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Rising minimum daily flows in northern Eurasian rivers: A growing influence of groundwater in the high-latitude hydrologic cycle

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[1] A first analysis of new daily discharge data for 111 northern rivers from 1936–1999 and 1958–1989 finds an overall pattern of increasing minimum daily flows (or "low flows") throughout Russia. These increases are generally more abundant than are increases in mean flow and appear to drive much of the overall rise in mean flow observed here and in previous studies. Minimum flow decreases have also occurred but are less abundant. The minimum flow increases are found in summer as well as winter and in nonpermafrost as well as permafrost terrain. No robust spatial contrasts are found between the European Russia, Ob', Yenisey, and Lena/eastern Siberia sectors. A subset of 12 unusually long discharge records from 1935–2002, concentrated in south central Russia, suggests that recent minimum flow increases since ~1985 are largely unprecedented in the instrumental record, at least for this small group of stations. If minimum flows are presumed sensitive to groundwater and unsaturated zone inputs to river discharge, then the data suggest a broad-scale mobilization of such water sources in the late 20th century. We speculate that reduced intensity of seasonal ground freezing, together with precipitation increases, might drive much of the well documented but poorly understood increases in river discharge to the Arctic Ocean.

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1. Introduction and Literature Review

[2] Twentieth century discharge increases observed in river runoff to the Arctic Ocean have attracted considerable scientific attention, including this special section of *Journal of Geophysical Research*. From a global perspective a key interest in the phenomenon lies in the extent to which it may increase Arctic Ocean freshwater export to the North Atlantic, thereby weakening or halting North Atlantic Deep Water (NADW) formation, causing subsequent disruptions to the Atlantic thermohaline circulation and global climate [*Rahmstorf*, 1995; *Broecker*, 1997; *Rahmstorf*, 2002; *Vellinga and Wood*, 2002; *Arnell*, 2005]. Declining salinities in recent decades suggest a North Atlantic freshening could already be underway [*Curry et al.*, 2003; *Curry and Mauritzen*, 2005]. However, NADW formation may be more sensitive to some freshwater inputs than others, so the geographic location of river discharge changes is relevant to the problem [*McClelland et al.*, 2006; *Rennermalm et al.*, 2007]. Discharge timing may also be a factor. For example, increasing winter flows relative to summer flows could stall convection on the Eurasian shelf [*Macdonald*, 2000; *Yang et al.*, 2004a]. At more local scales, high river flows facilitate the exchange of water, sediment, and nutrients between channels and surrounding wetlands [*Smith and Alsdorf*, 1998] and (together with ice regime, geochemical and sediment loads, and temperature) exert an important control on primary production, habitat, and food web dynamics in northern rivers and estuaries [*Scrimgeour et al.*, 1994; *Prowse et al.*, 2006]. For these and other scientific reasons, better knowledge of the volume, timing, and natural variability of river discharge has been defined as a major priority in the study of Arctic systems [*Vörösmarty et al.*, 2001].

[3] Much of the clearest evidence for rising high-latitude river discharge comes from Eurasia. In western Siberia and European Russia, *Georgievskii et al.* [1996] found late summer, fall, and winter discharge increases of +20–40% over the period 1978–1990 relative to long-term discharge means for 70 medium-sized (5 to 50,000 km^2) rivers with long station records (>60 years (a)). *Lammers et al.* [2001] found statistically significant increases in winter runoff to the Beaufort, Kara, Laptev, and Bering seas beginning in the 1980s. An integrated assessment of total annual river outflows from the Yenisey, Lena, Ob', Pechora, Kolyma, and Severnaya Dvina rivers to the Arctic Ocean revealed a +7% overall discharge increase over the period 1936–1999 [*Peterson et al.*, 2002]. *Berezovskaya et al.* [2004] showed much of that increase was driven by positive trends in the

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Lena and Yenisey Rivers (+20 and +9 mm/63 a, respectively, over the nearly identical period 1936–1998), with no corresponding increase in the Ob' River. *Serreze et al.* [2002] showed that the Lena and Yenisey increases are greatest from October through May, particularly in the Yenisey (~6–8 mm/29 a as opposed to ~1–2 mm/29 a in the Lena). However, for the Yenisey, at least part of this effect is attributed to the construction of six large reservoirs during the 1950s–1960s, including the basin's largest (169 km^3), completed in 1964 at Bratsk [*Yang et al.*, 2004a]. A similar effect is seen on the Ob' River, where wintertime discharge increases associated with dam regulation are offset by summertime decreases [*Yang et al.*, 2004b]. In general, the effect of reservoirs is to alter discharge seasonality by suppressing flows in summer and increasing them in winter [*McClelland et al.*, 2004]. On the Lena River this began after 1967 when dam construction commenced on one of its major tributaries, the Vilui River [*Ye et al.*, 2003]. Since 1970, winter discharge measured at the Lena River outlet (at Kusur) has increased by about the same amount as the reservoir-induced increase in the Vilui (+800 m^3/s [*Berezovskaya et al.*, 2005]). Analysis of gauging stations upstream of the Vilui, however, suggests that increased precipitation and rising temperatures may also play a significant role in observed discharge increases on the Lena [*Ye et al.*, 2003; *Yang et al.*, 2002].

[4] In addition to the complications posed by dams, it is now also clear that discharge changes are not universal, evenly distributed, or even necessarily of the same sign from region to region [*McClelland et al.*, 2006]. Within Eurasia an exhaustive analysis of 198 basins found many regional contrasts in even the direction of trend [*Pavelsky and Smith*, 2006]. In northern Canada, overall total annual outflows declined 10% from 1964–2003, except for outflows to the Arctic Ocean, which increased by +2% [*Déry and Wood*, 2005]. In Canada's Mackenzie River, total annual discharge did not change over the period 1968–1999 despite a warming trend [*Woo and Thorne*, 2003]. A clear explanation for these apparent contrasts is currently lacking, but part of the problem lies in the use of different analysis periods and data sets [*McClelland et al.*, 2006]. Hydrologic systems are also inherently variable in both time and space.

[5] The physical mechanism(s) driving the observed trends in both monthly and annual river discharge continue to fuel debate. Changes in precipitation, permafrost, fire frequency, and plant transpiration (from CO_2-induced stomatal closure) have all been posited [e.g., *Serreze et al.*, 2002; *Peterson et al.*, 2002; *Zhang et al.*, 2000, 2005; *McClelland et al.*, 2004; *Gedney et al.*, 2006]. Reservoir effects, while not responsible for the observed long-term increases in annual discharge [*McClelland et al.*, 2004], alter the seasonality of streamflow substantially, rendering difficult mechanistic interpretations of subannual discharge data. Similarly, the apportionment between snowfall and rainfall can affect streamflow seasonality [*Rawlins et al.*, 2006]. The finding of a general inconsistency between runoff and several precipitation data sets [*Berezovskaya et al.*, 2004] suggests that either the existing precipitation products are unable to adequately capture the high-latitude precipitation field, or some other process (or processes) is at play. Permafrost thaw, with its associated melting of ground ice, is a potentially large water source and has thus drawn considerable scrutiny [*Zhang et al.*, 1999, 2000, 2005; *Serreze et al.*, 2002; *McClelland et al.*, 2004; *Lawrence and Slater*, 2005; *Pavelsky and Smith*, 2006; *Walvoord and Striegl*, 2007]. However, on the basis of volumetric calculations using plausible thaw depths, *McClelland et al.* [2004] argue that unreasonably deep permafrost thaw is required to explain the observed discharge increases. Returning to precipitation, recent high-resolution studies using additional river gauging stations in Russia [*Berezovskaya et al.*, 2005; *Pavelsky and Smith*, 2006] and Canada [*Déry and Wood*, 2005] report better agreement between runoff and precipitation, as does a recent modeling study [*Manabe et al.*, 2004; *Wu et al.*, 2005]. However, *Rawlins et al.* [2006] find such correlations only from 1936–1970, after which annual discharge increases but precipitation declines. *Dai et al.* [2004] suggest that evaporation losses must also be considered in addition to precipitation, but *Serreze et al.* [2002] found rather low correlations between P-E and discharge except over the Lena basin. *Adam and Lettenmaier* [2007] suggest that the mechanism behind observed discharge increases may vary from region to region, with permafrost thaw dominating the Yenisey basin, precipitation driving Ob' discharge, and some combination of increased precipitation and melting ground ice influencing the Lena. Clearly, the issue of mechanism(s) remains an important open question.

[6] All of the described studies use either annual or monthly means of river discharge, and nearly all focus on the largest rivers, which are prone to the effects of damming. Here we present a first analysis of a new data set of daily discharge records from 138 small to medium-sized unregulated rivers in northern Eurasia [*Shiklomanov et al.*, 2007]. Furthermore, we advance the use of daily minimum flow (or "low flows") as a different and possibly more illuminating hydrologic variable than mean flow for the purpose of climate change detection. Our prime motivation lies in the presumption that low flows are more indicative of slow release water sources (i.e., subsurface or groundwater contributions) than are mean or maximum flow. As such, our approach differs somewhat from other studies that employ daily hydrologic data, e.g., maximum daily flow [*Burn*, 1994; *Shiklomanov et al.*, 2007] and ice timing [*Smith*, 2000; *Magnuson et al.*, 2000; *Hodgkins et al.*, 2005].

