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Siberian Lena River hydrologic regime and recent change

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[1] The long-term (1935–1999) monthly records of temperature, precipitation, stream flow, river ice thickness, and active layer depth have been analyzed in this study to examine Lena River hydrologic regime and recent change. Remarkable hydrologic changes have been identified in this study. During the cold season (October–April), significant increases (25–90%) in stream flow and decrease in river ice thickness have been found due to warming in Siberia. In the snowmelt period (May–June), strong warming in spring leads to an advance of snowmelt season into late May and results in a lower daily maximum discharge in June. During summer months (July–September) the changes in stream flow hydrology are less significant in comparison to those for winter and spring seasons. A slight stream flow increase is discovered for both July and August, mainly owing to precipitation increase in May and June. Discharge in September has a slight downward trend due to precipitation decrease and temperature increase in August. The magnitudes of changes in stream flow and river ice thickness identified in this study are large enough to alter the hydrologic regime. Investigation into the hydrologic response of the Lena River to climate change and variation reveals strong linkages of stream flow with temperature and precipitation. We therefore believe that Lena River hydrologic regime changes are mainly the consequence of recent climate warming over Siberia and also closely related to changes in permafrost condition. *INDEX TERMS:* 1823 Hydrology: Frozen ground; 1833 Hydrology: Hydroclimatology; 1860 Hydrology: Runoff and streamflow; *KEYWORDS:* hydrologic regime, climate change, Lena River

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1. Introduction

[2] Climate over Siberia has experienced significant changes during the past few decades. These include considerable winter warming [*Chapman and Walsh*, 1993; *Serreze et al.*, 2000], winter and fall precipitation increase [*Wang and Cho*, 1997], winter snow depth increase [*Ye et al.*, 1998], and ground temperature rising and permafrost thawing [*Pavlov*, 1994]. Climate models project a 1–4°C global surface air temperature increase in the 21st century, with even greater increase in the Arctic regions [*Serreze et al.*, 2000]. This warming trend will impact the structure, function, and stability of both terrestrial and aquatic ecosystems and alter the land-ocean interaction in the Arctic.

[3] Arctic rivers are important to global ocean and climate systems. Discharge from the Arctic rivers contributes as much as 10% to the upper 100 meters of water column of the entire Arctic Ocean. The amount and variation of this freshwater inflow critically affect the salinity and sea ice formation, and may also exert significant control over global ocean thermohaline circulation [*Aagaard and Carmack*, 1989]. Arctic hydrologic systems exhibit large temporal variability due to changes in large-scale atmospheric circulation [*Proshutinksy et al.*, 1999; *Walsh*, 2000]. This variation significantly influences the cross-shelf movement of water, nutrients and sediments. Examination of stream flow regime and change in the major northern river basins and their relations to surface climate and atmosphere are therefore critical to better understand and quantify the atmosphere-land-ocean interactions in the Arctic and consequent global impacts [*Vörösmarty et al.*, 2001].

[4] Efforts of assessing river runoff and its change in the high latitude regions have been reported. *Georgievskii et al.* [1996] examined the runoff features for selected Russian rivers and found some rivers experienced changes in the annual runoff during the late 1970s in Eurasian and western Siberia. They also predicted increased annual discharge under a warming climate. Recently, *Prowse and Flegg* [2000] quantified the magnitude of river stream flow into the Arctic Ocean, compared their results with other estimates, and identified the reasons for discrepancy in the estimates. *Shiklomanov et al.* [2000] and *Grabs et al.* [2000]

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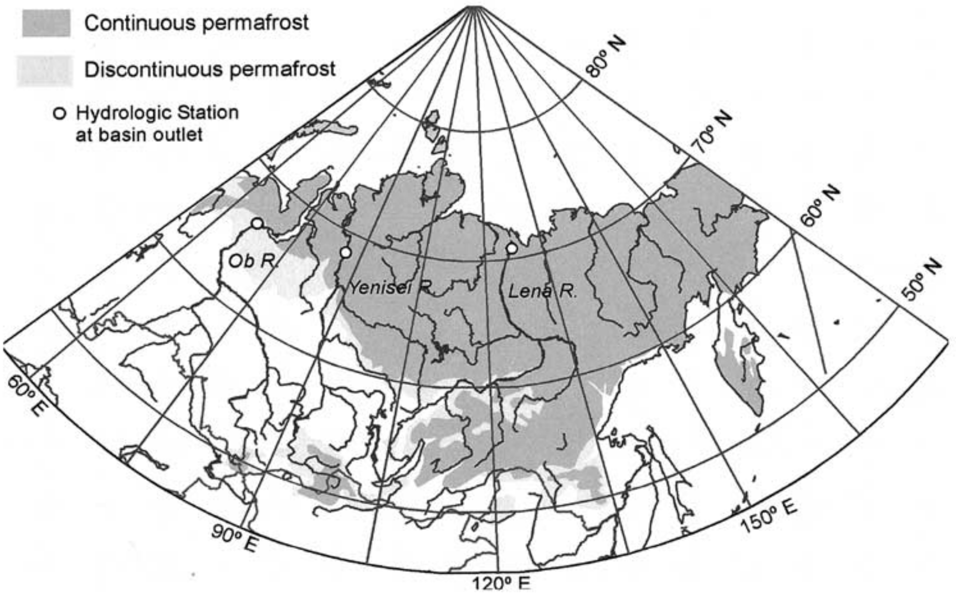

Figure 1. The three major rivers (Lena, Yenisei and Ob) in Siberia. Also shown are permafrost distribution and locations of gauging stations at the basin outlets.

analyzed the historical changes in runoff of major Arctic rivers over the past several decades and found that the trends of annual discharge from the Arctic rivers over all are not large and that different regions behave asynchronously. *Lammers et al.* [2001] reported winter runoff increase in Alaska and Siberia during the 1980s relative to the 1960s and 1970s. *Zhang et al.* [2001] found large parts of southern Canada and Yukon Territory have experienced reduced runoff. *Serreze et al.* [2002] recently examined the large-scale hydro-climatology of the terrestrial Arctic drainage system, with an emphasis on determining atmospheric and surface water budgets for the Ob, Yenisei, Lena and the Mackenzie watersheds.

