# Streamflow Characteristics and Changes in Kolyma Basin in Siberia

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## ABSTRACT

This study documents major changes in streamflow hydrology over the Kolyma watershed due to climatic variations and human impacts. Streamflow seasonal cycles over the basin are characteristic of the northern region, with the lowest runoff in April and peak flow in June. Analyses of monthly flows and trends show that reservoir construction and operation have considerably affected streamflow regimes. Comparisons of mean monthly discharge records between pre- and post-1986 dam periods indicate that the mid–lower basin (downstream of the dam) experienced significant increase in low flows and decrease in peak flows after dam construction. For example, mean monthly flows during the post-dam period at the Ust'-Srednekan station (located 1423 km downstream of the dam) has strongly increased by about 205 $m^3 s^{-1}$ (or 522%–3157%) during December–April, and decreased by 133 $m^3 s^{-1}$ (41%) in June. Long-term monthly discharge data reveal an overall increase in streamflow during low flow seasons; the increase is greater for the stations located downstream of the dam. The Srednekolunsk station (1720 km from dam) shows low flow increase ranging from 130 (43%) to 268 $m^3 s^{-1}$ (454%) during November–April, and high discharge decrease by 2550 to 519 $m^3 s^{-1}$ during June–August in the post-dam era (1986–2000). These changes in flow patterns are mainly caused by reservoir regulation, as reservoirs release water in winter for power generation and store water in summer for flood control. Dam impact on flow regimes and changes are visible along the main river trunk; thus, the cold season discharge increase at the basin outlet is primarily the result of reservoir regulation. Annual discharge records show different changes within the Kolyma basin, with moderate increases in the upper basin and weak decreases in the mid–lower basin. Overall annual discharge near the basin outlet has decreased by 1.5% during 1978–2000. This study emphasizes the importance of human activities (particularly reservoirs) on seasonal and regional hydrology changes and points to the need to further examine natural causes and human impacts over other high-latitude watersheds.

## 1. Introduction

Rivers in the Arctic play a significant role in the global climate system by contributing a large amount of discharge into the Arctic Ocean. The Arctic Ocean receives 3685 $km^3$ of freshwater discharge in a year, which is about 11% of annual freshwater discharge into the global oceans (Shiklomanov 2000; Shiklomanov and Shiklomanov 2003). The amount of freshwater inflow affects ocean salinity, thermohaline circulation, and sea ice formation (Aagaard and Carmack 1989). The Arctic Ocean is the most landlocked and most river-influenced of all oceans (Vörösmarty et al. 2000). River influence to the Arctic Ocean is pronounced on the shallow shelf regions, particularly in Russia (Lammers et al. 2001). The Arctic hydrological system varies over space and time because of large-scale variations in atmospheric circulation (Kane 1997; Walsh 2000; Serreze 2003). Variations and changes in the hydrological cycle at local and regional scales affect vegetation patterns (Foley et al. 1994), permafrost dynamics (Nelson and Anisimov 1993; Kane et al. 1990), and gas fluxes (Oechel et al. 1993).

Significant changes have been observed in the large Arctic river basins. For instance, Ye et al. (2003) and Yang et al. (2003, 2004a,b) found discharge increase during the winter months and shift in peak discharge timing related to winter and spring warming over the large watersheds in Siberia. Recent studies have focused on the mechanisms driving these changes (McClelland et al. 2004). Peterson et al. (2002) suggested that the transport of moisture from the lower to higher latitudes might be responsible for river runoff in-

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creases. Berezovskaya et al. (2004) recently reported inconsistency in yearly precipitation and runoff trends for the large Siberian rivers. A better understanding of the hydroclimate system is critical to understand and explain the observed hydrologic changes. In addition to climate change, anthropogenic activities such as reservoir constructions, interbasin water diversions, and water withdrawal for industrial and agricultural uses also affect river discharge regimes and changes over space and time (Miah 2002; Vörösmarty et al. 1997; Revenga et al. 1998; Dynesius and Nilsson 1994). Slow economic growth and low population in the high-latitude regions have resulted in low impact by humans (Shiklomanov et al. 2000; Lammers et al. 2001). Among the human impacts, reservoir regulation has the most direct effects on hydrologic regimes and changes (Ye et al. 2003; Yang et al. 2004a,b). More efforts are needed to study hydrologic responses to climatic changes and human influences in the high latitudes. This study systematically analyzes long-term monthly and yearly discharge for the Kolyma River watershed, with the emphasis on defining streamflow regimes and long-term changes induced by climate variations and human impacts. The results of this study will improve our understanding of hydrologic response to climate change in the Arctic regions.

## 2. Basin description, datasets, and methods of analyses

The Kolyma watershed situated in eastern Siberia is the sixth largest river flowing into the Arctic Ocean (Tsuyuzaki et al. 1999; IUCN 2006). The river is 2410 km long; it rises in the Kolyma and the Chreskogo ranges and flows into the Arctic Ocean. The Kolyma River discharges 100.8 $km^3 yr^{-1}$ to the Arctic Ocean. The Kolyma River is mostly fed by spring snowmelt and summer rainfall with the annual precipitation inputs to the watershed of 47% snow and 53% rain (Welp et al. 2005). The dominant land cover types in the Kolyma region are shrub (41%) and forest (31%; Revenga et al. 1998). The basin is characterized by taiga flora (Swanson 2003). Tree lines are lower than 1000 m, above which exists alpine tundra. The primary tree types are *Larix Mill* (larch) and *Picea* A. *Dietr* (spruce), and upland shrubs consist mainly of *Pinus pumila* (pine; Swanson 2003). The Kolyma basin has the typical Arctic climate of a long winter and a short summer. Temperatures are low during September to May; mean January temperatures are about −30° to −40°C (Swanson 2003). Low temperatures promote continuous permafrost in the region (Kuchment et al. 2000). The active layer varies from 0.2 m in the tundra to 1.0 m in the taiga. The soil starts to thaw after snowmelt in late May and freezes in early September. Permafrost acts as an impermeable surface, resulting in limited exchange between surface water and subsurface permafrost (Panfilova 1986). The Kolyma region is not very developed except for the dam constructions during the late 1980s and widespread gold mining activities.

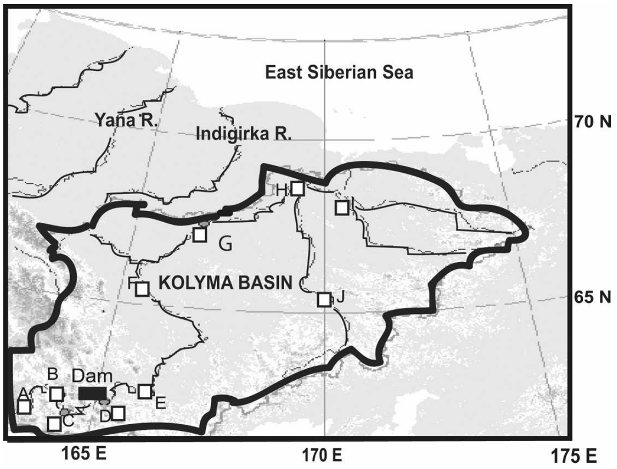

FIG. 1. The Kolyma watershed and the location of the dam and hydrologic stations used in this study.