[7] The new daily records of *Shiklomanov et al.* [2007] start as early as 1913 and end as late as 2003, with more than half beginning by the 1930s. Forty-eight records end between 1987 and 1994, a time of many station closures in the former Soviet Union [*Shiklomanov et al.*, 2002]. Prior to this new data set, daily discharge data have been rare in digital form except for a limited subset of stations near the largest river mouths (http://rims.unh.edu). Because this is one of the first examinations of a large daily data set, climate variables are not incorporated in the analysis, and complex hydrograph techniques (e.g., baseflow separation of rainfall-runoff events) are not attempted. Instead, we focus on providing a first continental-scale assessment of low-flow trends since the 1930s, with the expectation that future research will address trend attribution through cross correlation with causal variables. Specifically, our objectives are to (1) assess any changes in daily river low flows (minimum flows) across northern Eurasia since the 1930s;

(2) compare any low-flow changes with corresponding mean flow changes; (3) determine whether the presence or absence of permafrost appears important to observed low-flow trends; and (4) evaluate some very recent low-flow changes (up to 2002) using the most updated data possible. These objectives are achieved using ordinary linear regression and the nonparametric Mann-Kendall test to establish trend magnitude and significance, respectively, for month-of-year (m.o.y.) time series of minimum daily discharge from 1936–1999 and 1958–1989. These particular study periods were chosen to maximize overlap among the available records and also conform with *Pavelsky and Smith* [2006]. Very recent changes, as well as some temporal context between the two study periods, are established with a small subset of 12 unusually complete discharge records from 1935 to 2002.

2. Methodology

2.1. Significance of Minimum Flows

[8] To gain a process-based understanding of river flow, daily time series of discharge (hydrographs) are superior to monthly or annual discharge means, as their higher temporal resolution allows fine-scale phenomena to be resolved. In particular, the timing and magnitude of flow extremes, as well as dynamic structures (e.g., flood waves and recession flows) are captured. Extraction of extremes (i.e. maximum or minimum discharge) is one of the more common uses of daily data. For example, minimum flow data are valued in fisheries science and to detect the effects of anthropogenic change [*Rogers et al.*, 2005; *Magilligan and Nislow*, 2005]. Identifying extremes within some arbitrary time step yields a derivative time series (typically yearly, quarterly, or monthly) of high or low flows, which is then used by hydrologists and civil engineers to construct probability density functions for flood and/or drought risk assessment [*Maidment*, 1993]. Here we examine discharge minima, the streamflow quantity most sensitive to groundwater and/or unsaturated zone water inputs to river discharge [*Smakhtin*, 2001]. The term "baseflow" is commonly used to describe these inputs and refers to that portion of river discharge produced from water movement through the subsurface into the river channel. In principle, it is possible for minimum daily flows to correspond to true baseflow, e.g., after a prolonged period with no rainfall. In practice, minimum daily flows are at best an approximation of, and almost always exceed, true baseflow.

[9] Over the years a variety of so-called "baseflow separation" techniques have been proposed to partition hourly or daily streamflow hydrographs into components of surface runoff and baseflow [*Sujono et al.*, 2004]. Most rely on visual methods or empirical approximations and are highly time-intensive. Results vary widely by method and are difficult or impossible to validate. Geochemical methods using isotopes or other conservative tracers hold promise for validation [*Marc et al.*, 2001] but require field sampling. In this study we maintain that minimum flows are not equivalent to true baseflow but are nonetheless sensitive to baseflow (a presumption of all separation techniques). They are certainly more correlative with groundwater input to streams than either mean or maximum discharge [*Smakhtin*, 2001]. Therefore an analysis of minimum flow explores something fundamentally different from either mean or maximum flow. This study presumes minimum flow to be the hydrologic variable most sensitive to subsurface water contributions to river discharge.

2.2. Daily River Discharge Data from R-ArcticNet Version 4.0

[10] Daily time series of river discharge for 138 stations were manually digitized from paper yearbook records archived at the State Hydrologic Institute (SHI) in Saint Petersburg, Russia. The primary criteria for station selection were small to medium basin size (16.1–49,500 km^2), inclusion of stations from permafrost as well as nonpermafrost terrain, an absence of dams or other impoundments, and long data records. The basin-size criterion was imposed to enhance capture of process-scale signals in the hydrographs (i.e., melt pulses, rainfall-runoff events, and recessions that more closely approach true baseflow), features that are typically muted in hydrographs from larger basins. Record lengths range from 18–69 a and the earliest generally start in the late 1930s. For full description of the new daily data set, the reader is referred to *Shiklomanov et al.* [2007].

[11] For each station record, monthly time series of minimum daily flow were generated from the new R-ArcticNet v4.0 daily database by extracting the lowest daily discharge for each month-of-year (m.o.y.) under the following data requirements. To extract a minimum daily flow value for each month, we required a minimum of 10 entries per month to be present in the daily discharge data during the ice cover season from October to May (discharge measurements through ice were not always collected every day) and at least 20 entries per month to be present from June–September (open water season). Once the minimum daily discharge values were identified for each month, the resulting m.o.y. time series were selected for analysis only if they were >90% complete over the study period (1958–1989 or 1936–1999). Up to 12 monthly time series of minimum daily flow (January minimum flows, February minimum flows, etc.) were thus generated from each station record. Because the generated time series use a monthly time step, we used units of mm/month rather than mm/d; that is, the daily minimum flow value was multiplied by the number of days in that month. For those stations where time series for all 12 months were produced, annual means were computed by averaging all 12 monthly minimum values for each year.

[12] Trend slopes in the minimum flow time series were computed using ordinary least squares regression in the manner of previous studies [*Berezovskaya et al.*, 2004; *Yang et al.*, 2004a, 2004b; *Liu et al.*, 2005; *Pavelsky and Smith*, 2006]. Mean flow trends were also computed for comparison with the minimum flow trends. Trend significance at the 90% confidence level was determined using the nonparametric Mann-Kendall test [*Mann*, 1945; *Kendall*, 1975] which has emerged as something of a standard in high-latitude hydrologic trend studies [e.g., *Burn*, 1994; *Smith*, 2000; *Lammers et al.*, 2001; *Burn and Elnur*, 2002; *Déry and Wood*, 2005; *McClelland et al.*, 2006; *Pavelsky and Smith*, 2006]. The Mann-Kendall test is appropriate when a variety of stations are being tested in a single study or there is no a priori hypothesis of a time of change [*Hirsch et al.*,

Figure 1. Location of stations analyzed for 1936–1999 and 1958–1989 (dark gray squares); 1958–1989 only (light gray circles); and 1935–2002 (black diamonds). Shaded areas indicate permafrost [from *Brown et al.*, 1997], with darkest shade representing continuous permafrost and lightest shade representing isolated permafrost.

1991]. To avoid serial correlation and the need for ''prewhitening'' of the data [*Burn and Elnur*, 2002], the Mann-Kendall test was applied to the m.o.y. rather than continuous time series (i.e., January minimum daily flows, February minimum daily flows, etc.). Performing the analysis in this way also served to increase sample size, because records from stations having data for some months but not others could still be incorporated in the analysis. Finally, to test for the possibility that summer minimum flow changes are driven by precipitation (i.e., residual recession flows from storms), we compared all July, August, and September monthly minimum flow values with corresponding monthly precipitation totals previously compiled for 41 of our 108 study basins [*Pavelsky and Smith*, 2006]. Near-zero correlation between the two variables (r^2 = 0.08, 0.04, and 0.00 for July, August, and September, respectively) lends confidence to the presumption that summer minimum flows are correlative with variations in subsurface water sources, rather than precipitation events.

3. Results

[13] Of the 138 stations in the new R-ArcticNet daily discharge database [*Shiklomanov et al.*, 2007], 111 and 33 satisfied our data quality requirements from 1958–1989 and 1936–1999, respectively, for at least 1 month of the year (Figure 1 and Table 1). It should be noted that in no month do all of the stations meet our criteria; the maximum number of stations available in any 1 month is 108 and 30, respectively, for the two time periods. Twelve stations with long and unusually complete records from 1935–2002 were also identified (Figure 1). Analysis of these data yields the following: (section 3.1) a first synoptic assessment of Eurasian minimum flow trends, one that is spatially limited from 1936–1999 but quite comprehensive from 1958–1989, showing that the number of minimum flow increases substantially exceeded minimum flow decreases over the two study periods; (section 3.2) the minimum flow increases were generally consistent across the European Russia, Ob', Yenisey, and Lena/eastern Siberia subregions; (section 3.3) both permafrost and nonpermafrost areas were susceptible to these changes; and (section 3.4) the minimum flow increases since ~1985 are generally at or near their highest levels since 1935.

3.1. Synoptic Patterns in Minimum Flow, 1936–1999 and 1958–1989

[14] Linear trends fit through all month-of-year (m.o.y.) minimum and mean daily flows for all stations are presented for 1936–1999 in Figure 2 and for 1958–1989 in Figure 3. Annual values, computed for only those stations with complete data throughout all 12 months of the year, are shown in Figure 4. Trend magnitudes are ranked from most negative (decreasing flow) to most positive (increasing flow), with minimum flow trends shown in blue and mean flow trends shown in red. Note that the number of stations (*n*) was greatest from 1958–1989 and also varied with m.o.y. (*n* = 19–30 from 1936–1999 and *n* = 94–108 from 1958–1989). As is typical for high-latitude hydrologic data, station coverage was most extensive during summer.

