) (Figure 2b).

[12] Stream temperatures over the Upper Lena show positive trends from May 20 to June 30, and negative trends from July 10 to October 20 (Figure 2c). Relative to the Aldan regions, the warming trends over the Upper Lena are found only in the early open water season, and cooling trends are observed during mid-late open water season. Warming trends before June 30 (except May 20) are between 0.6°C and 2.8°C, statistically significant at 93–98% confidence, except for June 30 with 50% confidence. Cooling trends between −2.2°C and −0.1°C during July 10 to October 20 are generally less significant (confidence lower than 60%). Trends on August 10 and October 10 are −2.2°C and −0.8°C, and statistically significant at 95% and 75%, respectively.

3.3. Vilui Tributary

[13] Mean stream temperatures over the Vilui subbasin (station D in Figure 1) has a very similar seasonal cycle to the other two subbasins (Figure 2a). The inter-annual variations of stream temperatures over the Vilui subbasin are stable, with standard deviations between 0.3°C and 2.3°C over the open water season (Figure 2b). During 1950–92, stream temperatures at the Vilui outlet show warming trends over the open water season, except for July 10 and August 10 with weak cooling trends (Figure 2c). The upward trends are particularly strong (up to 2.5–3.6°C) during early open water season (May 30–June 20) mainly due to strong reservoir regulation– releasing warmer water from near the reservoir bottom. Trends are weak and mixed in summer (June 30–August 30) owing to higher streamflow contribution from unregulated tributaries and relatively weak reservoir impacts. The positive trends are strong (about 2.1–3.2°C) during late season (September 10–30).

[14] Reservoir regulations alter streamflow seasonal cycle [*Ye et al.*, 2003; *Shiklomanov et al.*, 2000] and affect thermal regime in the downstream river [*Webb and Nobilis*, 1995]. To quantify reservoir impact, we compared the stream temperature records and found visible differences in mean stream temperatures between pre- and post-dam periods at the Vilui valley outlet. Relative to the pre-dam period, the mean temperatures at Vilui outlet (900 km downstream of the dam) over the post-dam period are 1–2°C higher during May 30–June 20 and September 10–20 (Figure 3). Dam impact on stream temperature is much stronger near the dam, such as at the Santar station (E in Figure 1) about 350 Km downstream of the reservoir (Figure 3). Dam effects significantly altered water temperature regime toward early warming and lower maximum in the mid summer. The impacts of this regime shift on local ecological and biological systems need to be assessed.

3.4. Lena Basin Outlet

[15] Stream temperature data at the river mouth are particularly important as they represent the thermal conditions of the river flux to the ocean systems. Stream temperatures near the Lena basin outlet (the Kusur station, A in Figure 1) have similar characteristics as for the sub-

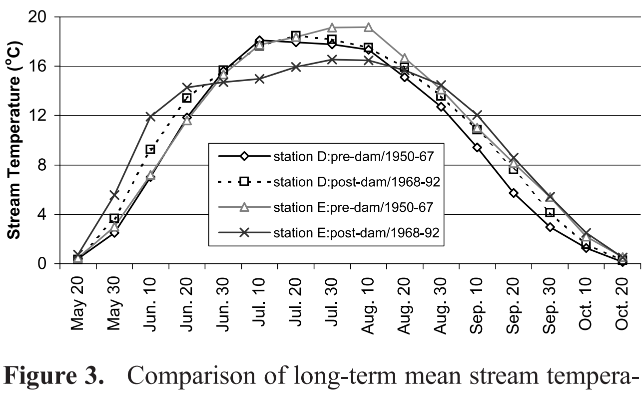

Figure 3. Comparison of long-term mean stream temperatures between pre-dam (1950–67) and post-dam (1968–92) periods at stations D and E in the Vilui valley. See color version of this figure in the HTML.

basins. However, relative to the sub-basins, stream temperatures at the Lena basin outlet are 3–8°C, 3–5°C, and 0–4°C lower, respectively, in the early, mid, and late open water season (Figure 2a), due to relatively cold climate in the northern Lena regions. Inter-annual variations in stream temperatures at the Lena basin outlet are relatively small, with the standard deviations between 1.6°C and 2.5°C for most of the warm season (Figure 2b). June is the period of peak flows, the relatively larger standard deviations in June indicate greater fluctuations in river thermal flux during the snowmelt period.