[5] The current study, based on a systematic analysis of long-term discharge records of Lena River, reports recently discovered significant changes in monthly stream flow, and assesses their impact on regional hydrologic regimes. It also discusses the key processes of interaction and feedback between climate, permafrost and river systems of the northern regions. The results of this study will improve our understanding of hydrologic response to climate change in the Arctic regions.

2. Data Sets and Method of Analysis

[6] The Lena River is one of the largest rivers in the Arctic that flow northward from mid latitudes to the Arctic coast (Figure 1), and it contributes about 15% of total freshwater flow into the Arctic Ocean [*Shiklomanov et al.*, 2000; *Prowse and Flegg*, 2000]. The drainage area of the Lena basin is 2,430,000 km^2, approximately 78–93% of which is underlain by permafrost [*Brown and Haggerty*, 1998; *Zhang et al.*, 1999, 2000]. Lena basin is less developed in comparison to other large rivers in Siberia, such as the Yenisei and Ob rivers [*Dynesius and Nilsson*, 1994]. Studies show that anthropogenic diversions of the Lena River appear to be minor factor at present, and thus the change in river discharge may serve as a reliable indicator of regional climate change and variation [*Shiklomanov*, 1997; *Shiklomanov et al.*, 2000; *Savelieva et al.*, 2000; *Dynesius and Nilsson*, 1994]. Since the late 1930s hydrological observations in the Siberian regions, such as discharge, stream water temperature, river-ice thickness, dates of river freeze-up and break-up, have been carried out by the Russian Hydrometeorological Services and the observational records have been quality-controlled and archived by the same agency [*Shiklomanov et al.*, 2000]. These data are now available from the R-ArcticNET, a digital archive (CD-ROM) for the Arctic drainage [*Lammers et al.*, 2001]. In this analysis, long-term (1935–1999) daily, monthly and annual discharge records collected at the basin outlet (namely Kusur station, 70.70°N/127.65°E) were used. It is known that winter discharge measurements under ice conditions are less accurate, with the potential errors being 15–30% over the Arctic regions [*Grabs et al.*, 2001]. In the former USSR, winter stream flow under ice conditions was determined by a standard procedure that involves direct discharge measurement, adjustment of the open water stage-discharge relation according to climatological data, and comparison of stream flow with nearby stations [*Pelletier*, 1990]. Application of this standard method in Siberian regions produces compatible and consistent discharge records over time and space. In addition, Lena basin mean monthly temperature and precipitation records derived from the global data sets [*Jones*, 1994; *Hulme*, 1991] are also utilized.

[7] The main objective of this study is to examine Siberian regional hydrologic change in the Lena River basin under a climatic warming condition. This analysis will quantify the annual and seasonal freshwater fluxes to the Arctic Ocean from the Lena River and their interannual variation and long-term trends, with an emphasis on defining the discharge regime and detecting its recent change (regime shift) through statistical approaches.

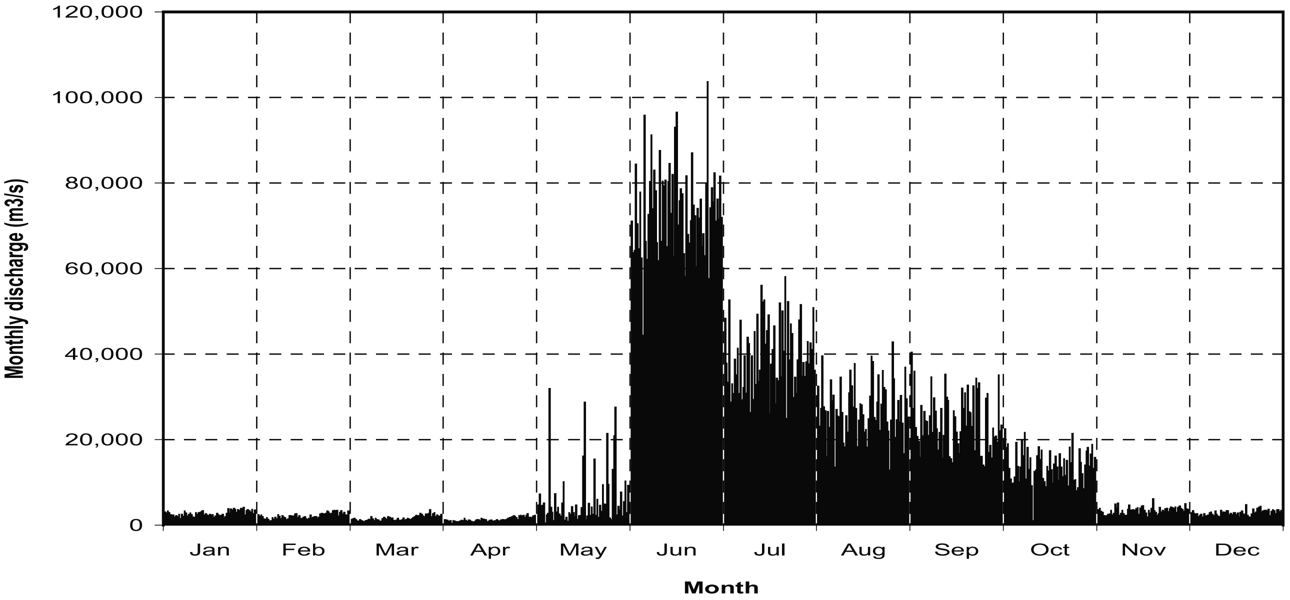

Figure 2. Monthly discharge during 1935–1999 at Kusur station of the Lena River. Note each bar in the graph representing an individual monthly value for each year during 1935–1999.