Hydrological observations in the Siberian regions, such as discharge, stream water temperature, river-ice thickness, dates of river freeze-up and breakup, have been carried out since the mid-1930s by the Russian Hydrometeorological Services, and the observational records were quality controlled and archived by the same agency (Shiklomanov et al. 2000). The discharge data are now available from the R-ArcticNet (version 3.0)—a database of pan-Arctic river discharge (online at http://www.r-arcticnet.sr.unh.edu/main.html). Within the Kolyma basin, a hydrologic observing network consisting of 13 stations has been set up since the mid-1930s. Ten stations with long-term monthly and annual discharge records (the Kolymskoye, Srednekolunsk, Yasachnaya, Ust'-Srednekan, Sinegor's, Duscania, Orotuk, Kulu, Bol'shoy Anuy, and Oloy) (Fig. 1) have been used for this analysis. Relevant station information is summarized in Table 1. In addition, basin-mean monthly and yearly temperature and precipitation records derived from the global (observational climatic) datasets (Jones 1994; Hulme 1991) are also utilized in this study.

The warming of permafrost is important for Arctic hydrology. As permafrost degrades surface water will become closely connected to the subsurface groundwater. As a result, soil drainage will improve and basin storage will also change. These changes will alter the streamflow seasonal cycle (Hinzman et al. 2005). Holmes et al. (2003) examined the potential role of permafrost thaw as a significant contributor to the ob-

TABLE 1. List of hydrologic stations used in this study.

| Station code (Fig. 1) | Station name /location | Latitude (°E)° | Longitude (°N)° | Data period | Discharge area × 1000 km$^2$ | % of Kolyma Basin | Annual runoff (km$^3$) | % of basin runoff | Dam information |
|---|---|---|---|---|---|---|---|---|---|
| H | Kolymskoye/basin outlet | 68.73 | 158.72 | 1978–2000 | 526 | 100 | 103 | 100 | Downstream of dam |
| G | Srednekolunsk/main river valley | 67.47 | 153.69 | 1927–2000 | 361 | 69 | 68 | 67 | Downstream of dam |
| F | Yasachnaya/tributary | 65.40 | 151.07 | 1972–88 | 32 | 6 | 9 | 9 | Unregulated subbasin |
| E | Ust'-Srednekan /main river valley | 62.43 | 152.30 | 1933–2000 | 99 | 19 | 23 | 22 | Downstream of dam |
| D | Sinegor's/main river valley | 62.07 | 150.47 | 1936–89 | 61 | 12 | 10 | 9 | Downstream of dam |
| C | Duscania/main river valley | 61.65 | 148.83 | 1948–80 | 50 | 10 | 11 | 10 | Upstream of dam |
| B | Orotuk/main river valley | 62.12 | 148.47 | 1957–97 | 43 | 8 | 9 | 8 | Upstream of dam |
| A | Kulu /main river valley | 61.90 | 147.42 | 1942–94 | 10 | 2 | 3 | 3 | Upstream of dam |
| I | Bol'shoy Anuy/ Konstantinovo | 68.15 | 161.16 | 1978–2000 | 49 | 12 | 8 | 8 | Unregulated subbasin |
| J | Oloy /Utuchan | 65.67 | 162.43 | 1975–88 | 15 | 5 | 4 | 3 | Unregulated subbasin |

served discharge changes over large rivers in Siberia. They found that thawing of permafrost may contribute to changes in yearly discharge but cannot be considered as a major driver. This paper did not investigate permafrost effect since we did not have permafrost data over the Kolyma basin. To examine the hydrological regimes and changes over the Kolyma basin, we first compiled the basic geophysical and hydrological information and identified dam-regulated and unregulated subbasins. We divided the basin into upper, middle, and lower subbasins to better examine the regional hydrological features and the effect of dam regulation. Second, we calculated and compared long-term monthly mean discharge, standard deviation, and trend for the major discharge stations. Trends were determined by a linear regression. The total trend was defined as the difference between the first and last point on the regression line. The trends for different stations have different time periods. We limited the trend calculations and discussions for flow records longer than 15 yr. The trend was expressed in terms of total discharge change over the observation period for each station. We understand that trend results are less compatible among the stations because of varying data periods used here. Flow trends in regulated basins are not very useful to examine climate impact on regional hydrology changes (Ye et al. 2003; Yang et al. 2004a,b). However, trend analyses and results are necessary to document flow regime changes due to regulation over time. Significance of the trend was evaluated by the standard Student's *t* test. Third, we compared the mean streamflow between the pre- and post-dam periods, so as to quantify the effects of reservoir operation within the basin and at the basin outlet. To better determine the impact of dam regulation over the basin, we also analyzed discharge budget (changes) along the main river valley, and examined and compared discharge changes between the regulated and unregulated subbasins. Finally, we discuss the relationship between monthly climate and hydrology changes over the basin as a whole.

## 3. Streamflow regime and change

This section discusses discharge regimes and changes at the 10 stations located in the main river valley and in the tributaries (Fig. 1). It also documents the dam in the basin and quantifies its influence on the seasonal characteristics of streamflow hydrology.

### *a. Kulu (upper basin)*

The Kulu station (A in Fig. 1) represents the source area of the Kolyma River. No dams exist in this subbasin of 10 300 km$^2$. The seasonal cycle shows the highest