[15] Figures 2, 3, and 4 reveal an overall pattern of abundant increases in minimum flow during the latter 20th century (see also Tables 2 and 3). Minimum flow declines also occurred but are clearly in the minority. In terms of absolute magnitude the minimum flow trends represent a large share of the overall trends in mean flow (Figures 2, 3, and 4). During 1936–1999 the number of minimum flow increases exceeded the number of minimum flow decreases for all months except May, June, and September (Figure 2; see also Table 2). From 1958–1989 the number of minimum flow increases exceeded the number of minimum flow decreases for all months of the year (Figure 3; see also Table 3). Interestingly, increases in mean flow, the variable examined in all previous studies, are less widespread and occur mainly in winter, when minimum and mean flow are more or less equivalent. For this reason,

Table 1. Summary Statistics for All 111 Basins Used in the Analysis[a]

Code	Name	Basin Area, km	Lat	Long	Perm Cat	Comp Ratio 58–89	Comp Ratio 36–99	Min Δ_{mm} 58–89	Mean Δ_{mm} 58–89	Min Δ% 58–89	Mean Δ% 58–89	Min Δ_{mm} 36–99	Mean Δ_{mm} 36–99	Min Δ% 36–99	Mean Δ% 36–99
							European Russia								
49017	Tumcha at Alakurtty	2100	66.9	30.33	L	0.98	0.52	2.616	5.154	15.295	15.950				
49033	Pueta at Kem	48	64.95	34.62	L	0.97	0.52	−0.309	−0.543	−0.152	−0.140				
49036	Kem at Yushkozero	19,800	64.78	32.17	L	0.93	0.69	0.000	0.001	0.002	0.003				
49052	Ukhta at Kalevala	361	65.22	31.15	L	0.97	0.56	0.007	0.004	0.042	0.012				
49055	Chirko-Kem at Andronova Gora	2730	64.15	32.38	L	0.90	0.54								
49070	Shuya at Shuyeretskoye	934	64.75	34.7	L	0.97	0.80	0.003	0.006	0.030	0.025				
49123	Suma at Sumskiy Posad	1990	64.25	35.43	L	0.96	0.72	0.000	0.000	0.002	0.001				
49126	Maloshuika at Maloshuika	481	63.75	37.4	L	0.97	0.60	0.001	0.002	0.013	0.007				
70016	Vozhega at Nazarovskaya	1590	60.53	39.55	L	0.97	0.52	3.645	−1.640	61.327	−6.271				
70023	Lekshma at Lyadiny	321	61.57	38.28	L	0.91	0.46	2.278	−0.727	16.349	−3.103				
70043	Kodina at Kodino	1800	63.72	39.62	L	1.00	0.61	0.844	−0.611	6.544	−2.276				
70047	Solza at Sukhie Porogy	1190	64.38	39.4	L	0.94	0.78								
70085	Sukhona at Raban'ga	15,500	59.43	40.22	L	0.85	0.56								
70117	Kubena at Troitse-Yenal'skoye	1110	60.55	40.42	L	0.97	0.76	2.957	−2.449	50.199	−9.123				
70129	Ema at Novoye	179	59.12	39.67	L	0.97	0.64	3.052	1.380	249.991	7.052				
70146	Uphtyuga at Koleno	2360	60.38	44.13	L	0.97	0.57	0.003	0.004	0.046	0.019				
70209	Voch at Verkhnaya Voch	1600	61.13	54.2	L	0.91	0.46	3.388	9.438	47.002	48.753				
70231	Egul at Chukhlom	123	61.25	50.1	L	0.97	0.66	3.304	6.536	93.227	38.804				
70238	Vim at Veslyana	19,100	62.98	50.88	L	0.97	0.74	1.568	−0.604	12.262	−2.212				
70302	Lel' at Zeleninskaya	2240	62.25	42.67	L	0.96	0.67	−0.115	0.070	−1.317	0.353				
70309	Yemtsa at Most	1860	62.97	40.32	L	0.95	0.74								
70363	Zolotitsa at Verkhnaya Zolotitsa	1840	65.67	40.42	L	0.97	0.50	0.000	0.000	0.002	−0.001				
70366	Kuloy at Kuloy	3040	64.97	43.52	L	0.91	0.82								
70452	Vel'-Yu at Konosh-Yel'	2050	63.4	55.8	L	0.92	0.46	0.000	0.000	0.000	−0.001				
70497	Khoseda-Yu at Khoseda-khard	2280	67.03	59.4	I	0.83	0.42								
70499	Kolva at Khorey-Ver	5470	67.42	58.07	S	0.91	0.46								
70509	Izhma at Ust'-Ukhta	15,000	63.62	53.9	L	0.94	0.71	1.469	1.054	14.170	4.101				
70530	Pizhma at Levkinskaya	2250	64.77	51.1	L	0.97	0.49	−0.749	−4.047	−5.557	−14.878				
70540	Sula at Kotkina	8500	67.03	51.13	S	0.97	0.81	−0.406	−0.381	−3.795	−1.299				
70542	Ruchey Nyashenny at Kotkina	16.1	67.03	51.15	S	0.93	0.65								
70579	Vya at Gavrilovo	2440	62.23	39.45	L	0.95	0.60								
71035	Titovka at 15.5 km ot ust'ya	942	69.55	31.88	L	0.96	0.62	0.881	0.945	4.831	2.365				
71044	Ura at Ura-Guba	1020	69.27	32.8	L	0.97	0.85	1.269	1.541	5.843	4.052				
71067	Pecha at Padun	1600	68.56	31.7	L	0.97	0.91	2.605	7.143	16.720	23.657	0.004	0.008	0.024	0.026
71085	Lotta at Kallokosky	2540	68.6	31.01	L	0.91	0.53	0.216	2.310	1.099	7.294				
71104	Kola at 1429 km Oktyabr'skoy	3780	68.83	30.8	L	0.97	0.90	2.603	4.922	17.869	16.527				
71139	Nivka at Ust'e	204	68.1	35.1	L	0.92	0.78								
71162	Iokan'ga at Kolm'yavr	392	67.83	36.83	L	0.79	0.51								
71175	Sosnovka at Sosnovka	584	66.48	45.5	I	0.96	0.69								
71188	Olenitsa at Olenitsa	374	66.48	33.7	L	0.93	0.62	0.001	0.004	0.010	0.012				
71192	Kuzreka at Kuzreka	250	66.63	34.8	L	0.96	0.74	4.097	6.935	28.590	24.861				
71193	Umba at Istok	2380	67.53	34.28	L	0.93	0.84								

Table 1. (continued)

Code	Name	Basin Area, km	Lat	Long	Perm Cat	Comp Ratio 58–89	Comp Ratio 36–99	Min Δ_{mm} 58–89	Mean Δ_{mm} 58–89	Min Δ% 58–89	Mean Δ% 58–89	Min Δ_{mm} 36–99	Mean Δ_{mm} 36–99	Min Δ% 36–99	Mean Δ% 36–99
71222	Kolviza at Kolviza	1260	67.08	30.7	L	0.96	0.86	3.787	−7.214	17.396	−19.450				
71241	Yena at Yena	1620	67.56	31.01	L	0.97	0.90	2.545	3.959	12.593	13.160				
71258	Monch at Monchegorsk	1480	67.96	32.86	L	0.92	0.84								
	Ob' Region														
10062	Chulyshman at Balukhcha	16,600	51.28	87.72	S	0.98	0.67	−0.256	1.044	−1.770	4.065				
10066	Katun' at Tyungur	13,500	50.13	86.32	C	0.89	0.55								
10126	Charysh at Ust'-Kumir	3480	51.02	84.32	S	0.99	0.93	−1.131	0.313	−6.166	0.926				
10176	Chumish at Zarinsk	15,900	53.73	84.95	L	1.00	0.69	1.334	−3.027	23.686	−15.113				
10219	Inya (Nyzhnyaya) at Kaily	15,700	55.32	84.1	L	1.00	0.97	−0.852	−1.698	−28.926	−23.617	−0.925	−3.908	−28.876	−43.623
10277	Kondoma at Kuzedeevo	7080	53.33	87.23	L	1.00	0.95	2.085	−4.318	20.356	−8.965	0.793	−6.671	7.506	−13.513
10317	Chulym at Balakhta	14,700	55.38	91.62	L	1.00	0.81	−1.978	−2.911	−17.840	−14.968				
10387	Kiya at Marizhinsk	9820	56.2	87.78	L	1.00	0.96	1.010	−0.461	6.735	−1.161	1.164	0.586	7.965	1.516
10407	Yaya at Yaya	3460	56.18	86.4	L	0.97	0.94	0.501	−5.584	9.840	−22.669	0.781	−9.191	14.440	−33.047
10428	Chaya at Podgoenoye	25,000	57.78	82.63	L	1.00	0.75	0.471	1.139	10.541	14.710				
10444	Iksa at Plotnikovo	2560	56.85	83.07	L	0.96	0.92	1.578	3.105	94.317	68.990				
10466	Paidugina at Berezovka	6500	59.37	82.83	L	1.00	0.67	−0.338	−2.433	−2.791	−11.387				
10478	Vasyugan at Sredny Vasyugan	31,700	59.22	78.22	L	1.00	0.93	−2.596	−3.245	−26.988	−21.577				
10489	Tim at Napas	24,500	59.85	81.95	I	1.00	0.94	−1.269	−0.342	−8.684	−1.590	0.120	1.995	0.886	10.148
10505	Bol'shoy Yugan at Ugut	22,100	60.5	74.02	I	1.00	0.76	0.068	0.606	0.696	3.589				
10524	Kulunda at Shimolino	12,300	52.97	80.18	L	0.51	0.60								
10549	Kargat at Zdvinsk	6440	54.7	78.67	L	0.87	0.71								
11309	Om' at Kuibyshev	12,200	55.45	78.32	L	1.00	0.93	0.973	0.821	70.176	23.252				
11353	Tara at Muromtsevo	16,400	56.38	75.25	L	0.97	0.81	2.302	3.123	68.803	55.429				
11496	Balakhley at Balakhley	2140	57.13	69.22	L	0.97	0.70	1.145	4.289	529.005	175.074				
11548	Lyapin at Saran-Paul	18,500	64.25	60.95	D	1.00	0.69	−0.896	−2.571	−5.905	−7.163				
11556	Sob' at Harp	1240	66.87	65.78	C	0.97	0.72								
11558	Poluy at Poluy	15,100	66.03	68.73	D	0.99	0.71	0.777	0.655	6.036	2.782				
12430	Sosva at Denezhkino	4390	60.22	60.42	L	0.94	0.80	2.494	4.541	26.006	22.221				
12517	Lobva at Lobva	2940	59.15	60.52	L	0.91	0.76	2.392	2.563	47.020	15.377				
	Yenisey Region														
7015	Verkhnyaya Angara	20,600	55.85	110.15		1.00	0.95	1.413	−0.329	6.847	−0.962	1.952	2.942	9.742	9.260
7024	Barguzin at Barguzin	19,800	53.6	109.6	I	1.00	1.00	0.333	1.531	2.998	10.022	0.869	−0.069	7.668	−0.415
7036	Turka at Sobolikha	5050	52.92	108.73	C	0.89	0.91					10.709	9.764	77.670	45.667
7072	Chikoy at Gremyachka	15,600	50.3	108.63	D	1.00	0.77	0.449	1.396	4.761	8.258				
7102	Khilok at Khailastuy	38,300	51.2	106.97	S	0.99	0.97	0.714	0.569	20.911	9.720				
7125	Uda at Khorinsk	7850	52.15	109.75	I	1.00	0.87	0.389	0.663	31.768	30.175				
7156	Bol'shaya Rechka at Posol'skoye	565	51.95	106.35	D	1.00	0.97	−3.916	−7.612	−11.520	−12.524	3.070	2.876	9.923	5.188
7172	Utulik at Utulik	959	51.53	104.07	C	1.00	0.92	0.276	−1.364	1.286	−3.137	1.530	−0.125	7.049	−0.280
8233	Iya at Tulun	14,500	54.58	100.62	I	0.96	0.78	1.259	2.758	8.266	10.306				
8291	Irkineeva at Bedoba	8950	58.8	97.23	I	0.92	0.57	−0.001	−0.003	−0.013	−0.023				
8331	Biryusa at Biryusinsk	24,700	55.97	97.78	L	0.97	0.81	0.002	0.002	0.014	0.006				
9207	Abakan at Abaza	14,400	52.65	90.1	I	1.00	0.90	0.592	1.706	2.122	3.094				
9252	Tuba at Bugurtak	31,800	53.8	92.87	L	1.00	0.91	−2.119	−5.401	−6.145	−8.211	0.423	2.173	1.303	3.598
9316	Mana at Mansky	9260	55.9	92.5	L	1.00	0.93	4.401	3.022	25.250	11.147				
9337	Kan at Kansk	23,000	56.22	95.7	L	1.00	0.83	−1.222	−2.117	−6.983	−7.340				
9372	Bol'shoy Pit at Bryanka	15,100	59.12	93.48	I	1.00	0.95	−1.299	−4.761	−11.958	−18.146				