[8] We use correlation analysis and statistical significance test to assess the associations among climatic and hydrologic variables. Long-term changes are identified by linear trend analysis, i.e. a nonparametric Kendall-tau based method [*Sen*, 1968; *Lettenmaier et al.*, 1994; *Wang and Swail*, 2001]. In addition, we will also present some complementary results on river ice thickness and permafrost data for the Lena River basin. The focus of this analysis is on the basin scale (as a whole at the outlet control station) in order to improve our understanding of the integrated, large-scale hydrologic processes in the northern regions. These analyses will enhance our capability of land-surface modeling particularly over large river basins in the high latitudes.

3. Hydrologic Regime and Change

[9] The seasonal cycle of monthly discharge at the basin outlet is presented in Figure 2. It generally shows a low flow period during November to April and a high runoff season from June to October, with the maximum discharge occurring usually 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 base flow, and a high summer peak flow [*Kane*, 1997]. The Lena River basin, mostly underlain by continuous permafrost (78–93%), has a very low winter flow and a very high peak flow in June, about 55 times greater than the minimum discharge. The runoff ratios (runoff/precipitation) are high (about 0.50) for the Lena basin compared with the Ob river (around 0.30) with only 30% permafrost [*Serreze et al.*, 2002]. The interannual variation of Lena River monthly runoff is generally smaller in the cold season and larger in summer months mainly due to floods associated with snowmelt and rainfall storm activities.

[10] Significant trends in seasonal stream flow have been discovered in this study. Since the mid 1930s, the Lena River winter (November to April) flow has increased 27–90%. Stream flow also changed during the snowmelt period (May and June) and the rest of the warm months (July to September). During May and June, discharge has gone up by 3900 m^3/s (63%) and 3000 m^3/s (4%), respectively, mainly due to increased snowmelt runoff contribution from a thicker winter snow cover [*Ye et al.*, 1998]. Stream flow in July and August increased by about 3900 m^3/s (10%) and 700 m^3/s (5%), while September and October experienced a decrease of 3200 m^3/s (−13%) and 460 m^3/s (−3%), respectively. Winter and spring discharge increases for Lena River are accompanied by reductions in stream flow in late summer and early fall. These changes are not always significant for an individual month, but their total impact over seasons/months is remarkable. The overall stream flow increase during winter and particularly early summer months was 491 km^3 (or runoff depth of 20.2 mm over the watershed) and the cumulative decrease in later summer and early fall seasons was 95 km^3 (3.9 mm runoff depth). These changes in seasonal stream flow results in a weak upward trend (6%) in the annual mean discharge for the Lena River over the study period.

[11] Changes in monthly discharge impact the stream flow seasonality. Comparison of mean monthly stream flow fraction to annual total discharge between 1935–1969 and 1970–1999 (Figure 3) shows a moderate increase (0.1–0.4%) during November to April, a jump (0.8%) in May, and a decrease (−1.8%) in June. July and August did not experience much change, and September and October contribution decreased slightly by 0.2%. It is important to point out that the changes in the monthly stream flow fraction are most significant during the snowmelt period. The increase in May and decrease in June suggest a hydrologic regime shift toward earlier snowmelt and early summer peak flow season. Analysis of the long-term daily discharge records at the Kusur station confirms an advance of snowmelt peak flood from June toward late May, i.e. the peak discharge

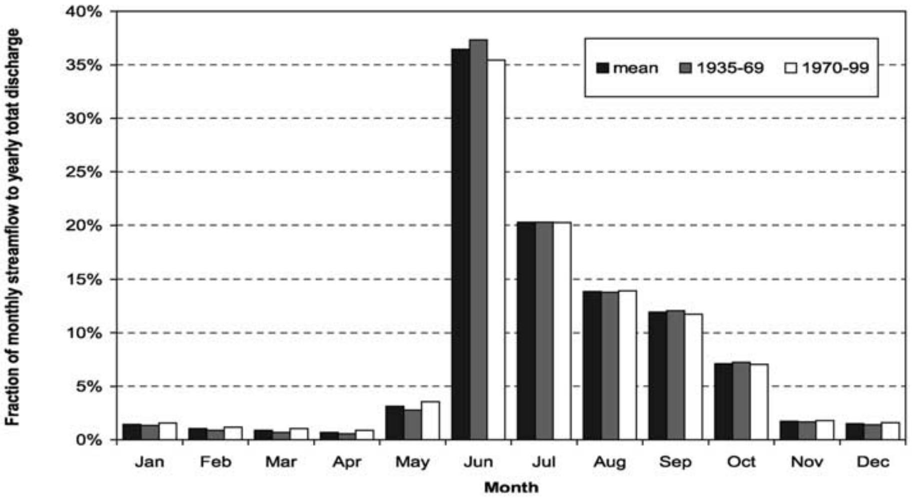

Figure 3. Fractions of mean monthly stream flow to annual total discharge between 1935–1969 and 1970–1999.

appearing 3–5 days earlier, and a decrease by about 10,000 m^3/s of the maximum daily flow in June (Figure 4). Similar changes were also found for some Canadian rivers in Yukon Territory [*Zhang et al.*, 2001]. We thus believe that the shift of snowmelt peak caused by significant warming in spring and early summer over the Lena basin is responsible for the increase in stream flow fraction in May and decrease in June.