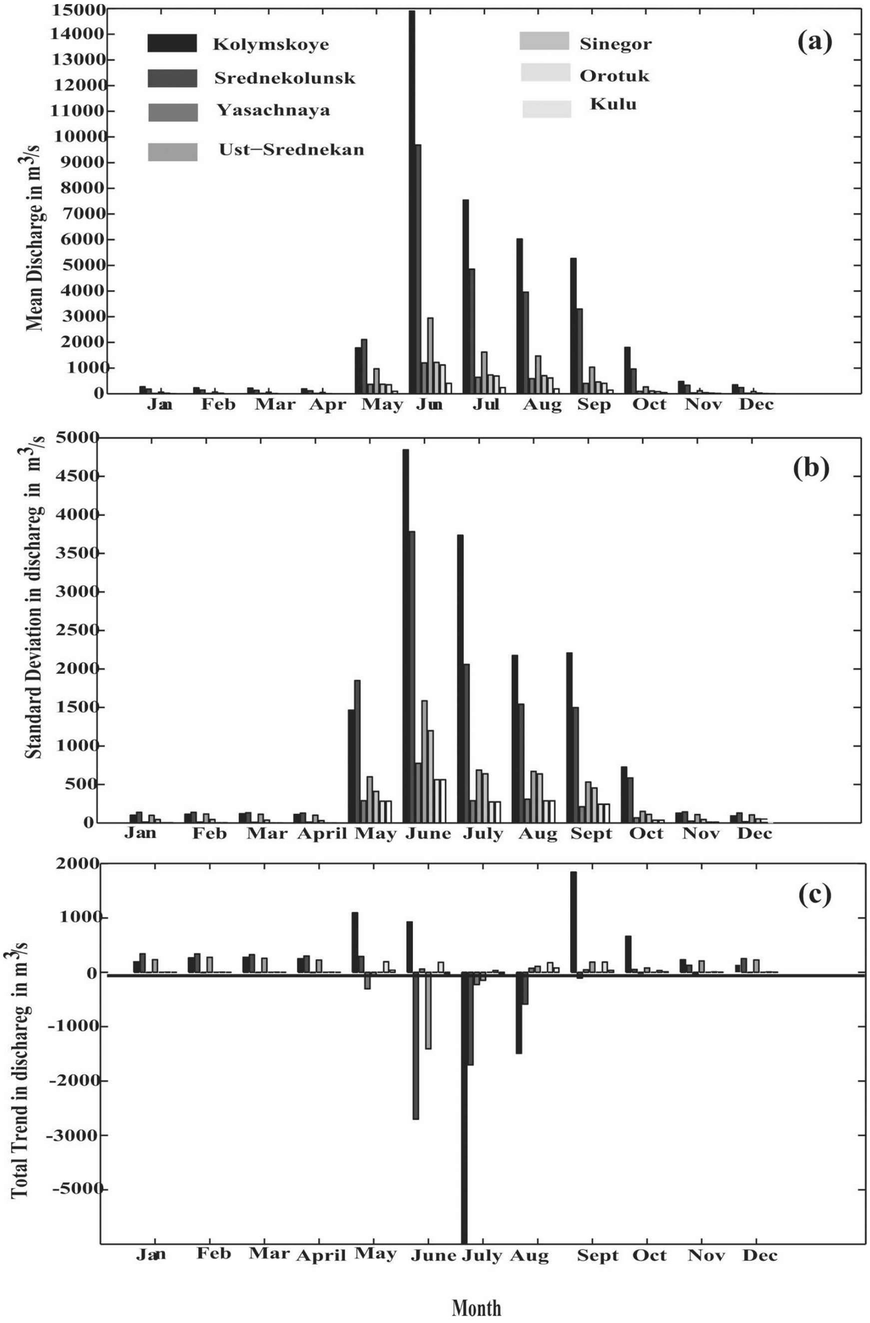

FIG. 2. (a) Monthly mean discharge, (b) standard deviation of discharge, and (c) trend analysis for selected stations on the Kolyma River. (Refer to Table 1 for data period for every station.)

flow in June (405 $m^3 s^{-1}$) and the lowest flow in April (1 $m^3 s^{-1}$) (Fig. 2a). The start of snowmelt discharge is in May (95 $m^3 s^{-1}$); the other high flow months are July (240 $m^3 s^{-1}$), August (189 $m^3 s^{-1}$), and September (139 $m^3 s^{-1}$). Low flows from November to April range from 42 to 1 $m^3 s^{-1}$ (Fig. 2a). The interannual variation of monthly discharge, measured by standard deviation, is small from October to April (17–1 $m^3 s^{-1}$), and large during June to August (199–78 $m^3 s^{-1}$) (Fig. 2b). Flow data during 1942–94 show (total) monthly streamflow increased strongly by 80 (53%) and 33 $m^3 s^{-1}$ (27%) in August and September, respectively, and weakly by 2 $m^3 s^{-1}$ (17%) in November and 38 $m^3 s^{-1}$ (49%) in May (Fig. 2c). On the other hand, discharge changed very little in January, and decreased by 25 $m^3 s^{-1}$ (−6%) in June and by 27 $m^3 s^{-1}$ (−11%) in July

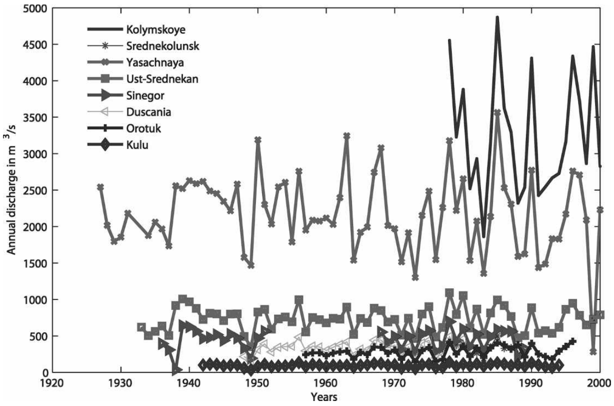

FIG. 3. Annual discharge plots for selected hydrologic stations in the basin.

(Fig. 2c). The annual discharge increased by 10% during 1942–94 (Fig. 3).

### *b. Orotuk (upper basin)*

The Orotuk station (B in Fig. 1) is located in the upper Kolyma basin; it has a drainage area of 43 600 km$^2$. Flow pattern at the Orotuk station is similar to that of the Kulu station, with high flow ranging from 360 to 81 m$^3$ s$^{-1}$ during May to October, and low flow from 25 to 2 m$^3$ s$^{-1}$ during November to April (Fig. 2a). This flow pattern is typical for regions with continuous permafrost. Because of limited subsurface storage in the shallow active layers, it is typical to have very low flow in the winter and very high peak flow in summer. The ratio between June (highest) and April (lowest) flows is about 500 in the Orotuk subbasin. Standard deviations of monthly flows are low from November to April (1–9 m$^3$ s$^{-1}$), and high during May to August (243–280 m$^3$ s$^{-1}$), with the maximum in June (539 m$^3$ s$^{-1}$) (Fig. 2b). Discharge changes during 1957–97 over the Orotuk subbasin are characterized by positive trends for all the months. Total increase during 1957–97 are weak (2–6 m$^3$ s$^{-1}$) over the cold season (November to April) and strong in May (195 m$^3$ s$^{-1}$), June (184 m$^3$ s$^{-1}$), July (183 m$^3$ s$^{-1}$), August (177 m$^3$ s$^{-1}$), and September (186 m$^3$ s$^{-1}$) (Fig. 2c). Streamflow changes in this unregulated subbasin are possibly due to climatic changes. The annual discharge shows a strong increase of 22% during 1957–97 (Fig. 3).

### *c. Duscania (upper basin)*

The Duscania station (C in Fig. 1) is located in the upper Kolyma basin; it has a drainage area of 50 100 km$^2$. Duscania shows similar pattern to that of the Kulu station, with high flow ranging from 364 to 92 m$^3$ s$^{-1}$ from May to October, and low flows from 26 to 2 m$^3$ s$^{-1}$ during November to April (Fig. 2a). Standard deviations of monthly flows are low from November to April (2–11 m$^3$ s$^{-1}$), and high during May to August (351–268 m$^3$ s$^{-1}$), with the maximum in June (809 m$^3$ s$^{-1}$) (Fig. 2b). Discharge changes during 1948–80 at the Duscania are characterized by negative (total) trends in June (79 m$^3$ s$^{-1}$) and November (2 m$^3$ s$^{-1}$). May has a positive trend of 261 m$^3$ s$^{-1}$, while low flow months during December to April show very weak positive trends of less than 2 m$^3$ s$^{-1}$ (Fig. 2c). The annual discharge increased by 19% during 1948–80 (Fig. 3).

### *d. Sinegor'e (upper basin)*

The Sinegor'e station (D in Fig. 1) is situated in the upper Kolyma basin. This station controls a drainage area of 61 500 km$^2$. Flow data are available from 1932 to 1989, with missing data during 1952–67 (a gap of 15 yr). The seasonal cycle of monthly streamflow shows high discharge (160–532 m$^3$ s$^{-1}$) from May to October, with the maximum discharge in June (1762 m$^3$ s$^{-1}$), and very low flows from November (54 m$^3$ s$^{-1}$) to April (10 m$^3$ s$^{-1}$) (Fig. 2a).