Table 1. (continued)

Code	Name	Basin Area, km	Lat	Long	Perm Cat	Comp Ratio 58–89	Comp Ratio 36–99	Min Δ_{mm} 58–89	Mean Δ_{mm} 58–89	Min Δ% 58–89	Mean Δ% 58–89	Min Δ_{mm} 36–99	Mean Δ_{mm} 36–99	Min Δ% 36–99	Mean Δ% 36–99
9419	Tembenchy at Tembenchy	18,900	64.95	98.9	C	0.99	0.61	0.991	−4.580	9.442	−12.005				
9425	Turukhan at Yanov Stan	10,100	65.98	84.27	D	0.94	0.81								
11574	Pyaku-Pur at Tarko-Sale	31,400	64.93	77.8	D	0.97	0.69								
11805	Nadym at Nadym	48,000	65.62	72.67	D	0.98	0.57	−1.208	−1.519	−7.812	−5.815				
							Lena and Eastern Siberia								
1095	Kulu at Kulu	10,300	61.9	147.42	C	0.99	0.81	0.779	2.614	7.175	11.042				
1151	Detrin at Detrin	3490	61.13	149.67	C	0.97	0.67	1.448	3.519	15.648	14.341				
1176	Bokhalcha at 5.4 km from ust'ya	13,600	62.1	150.67	C	0.99	0.93	1.712	5.096	22.163	23.363				
1397	Anuy at Ostrovnoye	30,000	68.1	164.17	C	0.76	0.38								
1623	Srednekan at Srednekan	1730	62.33	152.33	C	0.80	0.74								
3003	Lena at Kachug	17,400	53.97	105.88	I	0.97	0.75	−1.323	−1.146	−15.942	−8.317				
3087	Kirenga at Shorokhovo	46,500	57.63	108.12	I	0.97	0.83	−1.277	−1.532	−5.893	−4.069				
3156	Nuya at Kurum	32,600	60.27	114.73	D	1.00	0.84	1.008	2.162	62.643	25.113				
3157	Bol'shoy Patom at Patoma	27,600	60.17	116.8	D	0.99	0.83	−1.112	−0.446	−6.284	−1.334				
3202	Namana at Myakinda	16,600	60.9	120.8	C	0.96	0.74	−0.069	−1.653	−5.900	−27.650				
3206	Tuolba at Alekseevka	14,400	60.28	124	C	0.89	0.79								
3210	Buotama at Brolog	12,200	61.05	128.65	C	0.95	0.85	0.500	0.221	28.774	2.615				
3214	Shestakovka at Kamurdarustan	170	61.93	129.55	C	0.50	0.37								
3219	Aldan at Tommot	49,500	58.97	126.27	S	0.97	0.89	−0.780	−3.570	−6.635	−12.022				
3277	Allakh-Yun' at Allakh	24,200	60.68	135.03	C	0.95	0.66								
3291	Amga at Buyaga	23,900	59.67	127.05	C	0.97	0.87	0.940	0.096	23.290	0.685				
3414	Yana at Verkhoyansk	45,300	67.34	133.38	C	0.80	0.75								
3483	Bytantay at Asar	40,000	68.62	134.12	C	0.66	0.53								
3507	Algi at Algi	17,600	64.4	142	C	0.95	0.77								
3510	Bol'shoy Artyk-Yuryakh	644	64.46	141.86	C	0.49	0.41								
3518	Nera at Nerskaya Truda	22,300	64.43	144.37	C	0.62	0.55								

[a] Including basin area (km^2), latitude, longitude, permafrost category (Continuous, Discontinuous, Sporadic, Isolated, and permafrost-free Land, from *Brown et al.* [1997]), a ratio expressing the proportion of months in which a data value is present for the 1958–1989 (Comp Ratio 58–89) and 1936–1999 (Comp Ratio 36–99) time periods, and trends in minimum and mean annual discharge for both time periods expressed in mm/64 years (a) or mm/32 a (Δ_{mm}) and as percent increase or decrease over the period of analysis (Δ%).

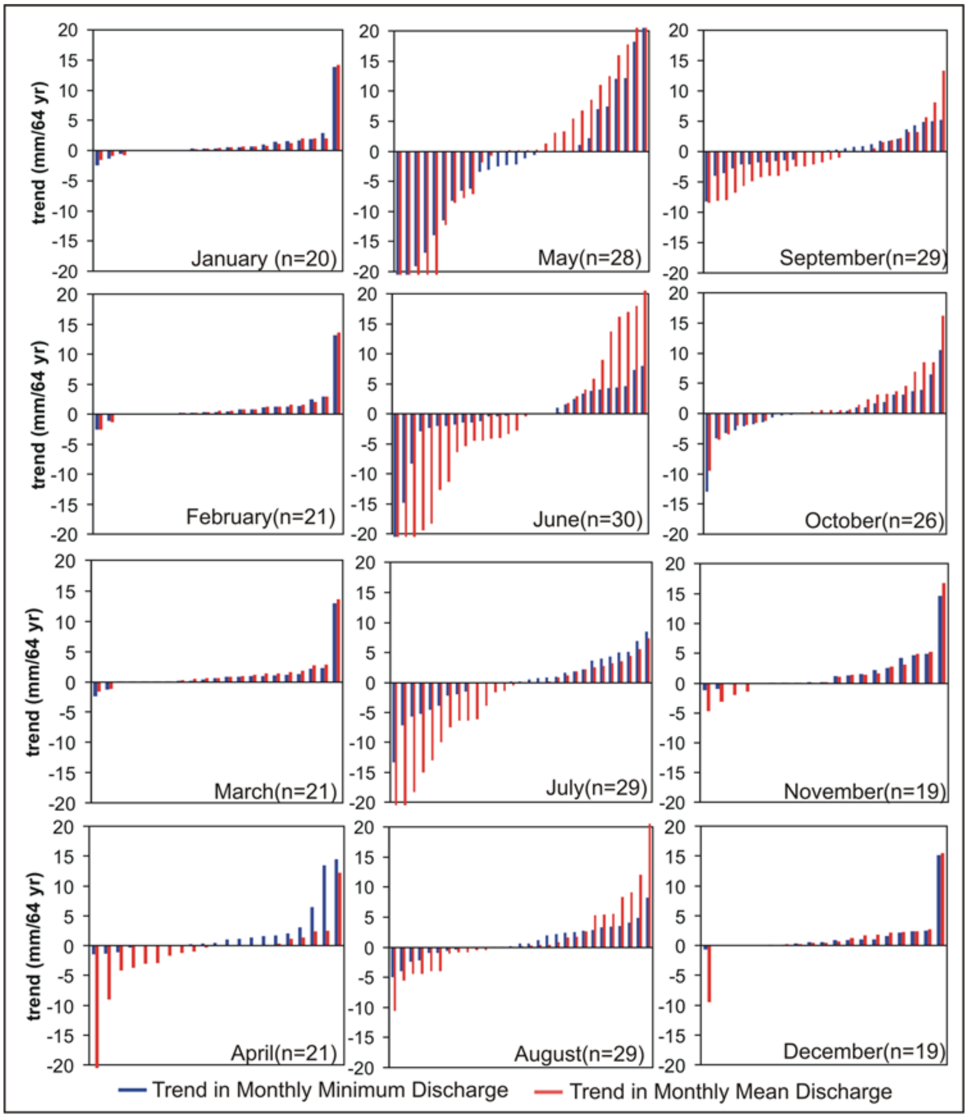

Figure 2. Linear regression trends in minimum daily discharge (blue) and mean daily discharge (red) for all basins, 1936–1999. Trends are ranked from most negative to most positive trend for all available stations for each month-of-year (m.o.y.). Note that the number of stations (*n*) varies by m.o.y. Minimum flow increases outnumber decreases in all months except May, June, and September and are more numerous than mean flow increases in April, July, August, and September.

minimum and mean flow trends are essentially the same from November to March (1936–1999), and from December to March (1958–1989). However, in spring and summer the equivalence disappears when surface runoff enters the river channels. In terms of pure numbers of stations, minimum flow increases (positive trends) outnumbered decreases (negative trends) for most months from 1936–1999 and for all months from 1958–1989. Furthermore, these increases were more abundant than increases in overall mean discharge in April, July, August, and September from 1936 to 1999 (Figure 2), and in April, May, June, and November from 1958 to 1989 (Figure 3). Put another way, during these open water months, minimum flows rose in a greater number of rivers than did mean flows. On an annual basis the number of positive minimum flow trends outnumbered negative trends by more than 2:1 for both study periods (Figure 4).