[12] It has been recently reported that rivers and lakes in the Northern Hemisphere during the past 150 years have been thawing earlier and freezing later due to global warming [*Magnuson et al.*, 2000; *Serreze et al.*, 2000]. This study analyzed long term river ice thickness records for Lena River basin and discovered a remarkable thinning of the river ice cover during winter and spring months. The decrease of ice thickness during March to May was particularly significant in the northern regions. For instance, the ice cover at Kusur station was 20–35 cm thinner for the 1970s–1980s when compared with 1950s–1960s (Figure 5). A strong negative correlation of maximum river ice thickness with air temperature in April (R = −0.54 to −0.72) was identified for the Lena basin, suggesting that changes in river ice condition is closely related to winter warming over Siberia. Increase in winter precipitation, hence a thicker snow cover [*Ye et al.*, 1998], might also be an important factor for the decrease in river ice thickness

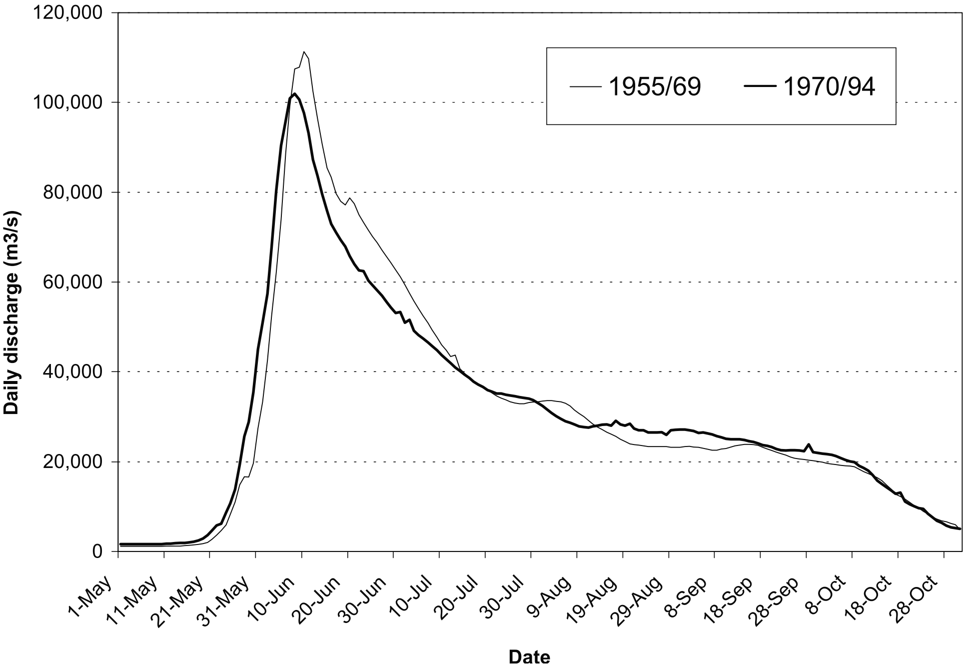

Figure 4. Comparison of long-term mean daily stream flow regimes at Kusur station, 1955–1969 versus 1970–1994.

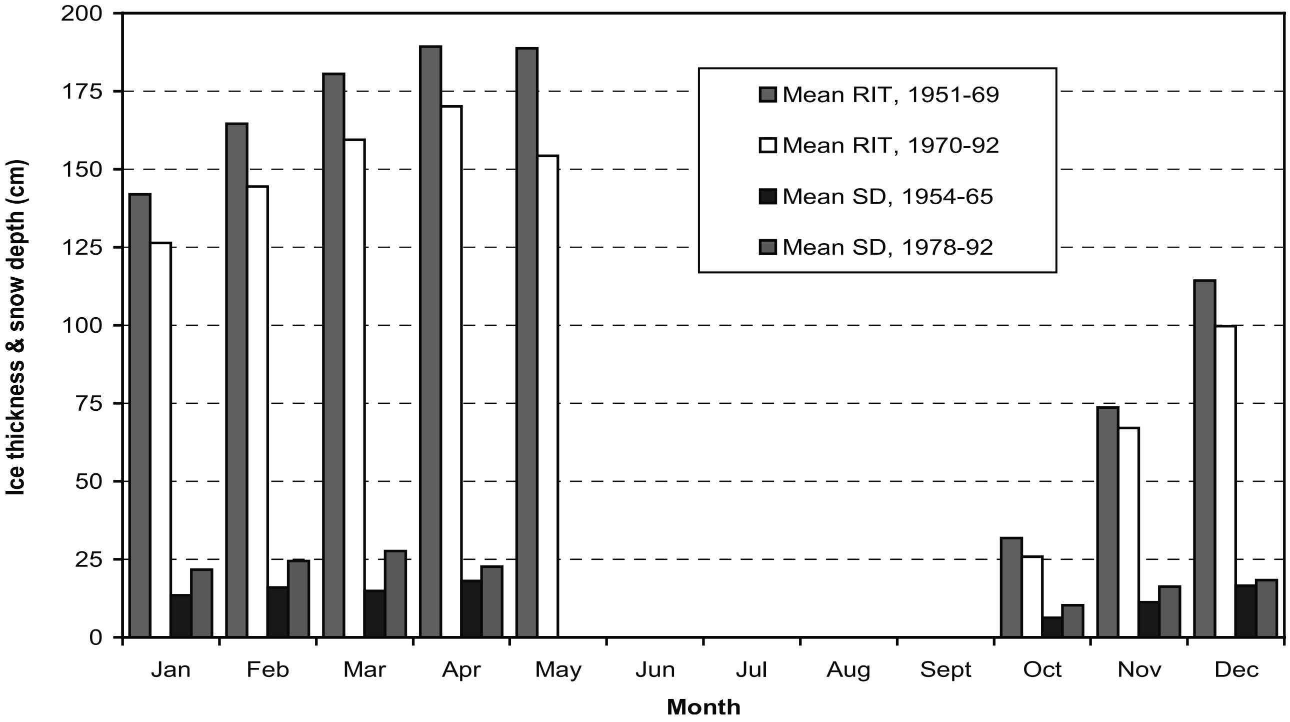

Figure 5. Long-term mean monthly river ice thickness (RIT) and snow depth (SD) at Kusur station, 1951–1992.

due to the insulation impact of snow cover (Figure 5). In addition, this study also found a negative relation (R = −0.73) between stream flow and river ice thickness at the Kusur station during November to April (Figure 6). This relation suggests that winter climate warming produces more runoff and less river ice.