A reservoir was built in the main river valley above the Sinegor'e station in the early 1980s. The dam is 130 m high, 780 m long, and its volume is 10 km$^3$. It is a rock-filled dam (with a soil core) with a surface area of $441 \times 10^3$ km$^2$ (Petrov and Losev 1976). The Kolymskoye is the biggest dam in the Kolyma River basin and the reservoir was filled during 1986–90. A power plant (capacity of $3.26 \times 10^9$ kW h$^{-1}$) was also built below the dam. Most of the reservoirs in Siberia were designed for multipurpose use, such as water supply and hydropower generation.

To quantify the dam impact on streamflow regime and change, we compare the mean monthly flows between the pre- and post-dam periods. The results show discharge decreases during the post-dam period by 498–397 m$^3$ s$^{-1}$ (or about 85%–36%) during May to July, and increases by 136–134 m$^3$ s$^{-1}$ (525%–1151%) from December to January (Fig. 4a). Monthly discharge records clearly show sudden changes in streamflow right after the dam completion due to reservoir regulation (Fig. 5). Streamflow increases in cold season (November–April) because reservoir releases water to generate more power in winter season; discharge decreases in June and July are due to reservoir storing water to reduce the snowmelt and rainfall floods (Fig. 5). The monthly flow records also suggest that, as result of dam regulation, monthly discharge varied within the range of natural variability (the difference between the maximum and minimum flow during the pre-dam period) over the high flow season, and fluctuated out of the range of natural variability during the low flow season due to significant increases in discharge over the post-

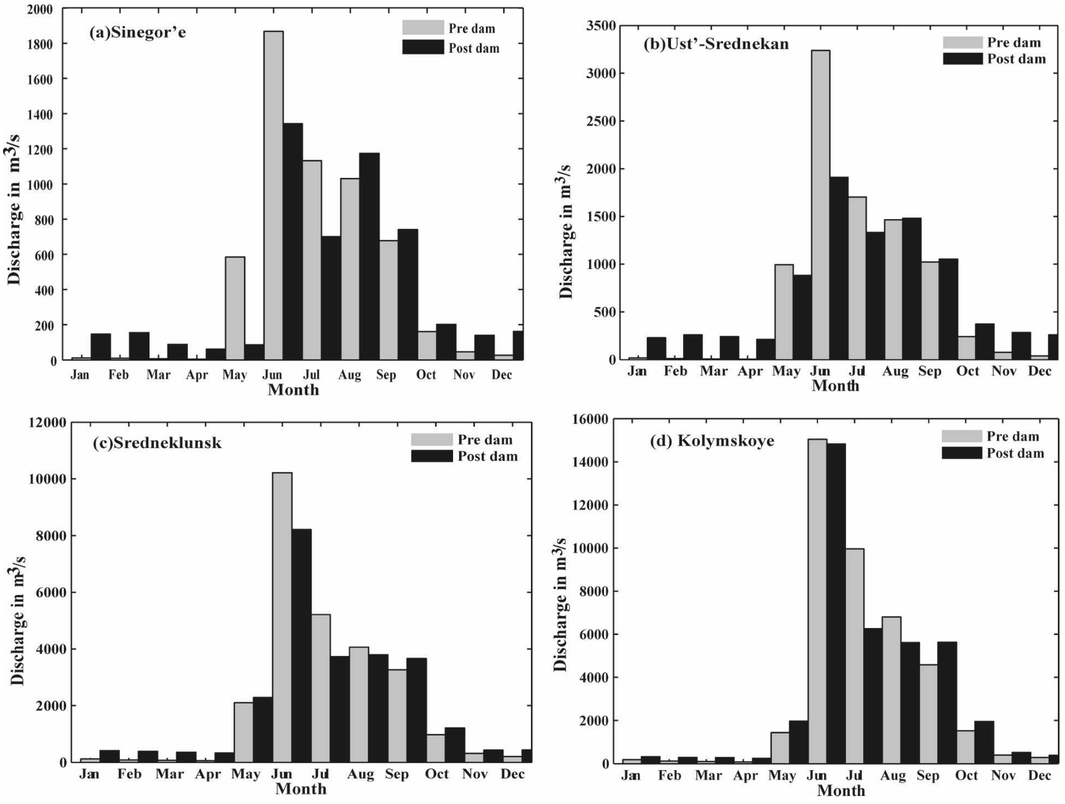

FIG. 4. Comparison of long-term mean monthly discharge at four stations between the pre- and post-dam periods.

dam period (Fig. 5). Similar discharge changes have been found in other regulated Siberian watersheds, such as the Lena, Yenisei, and Ob basins (Ye et al. 2003; Yang et al. 2004a). Ye et al. (2003) also reported that dam regulation affects long-term streamflow trends in Siberia. Their study reported overestimation of trends in winter and underestimation of trends in summer. Because of many missing discharge data at this station, dam impacts on streamflow trends cannot be determined.

### *e. Ust'-Srednekan (upper basin)*

The Ust'-Srednekan station (E in Fig. 1) controls a drainage area of 99 400 $km^2$. Similar to the upper basin, monthly discharge at the Ust'-Srednekan station is low from November (118 $m^3 s^{-1}$) to April (52 $m^3 s^{-1}$) and high during May to July (969–1621 $m^3 s^{-1}$), with the peak flow in June (2945 $m^3 s^{-1}$) (Fig. 2a). The interannual variation follows the pattern of monthly flow, with the maximum in June (1586 $m^3 s^{-1}$) and minimum in April (100 $m^3 s^{-1}$) (Fig. 2b). The standard deviations are small (100–108 $m^3 s^{-1}$) for the low flow months from November to April, and large (600–687 $m^3 s^{-1}$) for the high flow months during May to July (Fig. 2b).

The Ust'-Srednekan station is located 1493 km downstream of the dam. Usually dam impact is most significant at the location right below the reservoir. It is important, however, to note that the influence of the reservoir is clearly seen at the Ust'-Srednekan station. For example, comparisons of mean flows between the pre- and post-dam periods show flow increases for most months, except during May to July (Fig. 4b). Strong streamflow increase during the post-dam period by about 205 $m^3 s^{-1}$ (or 522%–3157%) in cold season (December–April) and decrease in June peak flow by 133 $m^3 s^{-1}$ (41%) are the most typical indications of dam regulation. Furthermore, long-term (total) trend during 1933–2000 also show moderate decreases from May (70 $m^3 s^{-1}$) to July (15 $m^3 s^{-1}$), and significant (at 99% confidence) increases during November (209 $m^3 s^{-1}$) to April (259 $m^3 s^{-1}$). These changes in seasonal streamflow characteristics are mainly due to reservoir recharge during the summer and fall seasons (Ye et al. 2003). As the result of monthly flow changes, the annual flow has increased by 2% during 1933–2000 (Fig. 3).

### *f. Yasachnaya at Nelemnoy (unregulated tributary/middle basin)*

The Yasachnaya station (F in Fig. 1) is located on a western tributary in the middle Kolyma basin. It has a drainage area of 32 000 km$^2$ and contributes 6% of the total Kolyma discharge. There are no dams in this subbasin. Flow data are available from 1977 to 1988. Monthly mean flow is typical, with highest discharge in June (1367 m$^3$ s$^{-1}$) and lowest in April (18 m$^3$ s$^{-1}$). The standard deviations show the same variation as monthly mean flows. The monthly discharge records in this unregulated subbasin did not show significant increases for the cold season (November–April) and very slight changes during the high flow months (May–July) (Fig. 5). The annual flow decreased by about 10% during the 12 yr (1977–88) (Fig. 3).