[16] The increases in minimum flow are generally ubiquitous during cold season months. However, the absolute magnitudes of these increases are greatest in summer. When averaged over the entire year (using only those stations with complete year-round data; $n = 12$ for 1936–1999 and $n = 80$ for 1958–1989), minimum flow increases occurred in roughly 2/3 of the rivers examined and appear to drive much of the overall mean flow increases observed here and in previous studies (Figure 4). Interestingly, minimum flow decreases appear less determinant of the other ~1/3 of rivers experiencing overall flow decreases, particularly from 1936–1999 (Figure 4a).

[17] Long-term trends for all >90% complete m.o.y. time series (19–30 stations from 1936–1999, Figure 2; and 94–108 stations from 1958–1999, Figure 3) may be averaged for each month-of-year to provide a synoptic assessment of minimum flow changes over the two study periods, as a

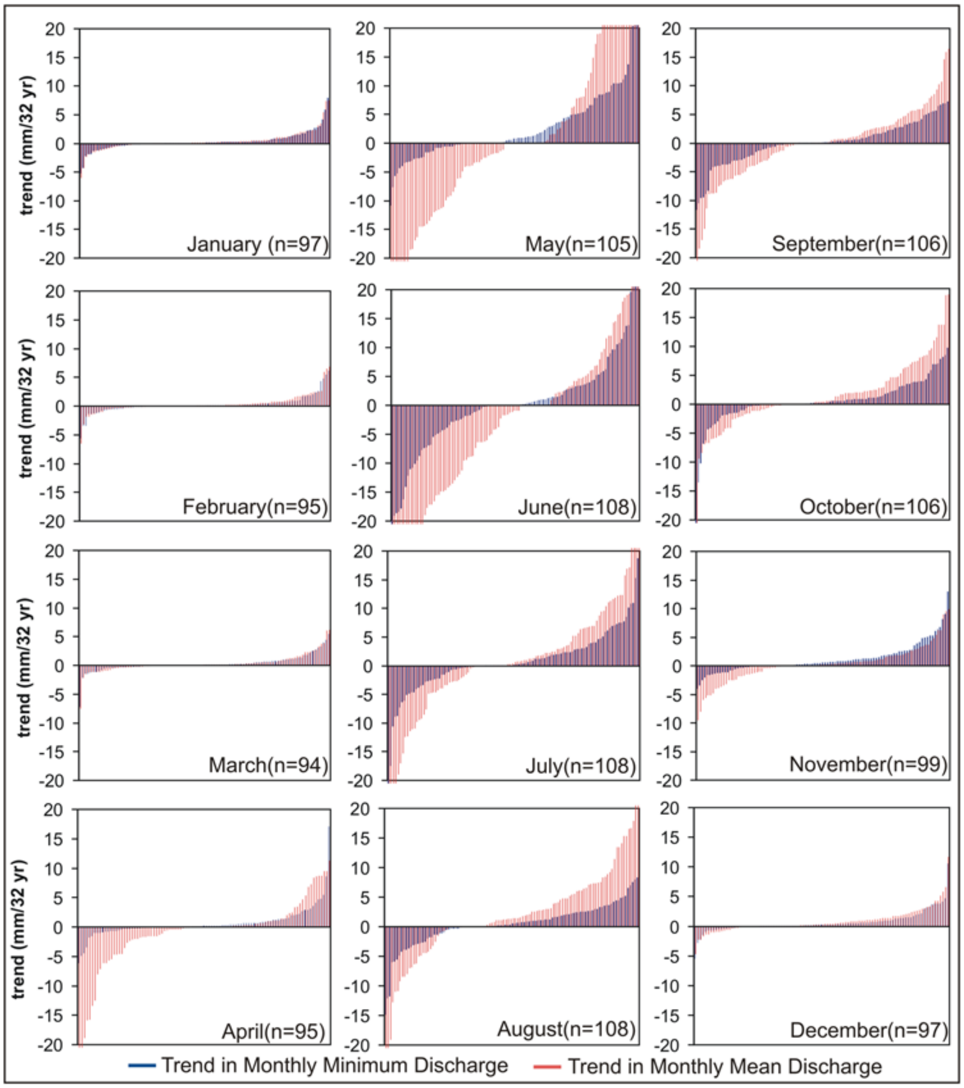

Figure 3. Linear trends in minimum daily discharge (blue) and mean daily discharge (red) for all basins, 1958–1989. Trends are ranked from most negative to most positive for all available stations for each m.o.y. Minimum and mean trends track closely during winter but not summer. Minimum flow increases exceed decreases in all months. Minimum flow increases outnumber mean flow increases in April, May, June, and November.

function of the time of year (Tables 2 and 3). These station-ensemble averaged trends are computed in both millimeters (Δ_{mm}) and percent ($\Delta\%$) over the 64-a and 32-a time intervals from 1936–1999 (Table 2) and 1958–1989 (Table 3). It is important to recognize that Δ_{mm} and $\Delta\%$ are not interchangeable unit conversions. Instead, each is sensitive to different characteristics of the original data set. Changes computed in millimeters reflect absolute trends in minimum flow but are influenced by spatial variations in specific discharge. In contrast, changes computed as percent of total are less affected by differences in specific discharge but are more easily biased by extreme values. For these reasons the changes in millimeters (Δ_{mm}) and percent ($\Delta\%$) do differ from each other and can occasionally have opposing sign. (Note: because the Δ_{mm} values in Tables 1, 2, and 3 are computed in mm/month rather than mm/d, values are roughly 30 times greater than would be generated using mm/d). Keeping these limitations in mind, the ensemble-averaged values of Δ_{mm} and $\Delta\%$, together with tallies (counts) of Mann-Kendall significance ($p = 0.10$, Tables 2 and 3), allow a concise and reasonably good summary description of the entire Russian data set.

[18] Like Figures 2 and 3, the ensemble-averaged values of Δ_{mm} and $\Delta\%$ indicate an overall pattern of rising minimum flows throughout the year (Tables 1 and 2). From 1936–1999 all months display clear positive trends in both variables except for May (Δ_{mm} and $\Delta\%$ both strongly negative) and June (Δ_{mm} weakly negative). In contrast, mean flows show declines in one or both variables for April, May (also strongly negative), June, July, August, September, and October (Table 2). Clear increases in mean flow occurred only from November through March, again during winter when minimum flow and mean flow are essentially equivalent. Put differently, over the period 1936–1999, ensemble-averaged minimum flows clearly increased 10 months out of the year, while mean flows clearly

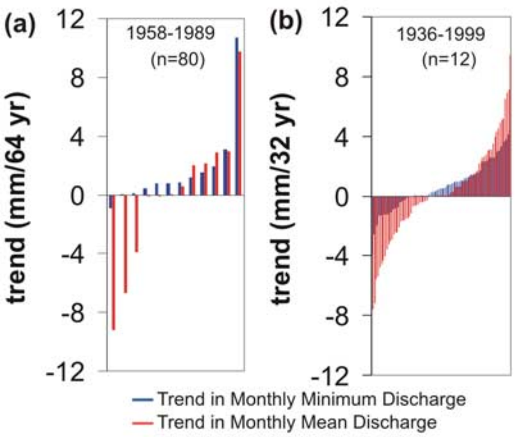

Figure 4. (a, b) Linear trends in annually averaged minimum daily (blue) and mean daily (red) discharge for each basin, 1936–1999 (Figure 4a) and 1958–1989 (Figure 4b), organized from most negative to most positive trend. Sample sizes are lower than Figures 2 and 3 because only those basins with complete data throughout all 12 months are used.

increased only 5 months out of the year. As computed from these 19–31 stations over this 64-a period, mean m.o.y. trends in minimum flow ranged from a −13% decline (May) to a +65% increase (April), with an overall average value (i.e., the mean of all 12 m.o.y. trends) of +23% (+10% using annually complete stations only; Table 2). Corresponding trends in mean flow ranged from a −13% decline (July) to a +45% increase (March), with an annually averaged value of +8% (−5% using annually complete stations only; Table 2).

[19] From 1958–1989, clear increases in minimum flow are apparent for all 12 months of the year (Table 3). Mean flows also increased for all months except April, June, and September. As computed from these 94–108 stations over this 32-a study period, mean m.o.y. trends in minimum flow ranged from +14% (June) to +33% (November), with a mean value of +22% (+14% using annually complete stations only, Table 3). Trends in mean flow ranged from +1% (April) to +27% (August and December), with a mean value of +17% (+6% using annually complete stations only, Table 3). On average, records displaying Mann-Kendall significance for positive trend outnumber those for negative trend by more than 3:1 from 1958–1989 and more than 7:1 from 1936–1999 (Tables 2 and 3).

3.2. Regional Variability

[20] The spatial distribution of minimum flow trends sufficiently robust to achieve Mann-Kendall significance is mapped for 1936–1999 in Figure 5 and for 1958–1989 in Figure 6. Symbol diameters are scaled by the trend slope (mm/a). Unlike Δ_{mm}, these slopes are neither cumulative nor averaged from many stations. Instead they simply show the rate of change for each station, thus enabling the two time periods to be directly compared.