4. Hydrologic Response to Changes in Climate and Permafrost Condition

[13] The observational evidences of the changes in Lena River stream flow and ice thickness suggest a hydrologic regime shift over Siberia. We believe that this regime shift is very likely the consequence of recent climate warming in the northern Russian regions and also closely related to changes in permafrost conditions. To better understand these changes, we need to examine hydrologic response to changes in climate and permafrost condition over the Siberian regions.

4.1. Temperature-Runoff Relation

[14] The seasonal regime of Lena basin mean temperatures and their trends determined by linear regression are shown in Figure 7 for the period 1935–1999. We see a strong warming in winter and spring over the Lena basin. The monthly temperatures during November to March have increased by 1.9–3.8°C over the last six decades, while April and May temperatures have also increased by about 0.7–1.4°C. Temperatures in June and July have not changed much during the period from 1935 to 1999. August, however, has a weak warm trend, and September and October became slightly cooler by 0.2–0.7°C over the study period. As a result of the strong warming in the winter months, Lena basin annual mean temperature has increased by about 1.3°C over the last six decades.

[15] Statistical analysis shows that annual stream flow did not correlate well with mean annual air temperature, and the monthly relation differs between seasons, i.e. negative for the warm months and positive for the cold season. From September to April, temperatures were positively correlated with river runoff (R = 0.21–0.45) for various lag times, ranging from 0–4 months for September to January and from 0–2 months for February to April. This positive relation suggests that winter warming may lead to a higher stream flow in the cold months over Lena basin. Snowmelt-generated floods are the most significant hydrologic events of the year in the Arctic regions. It is important to note that during the snowmelt period from May to June, the relationship changes from very strong positive (R = 0.45) to very strong negative (R = −0.51) (with a lag of one month). In May the correlation was the highest with a zero time lag, clearly indicating that higher air temperatures in May will melt more snow to produce larger snowmelt floods. For instance, we found that the extremely high floods registered in May were all associated with positive temperature anomalies. Usually June is the main snowmelt period in the Siberian rivers, but we found that June temperature did not statistically relate to June discharge (R = −0.03). We believe this is because a monthly scale analysis for June is too coarse to examine the snowmelt and evaporation processes occurring in this month. June is an important transition period as the watershed warms up to 10–15°C (Figure 7), during the early to mid part of the month snow cover melts at a higher rate, and in late June snow cover disappears and evaporation from the wet soil, wetlands, ponds, and lakes dominates. Evaporation processes starting

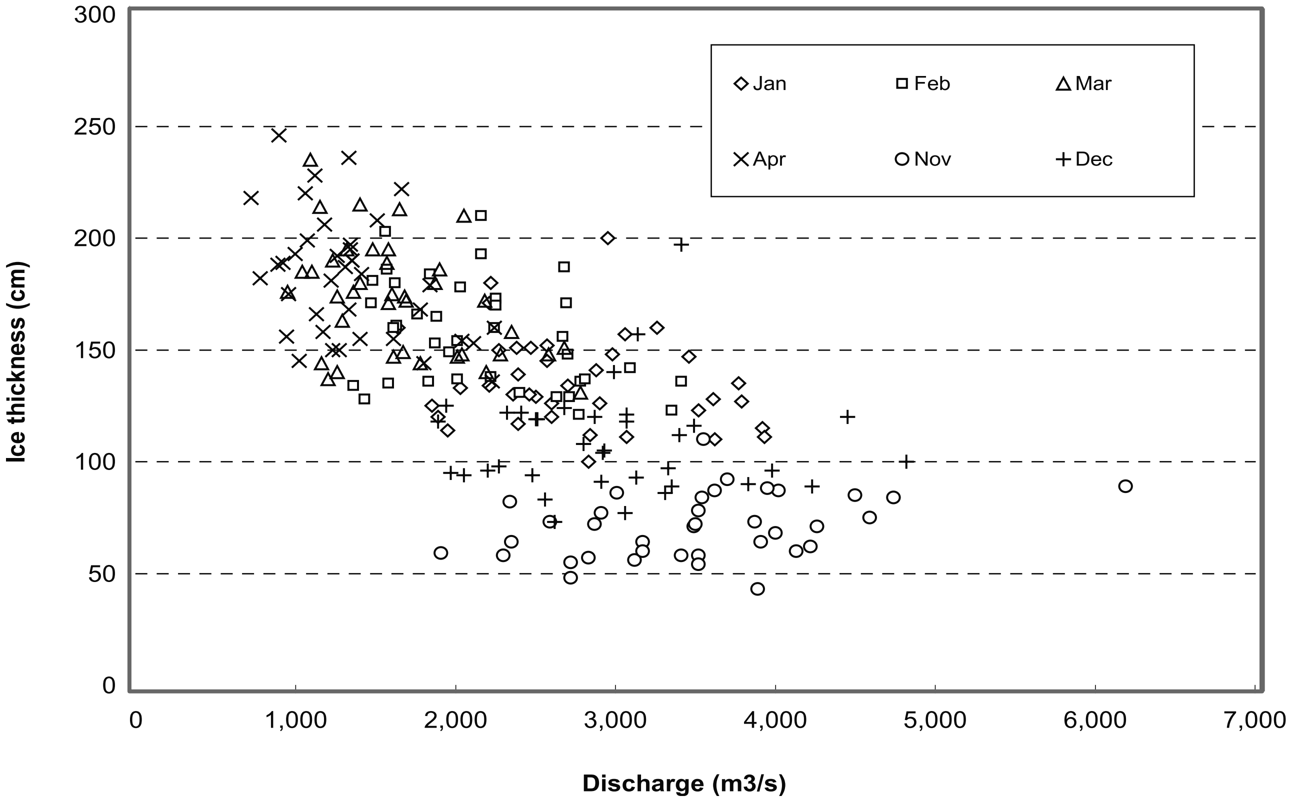

Figure 6. Relationship between stream flow and river ice thickness at the Kusur station during November to April, 1951–1992.

in late June after snowmelt are important for basin water and energy balances. We found that June temperature negatively correlates (R = −0.36) with July discharge (Figure 8). This negative, one-month-lagged, correlation (R = −0.36 and −0.18) also exists between temperatures of July to August and stream flow of August to September. These results imply that higher (lower) temperatures during summer months will result in higher (lower) evaporation, thus leading to lower (higher) stream flow for the following month.