### g. *Srednekolunsk (lower basin)*

The Srednekolunsk station (G in Fig. 1) is located in the lower part of main Kolyma River valley, 1720 km downstream of the reservoir. This station controls a drainage area of 361 000 km$^2$. Monthly mean discharge, standard deviation, and trend generally show similar patterns with other upstream stations, such as low flows (115–241 m$^3$ s$^{-1}$) during April to December and the peak flow (2107 m$^3$ s$^{-1}$) in June (Fig. 2a).

Reservoir regulation alters the seasonal discharge pattern (Shiklomannov 2000; Yang et al. 2003). The dam effect is still visible at this station, although the impact is much weaker relative to the upstream stations near the dam. Comparisons of pre- and post-dam mean monthly flows (Fig. 4c) show low flow increases by 130 (43%) to 268 m$^3$ s$^{-1}$ (454%) during November to April, and high discharge decreases by 2550 to 519 m$^3$ s$^{-1}$ during June to August in the post-dam era (1988–2000) (Fig. 2b). Monthly discharge records (Fig. 5) show long-term increases during November to April and slight decreases during May to July. The trend analyses of monthly flow data during 1927–2000 show significant increases in the cold season. The most extreme trend is in January, with the total increase of 338 m$^3$ s$^{-1}$ (4110%), and followed by February, 337 m$^3$ s$^{-1}$ (1234%), March, 323 m$^3$ s$^{-1}$ (868%), and April, 300 m$^3$ s$^{-1}$ (781%). The high flow season and early fall showed decreasing trends of 2701 m$^3$ s$^{-1}$ (30%) in June, 1703 m$^3$ s$^{-1}$ (4%) in July, 584 m$^3$ s$^{-1}$ (3%) in August, and 108 m$^3$ s$^{-1}$ (5%) in September, respectively (Fig. 2c). The *t*-test results reveal high significance for the low flow months, November, December, January, February, and April being statistically significant at 98%–99% confidence. Trends in May, June, and July flows are significant at 60%, 95%, and 98% confidence, respectively. Annual discharge has a decreasing tendency (−11%) over the 72 yr (1927–2000) (Fig. 3).

The effect of dam regulation is strong and easy to detect during the low flow season than the high flow season. To examine how the impact of dam regulation has been transferred downstream, we analyzed discharge budget along a selected section of the main river valley. We calculated the mean monthly discharge during 1978–2000 between the pre- and post-dam periods for the Srednekolunsk and the Ust'-Srednekan stations. The results show that low flow changes during November to April are about 2.3 km$^3$ at the Ust'-Srednekan station (near the dam site) and 3.5 km$^3$ at the Srednekolunsk station. The regulation effect is expected to decrease from the dam site to downstream. However, flow increases are higher at the Srednekolunsk station and lower at the dam site. The Srednekolunsk station is 1720 km downstream of the dam. It receives runoff contribution from other tributaries. Yearly flow at the Srednekolunsk station is much higher (71 km$^3$) than that (25 km$^3$) near the dam site. Because of lack of flow data for the tributaries above the Srednekolunsk station, it is impossible to use discharge data at these stations (currently available for this analysis) to accurately determine the impact of dam regulation in the mid- and lower parts of the basin. Additional flow data are necessary to calculate the tributary runoff contribution and secular streamflow budget. Differences in both yearly flow amount and trend found between the Srednekolunsk station and the dam site seem to imply that dam regulation cannot account for 100% of the observed increases in winter discharge near the basin outlet. It also suggests that other factors, such as climate effects and permafrost changes, may influence streamflow change over this part of the basin.

### h. *Kolymskoye (lower basin)*

The Kolymskoye station (station H in Fig. 1) is located above the mouth of the Kolyma River; it is the nearest station to the basin outlet. Discharge data collected at or near the basin outlet are particularly important, as they have been used for validations of hydrological/land surface models and GCMs. The monthly flow data at the Kolymskoye station are available during 1978–2000. The monthly mean discharge (Fig. 2a) is low from November to April (47–18 m$^3$ s$^{-1}$) and high during May to June (178–754 m$^3$ s$^{-1}$), with the highest flow in June (1490 m$^3$ s$^{-1}$) during the snowmelt season. Discharge from August to October varies from 602 to 180 m$^3$ s$^{-1}$. The peak flow in June is about 80 times greater than the lowest flow in April. Following the pattern of monthly mean discharge, the standard deviations of monthly flow are low for November to April (129–109 m$^3$ s$^{-1}$) and higher during May to June (1464–4844 m$^3$ s$^{-1}$) (Fig. 2b).

Comparisons of the long-term mean streamflow between the pre- and post-dam periods demonstrate significant changes (Fig. 4d). In the post-dam era, peak