[21] For both study periods, Figures 5 and 6 reveal a spatially mixed pattern of both increases and decreases in minimum flow, with the former outnumbering the latter. Summer trends generally equal or exceed winter trends over both time periods. Rates of change were markedly faster from 1958–1989, as indicated by the larger symbol diameters in Figure 6. From 1958–1989, increases in minimum flow were particularly consistent in May and November, perhaps reflecting a seasonal shift toward earlier spring melt and later autumn freeze-up, respectively. However, this is not particularly evident in the 1936–1999 maps. No strongly coherent spatial pattern is apparent for either increasing or decreasing flows during either study period, with the possible exception of reduced summer flows in south central Russia from 1936 to 1999. No strongly coherent spatial contrast is apparent between the European Russia, Ob', Yenisey, and Lena/eastern Siberia subregions. No strongly coherent spatial contrast is apparent between permafrost and permafrost-free areas.

[22] Table 4 summarizes by subregion the minimum flow and mean flow changes from 1958–1989. A comparable

Table 2. Summary Statistics for the 1936–1999 Period[a]

	Stations	Min 36–99−	Min 36–99+	Mean 36–99−	Mean 36–99+	Min Δmm	Min Δ %	Mean Δmm	Mean Δ %
January	20	1	14	2	11	1.16	37.7	1.20	24.7
February	21	1	14	2	12	1.10	46.8	1.14	33.6
March	21	2	15	2	15	1.06	49.4	1.31	44.6
April	21	1	13	2	3	2.05	64.3	−1.81	−3.7
May	28	7	7	5	6	−3.26	−13.2	−4.72	−5.1
June	30	1	4	4	7	−0.57	2.4	−2.59	−3.4
July	29	5	7	7	2	0.04	1.6	−3.68	−13.2
August	29	3	7	2	2	0.99	10.4	1.32	−0.3
September	28	3	6	3	2	0.09	4.3	−1.03	−6.6
October	26	4	9	4	3	0.29	8.2	1.44	−1.3
November	19	0	10	3	8	1.87	23.7	1.44	7.2
December	19	0	13	1	10	1.51	39.2	1.18	20.5
Annual	13	0	2	0	6	1.71	9.6	0.03	−4.6

[a] Showing the total number of stations tested, the number of statistically significant increasing (min 36–99+) and decreasing (min 36–99−) Mann-Kendall trends in minimum flow ($p = 0.10$), the number of statistically significant increasing (mean 36–99+) and decreasing (mean 36–99−) Mann-Kendall trends in mean flow, and the aggregate mean trends (all records) for both minimum flow and mean flow expressed in mm/64 a (Δ_{mm}) and percent change over the study period (Δ%). Note that Δ_{mm} and Δ% are not interchangeable unit conversions; they measure the underlying data set differently and can occasionally have opposing sign (see text).

Table 3. Summary Statistics for the 1958–1989 Period[a]

	Stations	Min 58–89−	Min 58–89+	Mean 58–89−	Mean 58–89+	Min Δmm	Min Δ %	Mean Δmm	Mean Δ %
January	97	7	22	8	24	0.32	25.2	0.39	22.2
February	95	10	22	7	19	0.24	17.8	0.36	24.1
March	94	9	28	10	24	0.30	19.0	0.34	19.1
April	95	10	31	8	8	0.62	23.6	−2.23	0.5
May	105	4	17	8	15	2.89	23.3	3.59	11.0
June	108	8	13	7	7	0.03	14.1	−3.44	1.3
July	108	11	17	8	10	0.63	14.9	0.68	20.1
August	108	7	20	7	20	0.37	19.0	1.62	27.1
September	106	10	21	6	10	0.04	17.3	−0.15	16.0
October	106	10	19	7	12	0.45	21.9	1.42	18.8
November	99	3	31	6	17	1.16	33.2	0.26	16.0
December	97	4	24	2	24	0.62	31.6	0.83	27.4
Annual	80	0	16	0	12	0.65	14.4	0.23	5.6

[a] Showing the total number of stations tested, the number of statistically significant increasing (min 58–89+) and decreasing (min 58–89−) Mann-Kendall trends in minimum flow ($p = 0.10$), the number of statistically significant increasing (mean 58–89+) and decreasing (mean 58–89−) Mann-Kendall trends in mean flow, and the aggregate mean trends (all records) for both minimum flow and mean flow expressed in mm/32 a (Δ_{mm}) and percent change over the study period (Δ%). Note that Δ_{mm} and Δ% are not interchangeable unit conversions; they measure the underlying data set differently and can occasionally have opposing sign (see text).

table cannot be created for 1936–1999 owing to small sample size. In all four regions the number of statistically significant positive trends in minimum flow strongly exceeds the number of statistically significant negative trends in minimum flow. Although weaker, the same generally holds for mean flows except in the Yenisey region. Mean trends in minimum flow are likewise positive for all four sectors, regardless of metric used (Δ_{mm} or Δ%). In contrast, mean trends in mean flow display some regional variability including opposing sign between Δ_{mm} and Δ% (Ob' and Yenisey). Of the four subregions, flow increases are weakest in the Yenisey. Otherwise, like the study area as a whole, the subregions have experienced widespread minimum flow increases, often outnumbering and outpacing corresponding increases in mean flow.

3.3. Influence of Permafrost on Observed Hydrologic Changes

[23] To examine the importance of permafrost to the apparent changes in minimum flow, the previously described regression trends and Mann-Kendall statistics were divided into two categories, i.e., stations located in areas underlain by permafrost and stations that are not (Figure 7). Note that for study period 1936–1999 this further reduces the number of available station records from 33 to just 19 and 14 stations (at best, depending on m.o.y.) for permafrost and nonpermafrost, respectively. This further splitting of an already low sample size must be considered when interpreting Figures 7a and 8a. Note also that no gauging stations are available from some expansive areas of permafrost, particularly in eastern Siberia (Figure 1). Permafrost extent was derived from *Brown et al.* [1997]. "Permafrost" is considered here to include any permafrost category (continuous, discontinuous, sporadic, or isolated) in the manner of *Frey and Smith* [2005] and *Frey et al.* [2007a, 2007b]. Similar to Figures 5 and 6, the mean trends shown in Figure 7 are expressed in mm/a, allowing direct comparisons to be made between the two study periods.

[24] Figure 7a indicates that winter minimum flow increases occurred in both permafrost and nonpermafrost environments from 1936–1999, with perhaps somewhat greater increases found in permafrost. In contrast, from 1958–1989 there were strong year-round increases in permafrost-free areas, whereas in permafrost there were few increases and even some notable summer decreases (Figure 7c). This apparent shift toward year-round increases does not appear to be an artifact of the differing sample size between study periods. The 1958–1989 increases are evident even when the analysis is restricted to the longest-running stations only (Figure 7b).

[25] Figure 8 presents the relative proportions of all statistically significant positive (+) and negative (−) trends (from Mann-Kendall tallies, Tables 2 and 3) for permafrost and nonpermafrost station ensembles (see caption, Figure 8). Note that a one-to-one comparison of the Mann-Kendall statistics cannot be made between the two time periods because their record lengths differ (64 a for 1936–1999 versus 32 a for 1958–1989). Mann-Kendall significance becomes more difficult to achieve as record length shortens, even with a constant trend [*Burn and Elnur*, 2002]. For this reason the number of stations achieving statistical significance from 1958–1989 (Figure 8b) is uniformly lower than for 1936–1999 (Figure 8a), despite the strong positive trends that did occur during this time (Table 3 and Figures 6 and 7a). Therefore the numeric values of Figures 8a and 8b should be used within study periods but not between them. The prime information content of Figure 8 lies in its relative contrasts between positive and negative flow trends and between permafrost and nonpermafrost stations. For both 1936–1999 (Figure 8a) and 1958–1989 (Figure 8b), more rivers experienced statistically significant positive trends in minimum daily flow than negative trends, particularly during winter. On a proportional basis the number of nonpermafrost rivers with statistically significant flow increases generally equaled or exceeded the number of permafrost rivers with such increases. We conclude from Figures 7 and 8 that minimum flow increases (and to a lesser extent, decreases) did not occur preferentially in permafrost. Instead, they are found everywhere.