4.2. Precipitation-Runoff Relation

[16] The Lena basin mean monthly precipitation and its trend over the study period are depicted in Figure 9. It shows

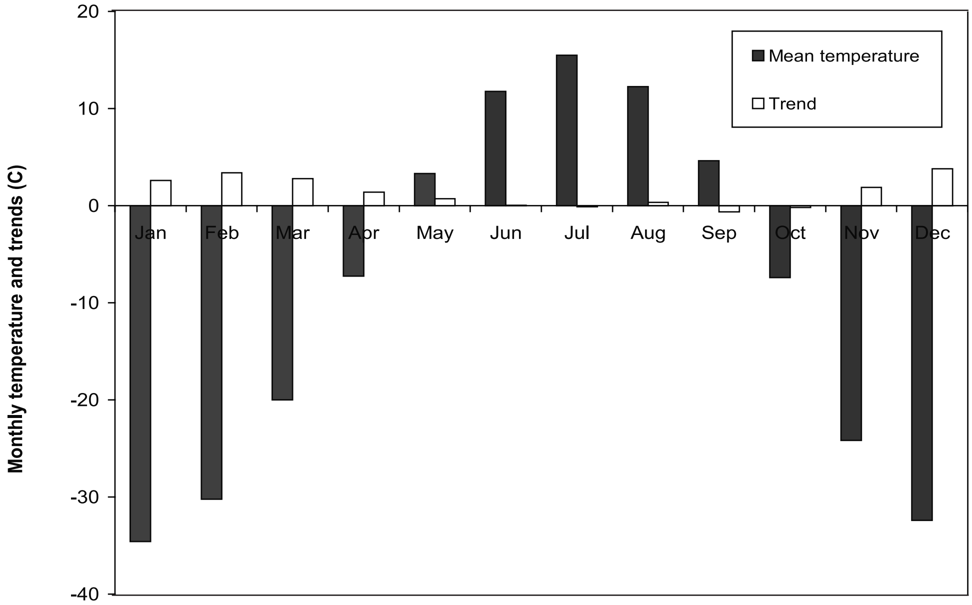

Figure 7. Lena basin mean monthly temperatures and their trends, 1935–1998.

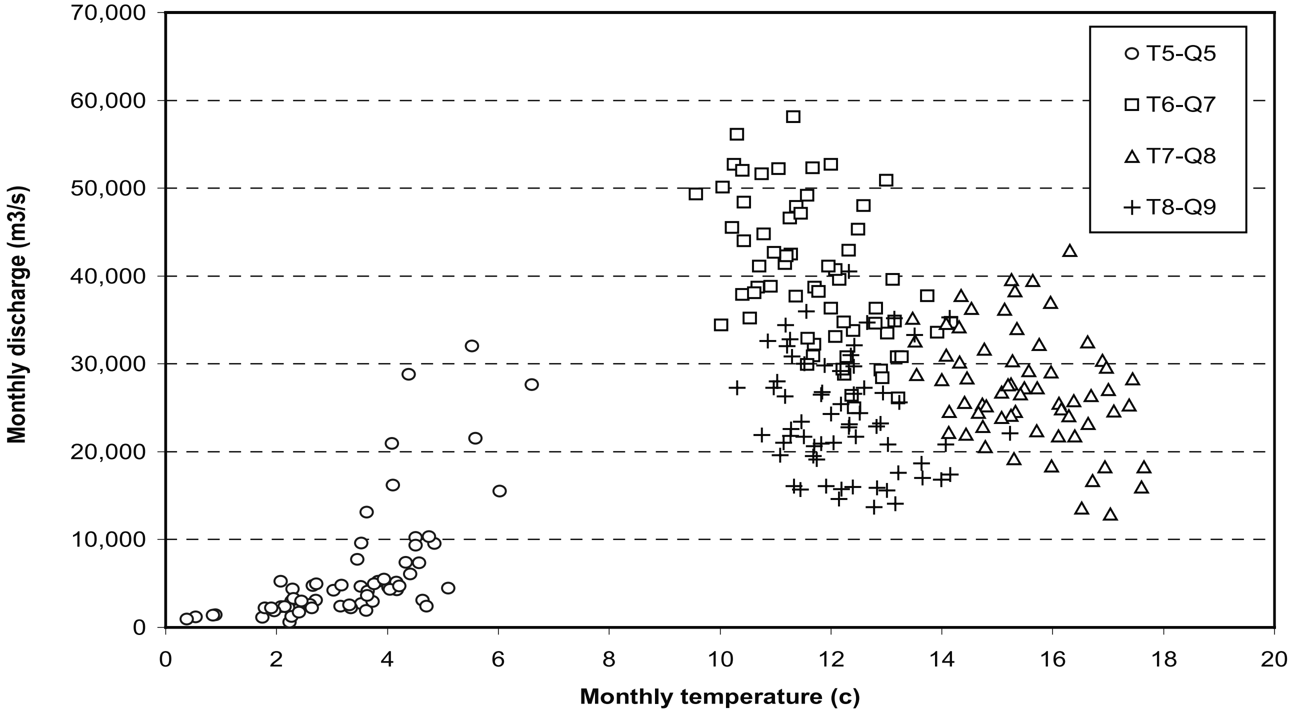

Figure 8. Relation between monthly discharge (Q) and basin mean temperature (T) during May (5) to September (9).

that the monthly precipitation varies from 10–30 mm during October to May, and the summer months are relatively wet, with the peak amounts being 65–70 mm in July and August. An upward trend in monthly precipitation was found during October to June, particularly for November, December, March and May when the monthly increase was over 2 mm over the study period. It is important to note that the total precipitation increase over the winter season was around 12 mm; this tendency is consistent with snow depth increase reported by *Ye et al.* [1998]. Precipitation in July and August has a downward trend, the decrease in August is strong (about 15 mm), and September shows little change. As a result of monthly precipitation changes, annual total precipitation declined by about 5 mm over the last several decades.