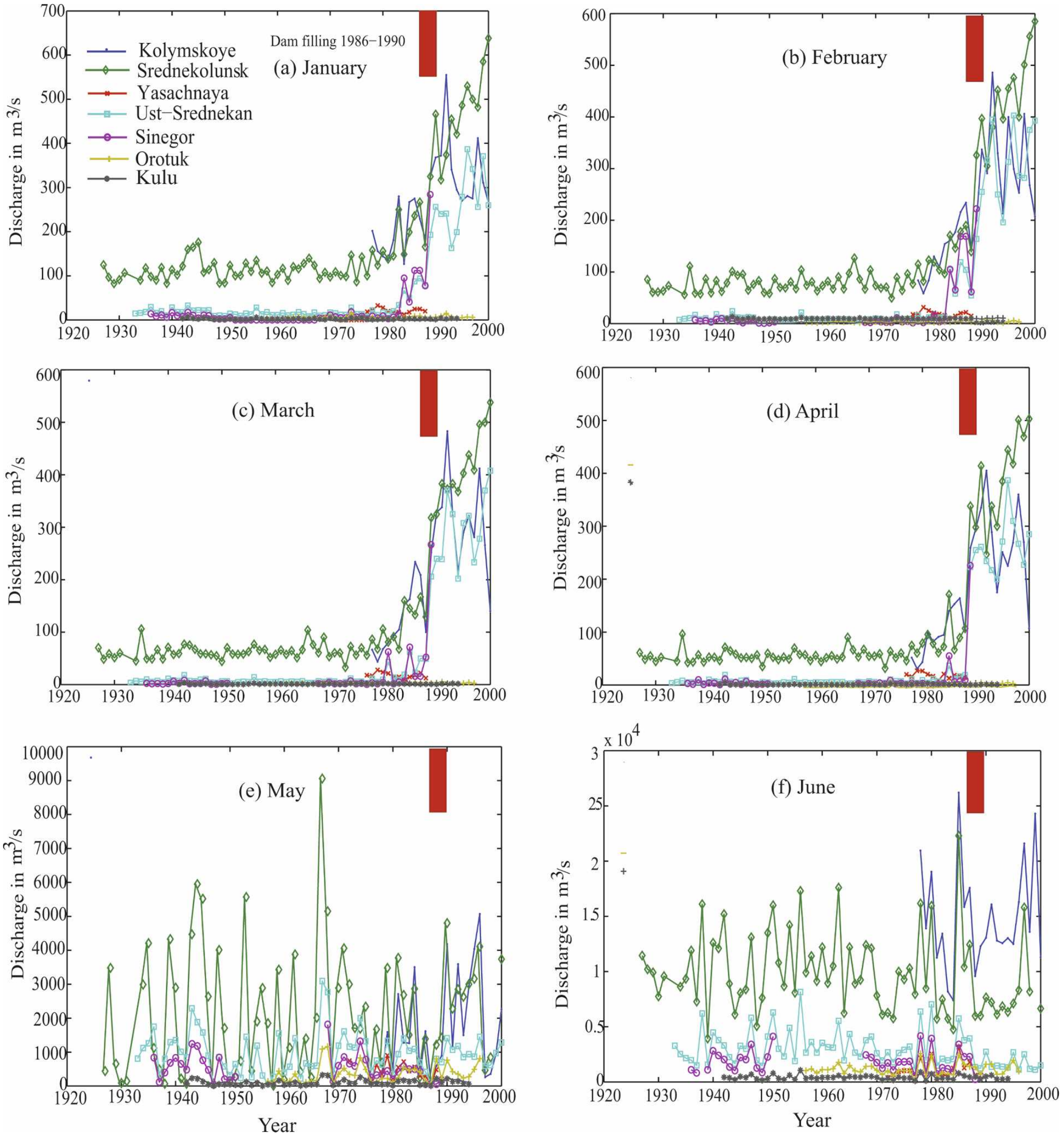

FIG. 5. Monthly discharge records at selected hydrologic stations in the basin; the bar indicates the filling period from 1986 to 1990.

flows decreased by 217 $m^3 s^{-1}$ (1%) in June, 3710 $m^3 s^{-1}$ (37%) in July, and 1189 $m^3 s^{-1}$ (17%) in August. Discharge increased by 1051 $m^3 s^{-1}$ in September and by 433 $m^3 s^{-1}$ in October, respectively. The most significant impact of reservoir regulation is seen during the cold season from November to April, when flows increased by 32% (127 $m^3 s^{-1}$) in December to 208% (164 $m^3 s^{-1}$) in April.

The Kolymskoye station is located 1902 km downstream of the reservoir. Streamflow routing and runoff contribution from tributaries subdue the effect of dam regulation. Monthly flow records during 1978–2000 at this station (Fig. 5) show significant changes. Total trends over 1978–2000 were 229 to 250 $m^3 s^{-1}$ during November to April (Fig. 2c), with the highest increase of 250 $m^3 s^{-1}$ (400%) in April. Changes in March and February were 275 (350%) and 263 $m^3 s^{-1}$ (275%), respectively. Negative trends were found for July, 4982 $m^3 s^{-1}$ (−49%), and August, 1490 $m^3 s^{-1}$ (−22%) (Fig. 2c), and a weaker increase of 925 $m^3 s^{-1}$ (6%) was seen in June. The remaining months have positive trends of 40%–109%. Annual discharge at the Kolymskoye station shows a weak decrease of 1.5% during 1978–2000 (Fig. 3). This decrease seems to be consistent with climate changes over the basin, since basin yearly temperature increased and precipitation decreased slightly during 1978–2000 (Fig. 6).

Dam regulation also affects the interannual variation

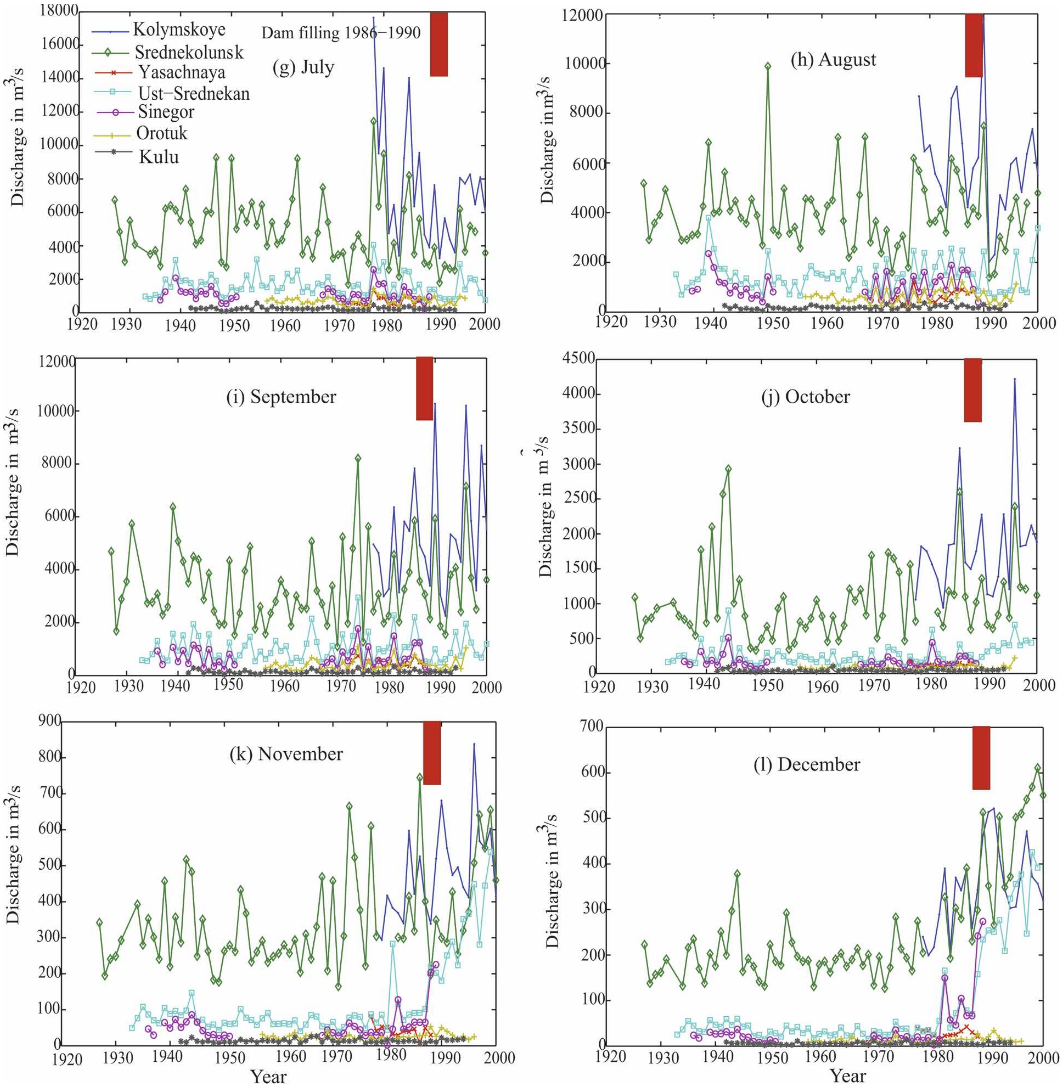

FIG. 5. (*Continued*)

in streamflow. To determine the changes in flow variation, we calculated and compared the standard deviation of monthly streamflow between the pre- and post-dam periods at the four stations downstream of the dam (Fig. 7). The results show that, relative to the pre-dam period, the post-dam streamflow variations increase during the low flow months (November–April), and decrease in high flow season (June–July). This means that dam impacts on flow variation differ over the season.