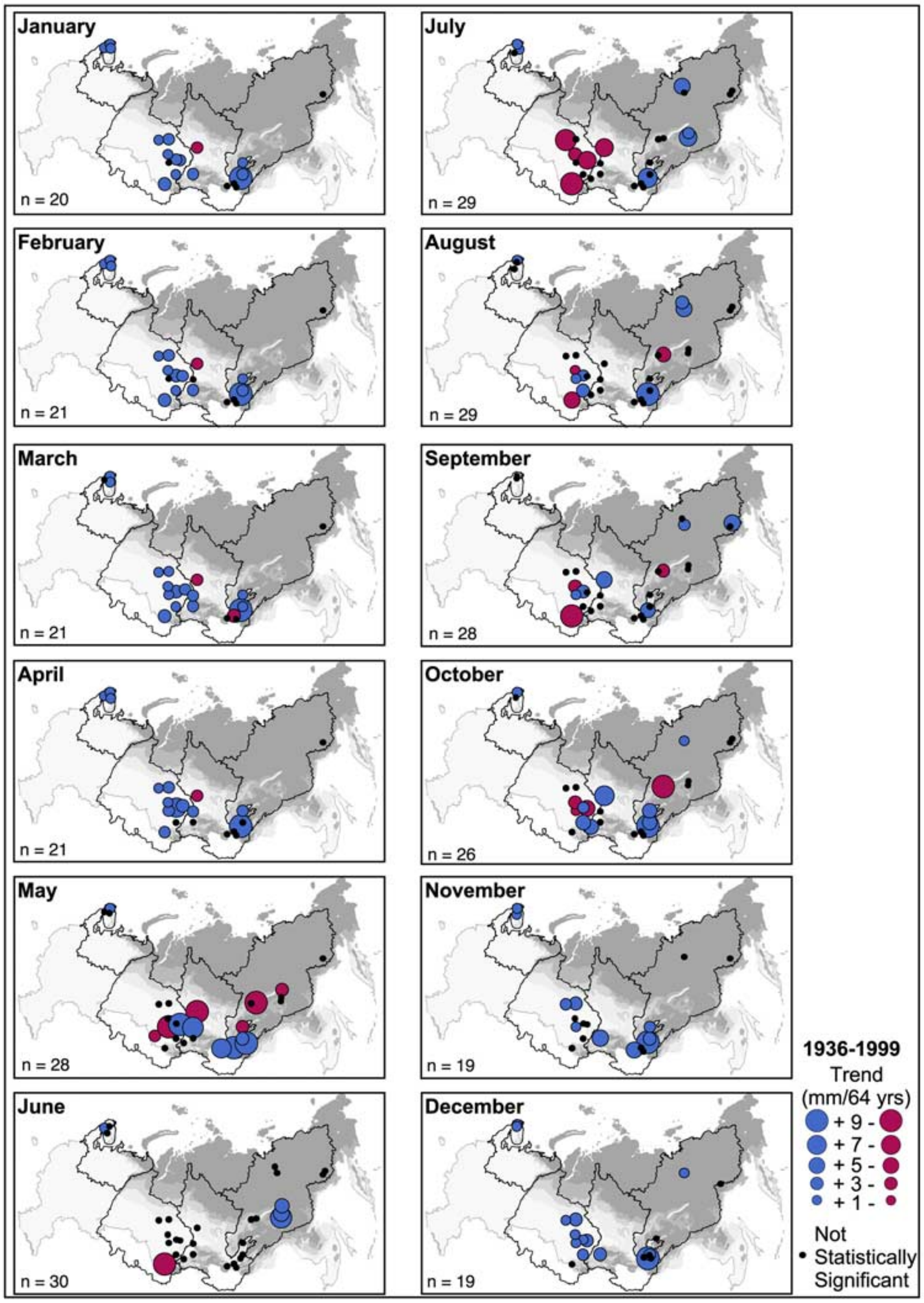

Figure 5. Spatial distribution of statistically significant trends in minimum flow, 1936–1999. Increases exceed decreases in all months except May. Symbol diameters are scaled by the trend slope (mm/year (a)) for stations achieving statistical significance, while other stations are represented by black dots. A spatially incoherent pattern of increases and decreases in minimum flow occurred from 1936–1999, with increases outnumbering decreases. No strongly coherent spatial contrast is apparent between permafrost and permafrost-free areas. Summer trends generally equaled or exceeded winter trends.

3.4. Evidence for a Recent Acceleration in Minimum Flow Increases Since ~1985

[26] A prevailing theme in most of the data presented so far has been a greater rise in minimum flow over the period 1958–1989 relative to 1936–1999 (cf. Table 3 and Figures 6 and 7a). It is perhaps natural to infer from this a recent "acceleration" in the rate of minimum flow increase, since the 1958–1989 study period occurs later in the 20th century. However, this is not strictly correct, as the 1958–1989 data ensemble ends a full decade before the 1936–1999 ensemble. Also, the two data sets differ substantially in both the distribution and number of stations they contain (Figure 1).

[27] To position the apparent 1958–1989 flow increases within the longest available instrumental record, and also to evaluate more recent daily data (up to 2002) available for a

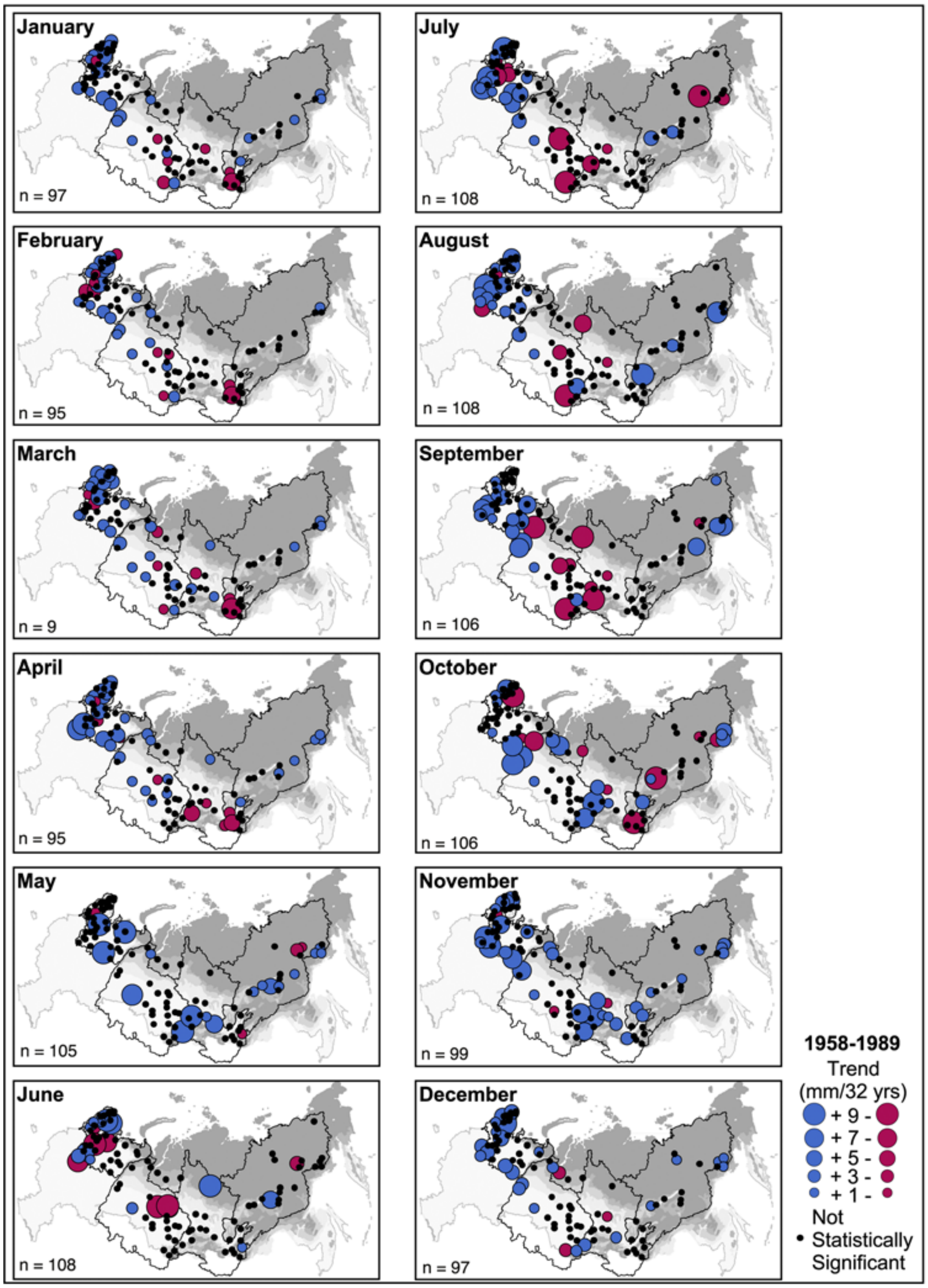

Figure 6. Spatial distribution of statistically significant trends in minimum flow, 1958–1989. Rates of change were greater than 1936–1999, as indicated by the larger symbol diameters as compared to Figure 5. From 1958–1989, increases in minimum flow were particularly evident in May and November, perhaps reflecting seasonal shifts toward earlier spring melt and later autumn freeze-up, respectively. No strongly coherent spatial contrast is apparent between permafrost and permafrost-free areas. Summer trends generally equaled or exceeded winter trends.

limited number of stations, we compute monthly anomalies in long-term mean minimum discharge for 12 stations with unusually long and complete records (90% for all m.o.y.) from 1935 and 2002 (Figure 9). Note that an even longer context for the late 20th century Eurasian runoff increases is provided to 1990 using dendrochronology elsewhere in this special section [*MacDonald et al.*, 2007]. Anomalies are expressed as percents to remove any effect of spatial variability in specific discharge and are averaged to present the mean anomaly for each year for all 12 m.o.y. Prudence must be maintained when interpreting these data because of the low sample size and limited geographic extent of these 12 stations (Figure 1).

[28] Like most natural hydrologic systems, Figure 9 displays considerable temporal variability. In any given year, monthly minimum flows may decrease up to –50% or

Table 4. Summary Statistics for the 1958–1989 Period (Like Table 3), Separated by Subregion Rather Than Month-of-Year[a]

	Stations	Total Months	Min 58–89–	Min 58–89+	Mean 58–89–	Mean 58–89+	Min Δ_{mm}	Min Δ%	Mean Δ_{mm}	Mean Δ%
European Russia	45	504	30	136	31	93	0.93	19.0	1.35	14.4
Ob'	25	282	25	54	17	50	0.49	31.4	−0.34	20.7
Yenisey	20	234	24	29	19	12	0.16	6.0	−0.04	6.6
Lena/Eastern Siberia	21	212	14	46	17	35	0.07	26.1	0.56	20.2

[a]Units are the same as Table 3; total station months are also shown.

increase up to +200%, particularly in April, May, June, and July when snowmelt, ice breakup, and spring flooding create highly variable discharge conditions. However, despite this inherent variability, there is clear indication of an "uptick" (recent increase) in minimum flows since ~1985 for the months of November, December, January, February, March, and April (Figure 9). With the sole exception of November (which experienced even higher minimum flows from ~1936–1938), these increases are unprecedented in the instrumental record. Furthermore, since ~2000, all 12 months show upward trajectories in minimum flow, with magnitudes at or near record levels for January, February, March, April, July, August, September, October, and December.