[17] Correlation analysis of monthly precipitation and discharge records shows different results between the cold

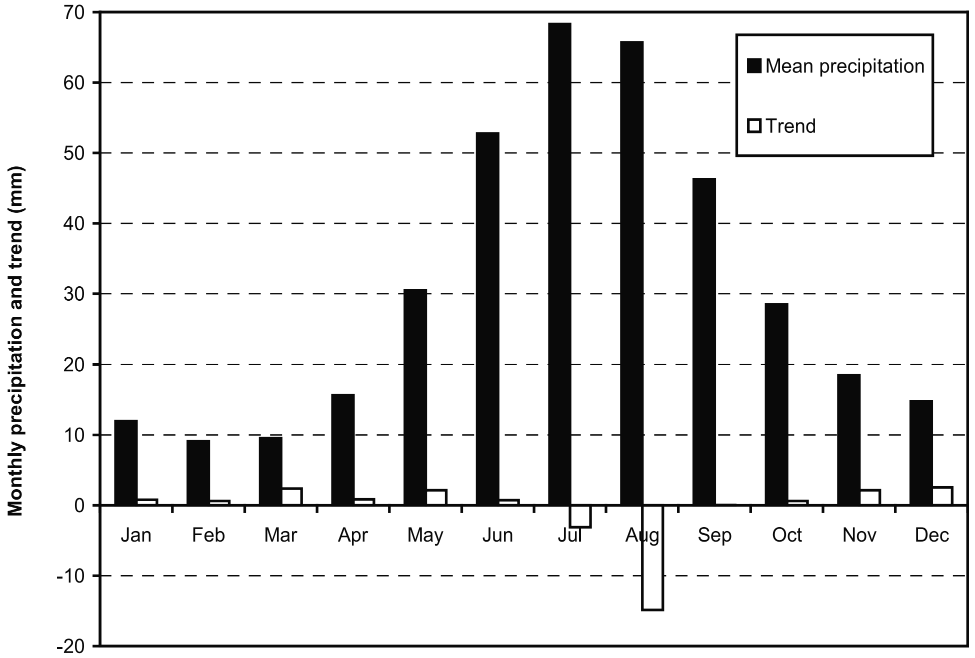

Figure 9. Lena basin mean monthly precipitation and its trend, 1935–1998.

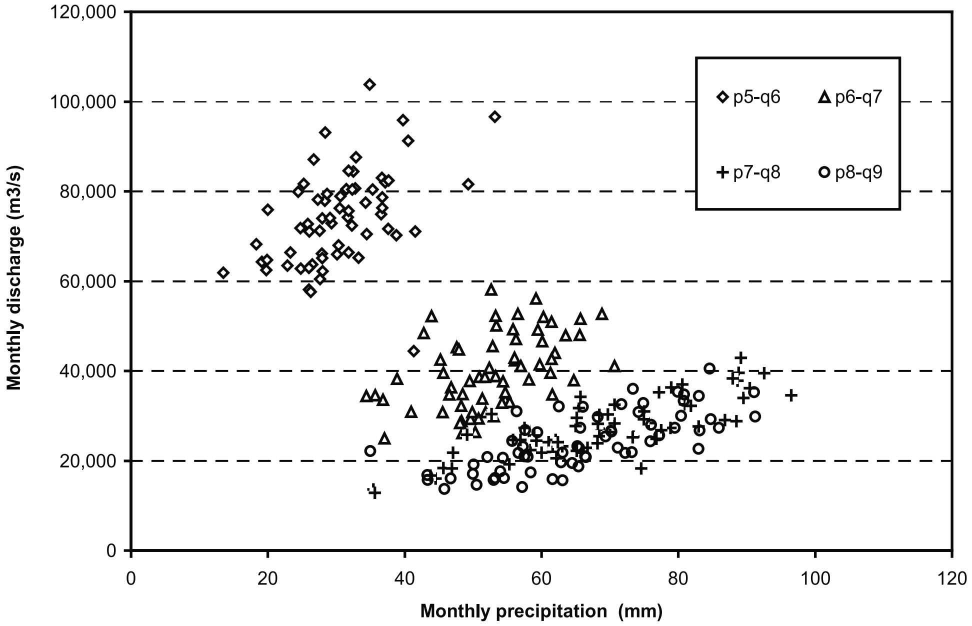

Figure 10. Relation between monthly discharge (Q) and basin mean precipitation (P) during May (5) to September (9).

and warm seasons. For the warm months from May to September, there exists a positive relationship that is very strong with the stream flow lagged by 0, 1 and 2 months. The highest correlation was found with a lag of 1 month during the warmest months, i.e. between July precipitation and August runoff (R = 0.81), and August precipitation and September runoff (R = 0.72) (Figure 10). This is reasonable, as heavy rainfall events in these months generate high floods over the watershed. On the other hand, no statistically significant correlation was detected for the cold season from October to April. During this cold period, snow cover accumulates and base flow (from subsurface water) dominates river discharge. However, winter month precipitation was found to have a weak correlation (R = 0.14–0.27) with spring/summer season stream flow from May to July, indicating some effect of winter snow cover to snowmelt runoff generation in early summer season.

4.3. Impact of Permafrost Change

[18] Studies show that in some regions of Siberia, permafrost temperature has warmed more than 2°C and active layer thickness has increased by up to 25–30% over the past several decades owing to higher air temperature and deeper snow cover over Siberia [*Pavlov*, 1994]. *Serreze et al.* [2002] reported that soil temperatures at depths of 0.2–0.8 m increased about 4°C at Norilsk in the Yenisey river basin and about 2°C at Bestyachakaya Zveroferma in the Lena River basin from the late 1960s to early 1990s. Our study illustrates that long-term thawing depth data collected near Yakutsk (central Lena basin) show a steadily increasing trend until about 1967 (Figure 11). The increase is particularly significant in the mid 1960s. Relative to earlier decades, the mean thawing depth during 1965 to 1985 was 15–35 cm greater in summer season, the maximum thawing (active layer depth) changed from 200 cm to 240 cm, and the timing of the maximum thawing shifted from August/September to September/October. The thawing depth in November and December also increased, particularly in November by about 25 cm in Yakutsk.