### i. Eastern tributaries

There are five major unregulated tributaries in the eastern part of the Kolyma basin. To understand the streamflow characteristics and changes mainly due to natural causes over the eastern Kolyma basin, two control stations on the main eastern tributaries, that is, the Bol'shoy Anuy (station I in Fig. 1) at the Konstantinovo Valley and the Oloy station (J in Fig. 1) at the Utuchan Valley were analyzed in this study. The Bol'shoy Anuy station has a drainage area of 49 600 km$^2$ and the Oloy station controls a drainage area of 15 700 km$^2$. The monthly mean flows at the Bol'shoy Anuy station are characteristic of the Kolyma basin, with high discharge (292–67 m$^3$ s$^{-1}$) from May to October, the maximum discharge in June (1272 m$^3$ s$^{-1}$), and very low flows from November (16 m$^3$ s$^{-1}$) to April (2 m$^3$ s$^{-1}$) (Fig. 8a). Flow records collected at the Oloy station during 1975–98 show that monthly mean streamflow are high (40–35 m$^3$ s$^{-1}$) from May to October, with the maximum discharge in June (488 m$^3$ s$^{-1}$), and very low discharge from November (13 m$^3$ s$^{-1}$) to April (7 m$^3$ s$^{-1}$) (Fig. 8a).

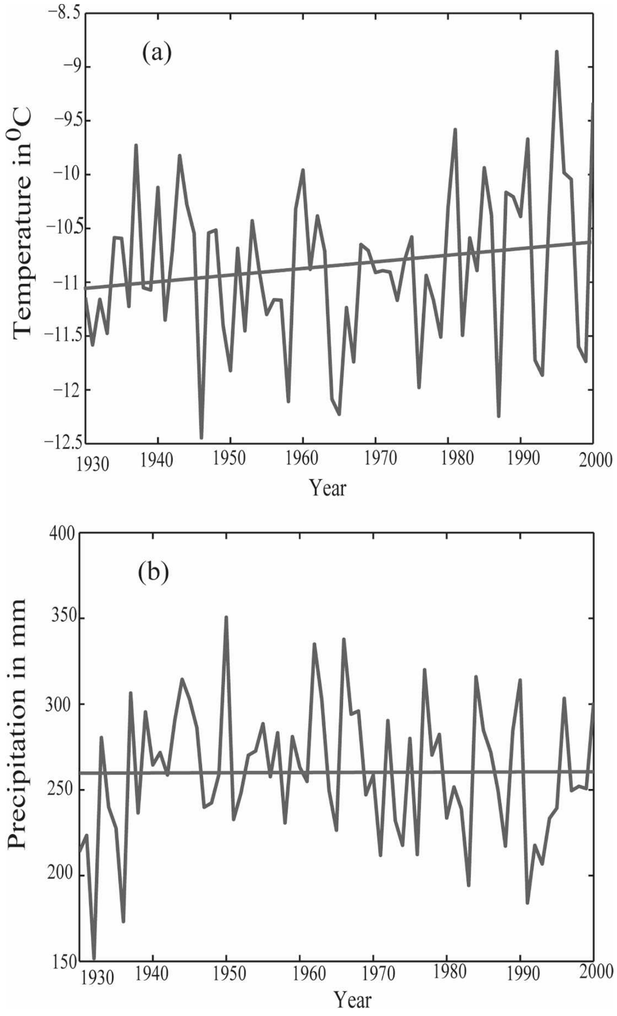

FIG. 6. (a) Basin-mean annual temperature and (b) annual precipitation records from 1930 to 2000.

Trend analyses for the Bol'shoy Anuy station during 1978–2000 show total flow decreases in May ($-17$ m$^3$ s$^{-1}$), July ($-426$ m$^3$ s$^{-1}$), August ($-135$ m$^3$ s$^{-1}$), and October ($-20$ m$^3$ s$^{-1}$); positive trends in June (239 m$^3$ s$^{-1}$), September (82 m$^3$ s$^{-1}$), and little changes during November to April (Fig. 8b). These monthly flow changes caused an annual discharge decrease of 8% during 1978–2000. Discharge data records at the Oloy station during 1975–88 indicate increasing trends (0.2–9.8 m$^3$ s$^{-1}$) during November to April, and decreasing trends of 0.8 m$^3$ s$^{-1}$ in June, 33.9 m$^3$ s$^{-1}$ in July, and 85.5 m$^3$ s$^{-1}$ for September. Annual discharge decreased by 3 m$^3$ s$^{-1}$ (3%) over the period 1975–88. It is important to notice the clear difference in flow trends between the regulated and unregulated subbasins of the Kolyma River. For instance, low flow trends are much smaller in the unregulated eastern tributaries (Fig. 8b) and very high in the regulated main valley, such as at the Kolymskoye station near the basin outlet (Fig. 2a). This clearly demonstrates the effect of dam regulation that caused winter flow increases in the main river valley.

## 4. Conclusions

Climate over the Arctic regions has significantly changed in the last decades (Chapman and Walsh 1993; Serreze et al. 2000). This study investigates Kolyma River hydrologic regimes and changes induced by reservoir regulation and climate variations. Streamflow records show that the Kolyma basin has the basic characteristic of permafrost regions, with low flow from November to April and high discharge during May to August. Changes in monthly discharge are different for the upper, middle, and lower parts of the basin. In the upper basin without dam regulation, streamflow increased for most months. The increases were weak during November to May, and strong for August and September, while flow decreased weakly in June and July over the Kulu Valley (source of the Kolyma basin). The two eastern tributaries did not show consistency in streamflow trends. In the Konstantine Valley, discharge decreased weakly in March, May, and October and strongly in July and August; and increased strongly in both June and September and weakly during November–February and in April.

Dams have a major influence on watershed storage, discharge regime, and change (Vorosmarty et al. 1997; Yang et al. 2004a,b; Ye et al. 2003). Over the mid–lower parts of the basin (downstream of the dam), streamflow increased during the low flow season, and decreased in the high flow months, because reservoirs store water during the peak flow season and release water during the low flow season. For instance, over the post-dam period (1986–2000), streamflow at the Ust'-Srednekan station (1493 km downstream of the dam) suddenly increased by 522%–3157% during December to April, and decreased by 41% in July. Similarly, comparisons of pre- and post-dam mean monthly flows at the Srednekolunsk station (1720 km downstream of the dam) show low flow increases of 130 m$^3$ s$^{-1}$ (43%)–268 m$^3$ s$^{-1}$ (454%) from November to April, and high discharge decreases by 2550–519 m$^3$ s$^{-1}$ during June to August in the post-dam era. Comparisons of flow changes between the two downstream stations demonstrate the diminishing effect of the dam as the distance between the dam and the station increases. Changes in seasonal streamflow, particularly the increases in low flows, over the mid–lower reaches of the Kolyma basin is partly due to dam regulation. A study by Ye et al. (2003) for the Lena basin found similar results, and they reported that cold season increase in discharge is a combination of both reservoir regulation and natural