[16] Water temperatures at Lena basin outlet show weaker changes relative to those in the southern subbasins (Figure 2c). This is reasonable as the magnitudes of changes usually decease with increase in basin size. Trends on May 20 and 30 cannot be determined at the Kusur station due to many missing dada. Positive trends are 1.0°C (statistically significant at 99%) on June 10, and 0.9°C (statistically significant 52%) on June 20, respectively, at the basin outlet. These changes are consistent with the strong positive trends in the upper basin, particularly in the Vilui valley due to dam regulations. This consistency in trends over various parts of the watershed indicates a general warming tendency throughout the entire basin during this period, although the trends are weaker at the basin scale perhaps mainly due to runoff contribution in the northern Lena regions. This consistent warming trend may have enhanced the thermal erosion along the riverbanks, because warmer water temperatures result in greater erosion rates in the Lena basin [*Costard et al.*, 2003].

[17] During June 30 and July 10, cooling trends of about 1°C were found at the Kusur station, while the upper basins show warming trends on June 30 and mixed changes on July 10 (Figure 2c). During July 20 to Aug 10, moderate positive trends of 0.8–1.3°C were observed at the Kusur station. The Vilui and Aldan subbasins also show positive trends during July 20–30 and the upper Lena has little change (Figure 2c). Trends on August 10 were not consistent, as the sub-basins have negative changes, particularly in the upper Lena regions with a very strong cooling trend (Figure 2c). This discrepancy during mid summer probably suggests that other factors, such as rainfall runoff contribution over the northern Lena basin, may also affect water temperature change at regional scales. During August 20 to October 20, stream temperatures trends at the Kusur station are very weak (less than 0.5°C over the study period) (Figure 2c). Strong upward trends were found in the regulated Vilui valley and moderate downward trends were seen over the upper Lena basin. These different trends among the subbasins interact each other through basin integration (mixing of flows from sub-basins) over the northern parts of watersheds, leading to weaker trends at the basin outlet.

4. Summary

[18] The open water season can be divided into three consecutive stages – a period of rising stream temperature in the early open season, stable temperatures in the mid season, and a period of falling temperature in the late season. Stream temperature conditions are generally similar over the Aldan and upper Lena regions. However, water temperatures at the Lena basin outlet are up to 8°C colder than those over the southern subbasins, indicating that the latitudinal difference in climatic conditions, particularly air temperature, may affect stream temperature regime.

[19] Reservoir regulations have a strong influence on the regional water temperature regime and change in the regulated sub-basin. For the downstream Vilui valley, the reservoir acts as a warm source in May, and a cold source in June, July, and August. Relative to the pre-dam condition, post-dam mean water temperatures in the mid section of the Vilui valley have increased by 2–5°C in the early open water season, and decreased by about 2–3°C in the mid open water season. As a result, the seasonal cycle of water temperature shifted toward an earlier warm season. Generally, the water released from the reservoir has increased (reduced) the downstream water temperatures in the Vilui valley during the early (middle) open water season, and the reservoir has not significantly influenced downstream water temperatures in the late open water season.

[20] Trend analyses show consistent stream temperature warming during 1950–1992 across the entire Lena River basin in the early open water season, perhaps indicating a response to earlier snowmelt over the Lena River watershed. Trend results also demonstrate regional characteristics in long-term changes. The Aldan tributary has warming (cooling) trends in the first (second) half of the open water season, leading to a stream temperature regime shift toward early open water season. The Upper Lena River shows warming trends in the early open water season, and cooling trends over the mid-late season. Over the regulated Vilui tributary, however, stream temperatures have significantly increased in the early and late parts of the season. For the Lena basin as a whole, positive changes in stream temperatures have been discovered during the early and mid June. River discharge also increased in this peak flow period [*Ye et al.*, 2003] and on a yearly basis [*Yang et al.*, 2002]. This may lead to heat flux increases over the Lena basin. The impact of this change to thermal erosions along the river valley and to the Laptev Sea needs research attention.

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