[19] The active layer over permafrost is generally saturated during the thaw season, thickness of the active layer in late summer and the date of active layer freeze-up in the mid-winter significantly impacts hydrologic characteristics in permafrost regions. Changes in active layer depth over permafrost directly affect potential groundwater storage and river discharge through partitioning process [*Kane*, 1997]. A deeper active layer allows drainage to occur later in the winter. Analysis of soil moisture data in the upper (1 m) layer in the Former Soviet Union over the recent decades reveals a long-term increasing trend of soil moisture north of 50°N, mainly due to a precipitation increase [*Vinnikov and Yeserkepova*, 1991]. Observation records also show that the absolute amount of water content increases 10–30 mm in the 1 m soil layer, and groundwater level rose by 50–100 cm in Siberia [*Georgievskii et al.*, 1996]. This increased groundwater storage may result in more underground water recharge to the river system, and consequently, a significant increase of runoff in the winter months. The impact of changes in active layer thickness on runoff increase in the winter months is reported more pronounced over the Yenisey river basin [*Serreze et al.*, 2002].

5. Conclusions

[20] This study identifies significant changes in various components of the hydrologic regime of the Lena River over the past several decades. During the cold season (October–April), significant stream flow increase and thinning of river ice thickness were detected. These changes are postulated to be related to winter warming over Siberia. Warmer winter temperatures cause a decrease of river ice thickness and an increase of stream flow over the Lena basin. In addition,

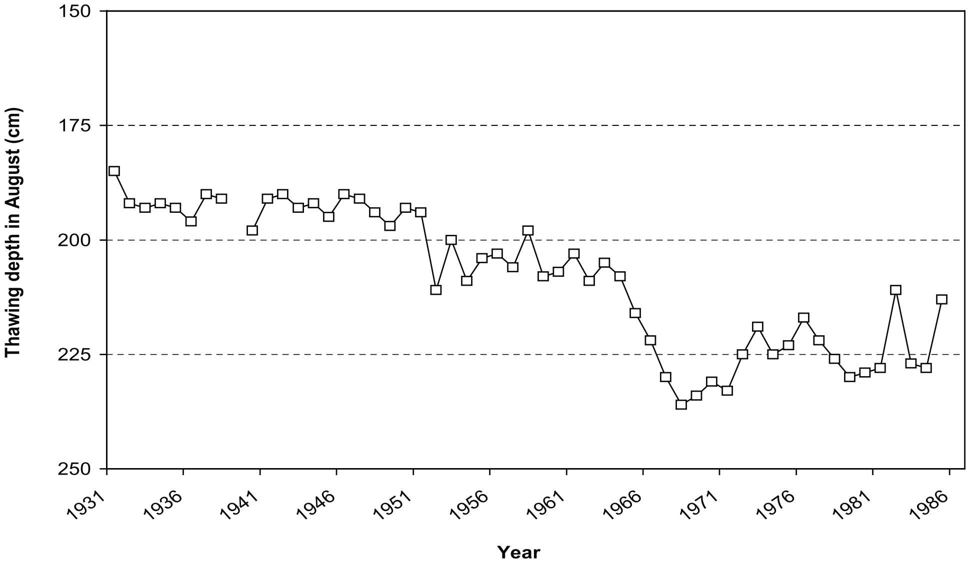

Figure 11. Thaw depth of the active layer at the end of August in Yakutsk, 1931–1985.

temperature and precipitation changes in the cold season also impact permafrost conditions. Winter warming and a thicker snow cover due to increase in winter snowfall in Siberia result in higher permafrost temperatures and a delay in both the initial and complete freezing of the deeper active layer. The thicker active layer, having a greater groundwater storage capacity, in fact, has more groundwater storage amount due to both melt of ground ice and increased precipitation input. This increased groundwater storage in turn results in a greater contribution of subsurface water to the river systems and hence increases the winter season stream flow. During the snowmelt periods, strong warming in spring season leads to an advance of snowmelt season from June into late May and results in a lower daily maximum discharge in June. These changes in snowmelt pattern cause stream flow increases in May and June, and alter the stream flow regime (monthly fraction) during the spring/early summer periods. In the summer months (July, August and September), the changes in stream flow hydrology were less significant in comparison to those identified for winter and spring seasons. A slight stream flow increase was discovered for both July and August mainly due to precipitation increase in May and June. Discharge in September has a slight downward trend due to precipitation decrease and temperature increase in August.

[21] Our analysis of the hydrologic response of the Lena River to climate change and variation demonstrates a strong positive relation of river stream flow with air temperature in May and a negative, lagged association for the rest of summer months. It is discovered that precipitation was positively correlated with a lag of 0–2 month to stream flow for the summer months, particularly in July and August when rainfall-generated floods dominate. Winter precipitation was also found to influence summer stream flow, mainly through winter snow cover accumulation, earlier spring snowmelt, and subsequent peak flow recession. These results improve our understanding of atmosphere-land interactions in the Siberian regions. Our future research will focus on identifying the changes in hydrologic regimes in different sub-basins of the watershed, and on examining the interannual variation of monthly discharge/river ice and their responses to surface climate and atmospheric circulation. Development of a coupled regional climatic-hydrologic model is also necessary in order to better understand and quantify the complex land-atmosphere interaction and feedback.

[22] **Acknowledgments.** This study was supported by the NOAA/CIFAR grant NA17RJ1224 and NASA grant NAG5-6820. The authors thank Mark Serreze and Martyn Clark and other two anonymous reviewers for their constructive comments and suggestions.

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