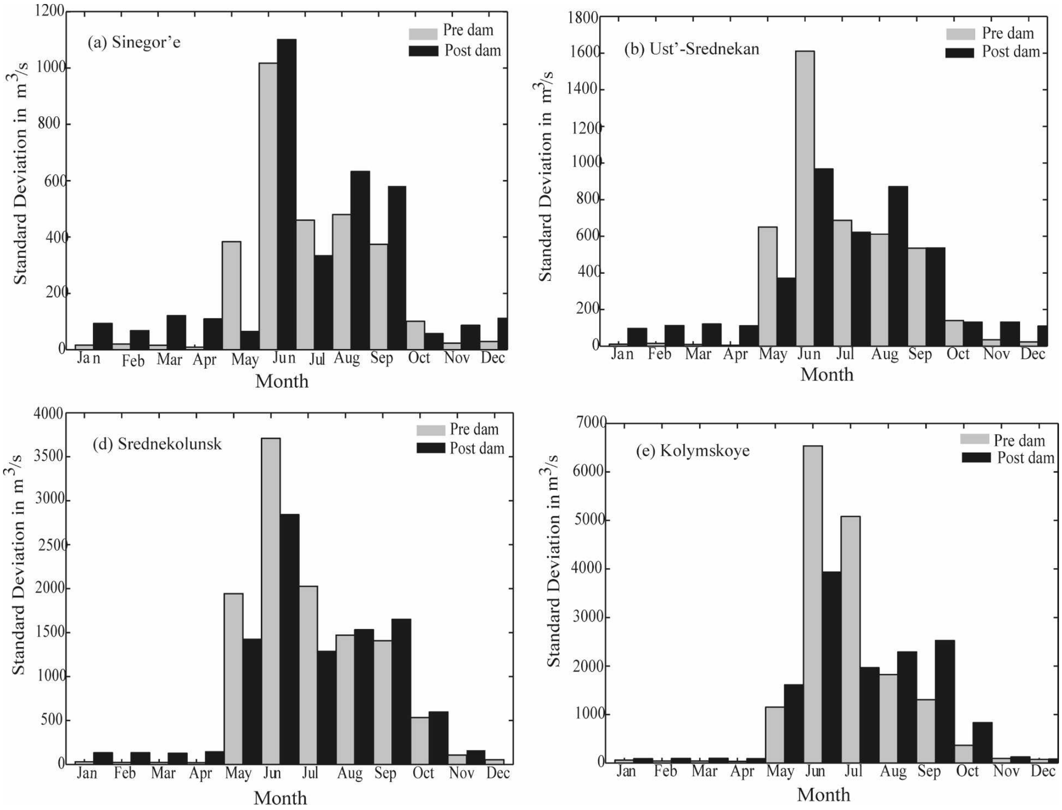

FIG. 7. Comparison of standard deviation of discharge at four stations between the pre- and post-dam periods.

runoff changes. Because of the dramatic hydrologic changes caused by the dam regulation in the Kolyma watershed, it is difficult to detect streamflow changes due to natural causes in the regulated mid–lower basins.

Annual discharge records show different changes within the Kolyma basin. The upper basin (upstream of the dam) shows yearly runoff increases of 10%, 19%, and 22% at the Kulu, Duscania, and Orotuk stations, respectively. The two eastern tributaries have flow decreases by 8% and 3% at the Bolsoy Anuy and Oloy stations, respectively. Annual flow decreased by about 2%–4% over the mid–lower basin (downstream of the dam) partly due to reservoir regulation. Similar to the temperature changes reported in Symon et al. (2005) over the Arctic regions, the Kolyma basin climate records show an annual warming trend of 0.4°C during 1930–2000. The seasonal basin temperatures show a cooling trend during November to December. Similar changes in winter temperatures were reported by Chapman and Walsh (1993) for the east Siberian regions. Basin yearly precipitation showed a decrease during the last 4–5 decades. These changes are somewhat consistent with river runoff decrease over the Kolyma basin as a whole; discharge changes in the unregulated subbasins are perhaps mainly due to climate variations. However, given the weak changes in climate over the basin, the weak decreases in yearly runoff near the basin outlet is also likely due to dam impact, such as infiltration and evaporation water losses from the large reservoir (Jansen 1988). Regardless of the cause, it is important to note that the Kolyma River discharge into the Arctic Ocean has decreased slightly over the past 20 yr. Long-term (1927–2000) data collected at the Srednekolunsk station (181 km above the Kolymskoye station) show discharge decrease by 11%. The Kolyma basin is one of the six largest Siberian rivers analyzed by Peterson et al. (2002), and this river showed no increase in yearly discharge.

Seasonal discharge changes are stronger and easier to detect than the annual flow changes. Recent analyses have shown discharge increases in the winter season for the Ob, Yenisei, and Lena Rivers (Ye et al. 2003; Yang et al. 2004a,b), where human impacts are predominant due to dam constructions, farming, mining, and other activities. Macdonald (2002) suggested that timing of freshwater input is important and change in seasonal streamflow, increase in winter flow at the expense of summer inflow, could stall convection of shelf. On the other hand, insignificant change was found for the less developed regions, such as the Mackenzie basin in

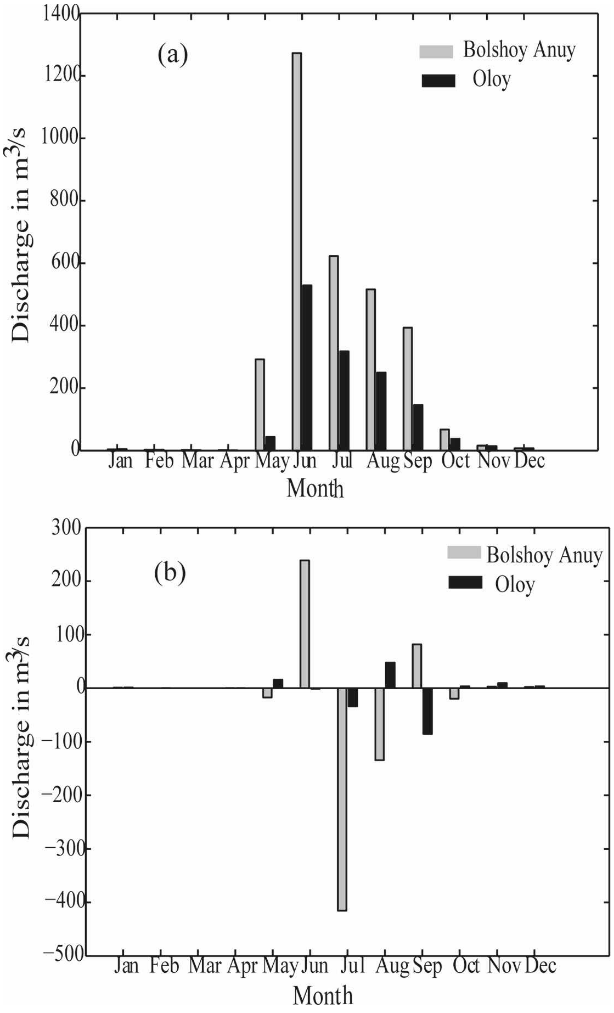

FIG. 8. (a) Monthly mean and (b) trend at two stations in the eastern tributaries (the Konstantine and Oloy Valleys).

northern Canada (Dynesius and Nilsson 1994; Revenga et al. 1998; Dery and Wood 2005). This study identifies major changes in streamflow seasonal cycle over the Kolyma basin due to reservoir regulation; it clearly underlines the importance of human activities in regional and global environment changes. Further research is necessary to better understand climate impact on river discharge changes, particularly the relationships among river streamflow, basin temperature, precipitation, and snow cover changes.

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