4. Discussion and Conclusion

[29] A clear result of this analysis is that, on balance, the monthly minimum values of daily discharge, or "low flows," have risen in northern Eurasia during the 20th century. This overall signal emerges despite a backdrop of intrinsic variability and some decreasing as well as increasing trends. In general, the increases in minimum flow are more numerous and have risen at a comparable or faster rate than have corresponding increases in mean flow. The analysis shows that the minimum flow increases have occurred year-round, a substantial advance over current knowledge of "winter baseflow" increases inferred from monthly mean discharges. This distinction is a direct result of our separation of minimum flows from mean flows using daily discharge records. This approach is necessary during the spring and summer months but is probably unnecessary in winter, when minimum and mean flows converge and therefore provide similar information.

[30] From 12 unusually complete records from 1935–2002 we see that the minimum flow increases are greatest since ~1985 (Figure 9). However, nearly all of these records are from south central Russia (Figure 1), and the instrumental record is still short. Discharge reconstructions (up to 1990) modeled from dendrochronology suggest that the late 20th century Eurasian discharge increase, while large, is not unprecedented over the past ~200 a [*MacDonald et al.*, 2007]. Therefore Figure 9 should be interpreted within that longer-term context.

[31] While the broad-scale pattern is clear, regional and local-scale patterns are not (Figures 5 and 6 and Table 4). To the extent that can be determined using 111 irregularly spaced gauging stations, the signal appears to be geographically broad, without robust spatial contrasts between subregions. Not even the presence or absence of permafrost,

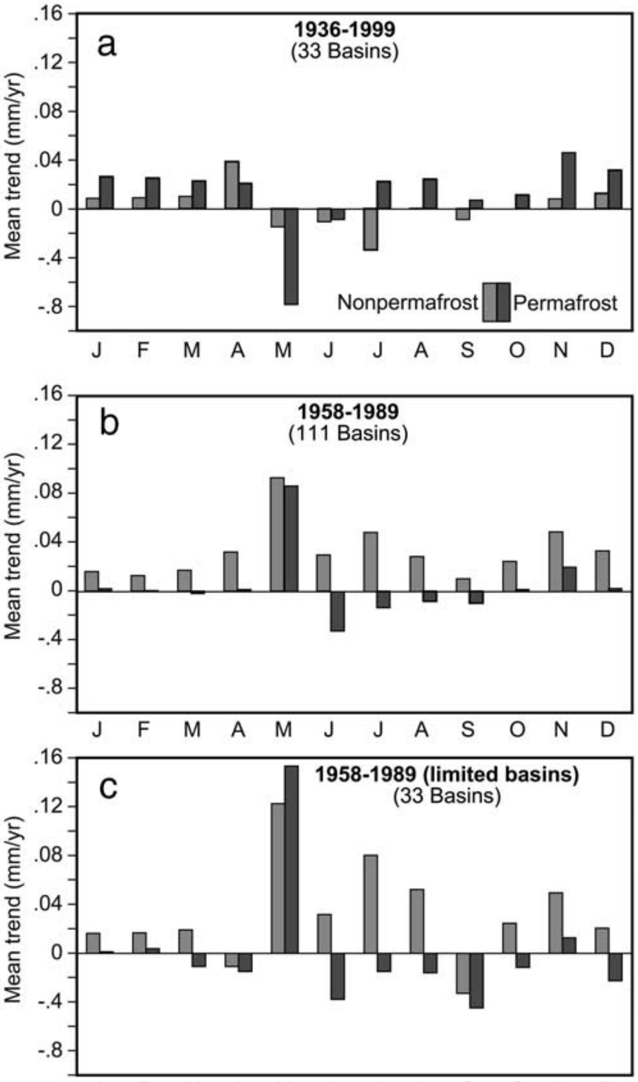

Figure 7. (a–c) Mean m.o.y. trends in minimum daily discharge for permafrost-free (light gray) and permafrost-influenced (dark gray) basins, 1936–1999 (Figure 7a) and 1958–1989 (Figure 7b). (Figure 7c) Mean m.o.y. trends for 1958–1989 but only those basins used in Figure 7a are included. From 1936–1999 positive minimum flow trends occurred in both permafrost and nonpermafrost environments, with slightly higher increases in permafrost. From 1958–1989 there were strong positive trends year-round in permafrost-free areas, but in permafrost areas there were few minimum flow increases and even some decreases.

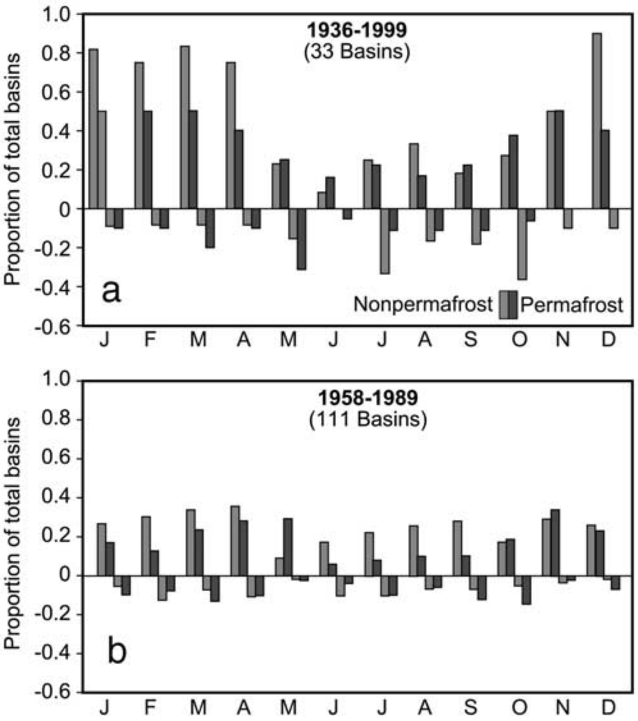

Figure 8. (a, b) Relative proportions of permafrost-free (light gray) and permafrost-influenced (dark gray) basins with statistically significant increases and decreases in minimum daily discharge, 1936–1999 (Figure 8a) and 1958–1989 (Figure 8b). Note that the absolute values for Figure 8a are higher than for Figure 8b because statistical significance is more difficult to achieve over the shorter record length. For both study periods, more rivers experienced positive statistically significant trends than negative trends, particularly in winter. The proportion of nonpermafrost rivers with statistically significant minimum flow increases generally equaled or exceeded those for permafrost rivers.

which would seem a primary control on low-flow variability, seems to matter much. While minimum flow decreases are more common in summer, and from 1936–1999 are somewhat more concentrated in south central Russia suggesting a possible link to agricultural consumption [*Yang et al.*, 2004b] (Figure 5), the latter breaks down from 1958–1989, and some substantial declines also occurred in remote areas of continuous permafrost at the same time (Figure 6). Also, the minimum flow increases are frequently found in rivers that have not experienced comparable increases in mean flow. One partial explanation for this contrast is that in terms of absolute magnitude, minimum flow variations represent a large fraction of overall discharge in winter but a trivial fraction in summer. This results in minimum flow changes being most noticeable (and more statistically evident) during winter. From a statistical standpoint a +2 mm minimum flow increase during winter will typically be more significant than a +2 mm (or larger) increase in summer, even though in terms of physical process (inferred groundwater contribution) the summer increase is just as meaningful. A second partial explanation may be that the minimum flow increases have been offset in some river basins by reductions in peak flows, such that overall mean discharges are retained. Peak flows were not examined in this study; however, *Shiklomanov et al.* [2007] do examine them, and they report significant decreases in spring daily maximum discharge across the southern part of western and central Siberia and the Far East, but increases in European Russia and within the Lena basin. Further study of these new daily discharge records, together with ancillary data, is required to resolve these apparent patterns.

[32] With regard to physical mechanism(s), if minimum flows are presumed to approximate, or at least correlate, with soil- and groundwater inputs to rivers, then our results indicate a broad-scale mobilization of subsurface water activity during the 20th century. This is not a new idea: The possibility that thawing permafrost and associated melting of ground ice may be releasing stored water to streams has been an important hypothesis in the debate over the terrestrial runoff increases. Recent evidence of shrinking or draining lakes in Alaska and Siberia does suggest that thawing of transitional permafrost may promote water infiltration to the subsurface [*Yoshikawa and Hinzman*, 2003; *Smith et al.*, 2005]. Furthermore, a geochemical survey of both permafrost and permafrost-free parts of west Siberia strongly suggests that permafrost strongly reduces the flow of mineral-rich groundwater to streams [*Frey et al.*, 2007a, 2007b]. However, our results suggest little if any unique role for permafrost in the observed minimum flow increases because some of the greatest increases have occurred in nonpermafrost (Figures 7b, 8a, and 8b), particularly from 1958–1989 when our sample size is largest. Nonetheless, the rising minimum flow signal is consistent with a “thaw-like” process, one that would promote increased soil infiltration, subsurface water movement, and connections to stream networks. We speculate that decreased seasonal freezing of soils [*Frauenfeld et al.*, 2004; *Groisman et al.*, 2007], caused by warmer winters and/or deeper snowpack, might promote such activity in both permafrost and nonpermafrost environments alike. Climate records certainly show warmer winter and spring temperatures over central and western northern Eurasia since at least 1979 [cf. *Rigor et al.*, 2000, Figure 9]. We further speculate that a more deeply thawed, or more frequently thawed, landscape would not only accept more infiltration from the surface, but also shift water storage from the surface/near-surface (i.e., in lakes, ponds, and wetlands) to the subsurface (i.e., in soil and groundwater), thereby reducing free-surface evaporation loss (potential ET) to the atmosphere. In terms of the regional water balance this reduced evaporation loss term would be equivalent to a precipitation increase. However, these ideas remain untested and require a proper trend attribution study to correlate the observed flow increases with candidate causal variables.

[33] It is also conceivable that the observed minimum flow increases are solely a manifestation of increased precipitation, with no “thaw-like” mechanism required. Indeed, our own recent work using the same two study periods as the present study attributes 32–65% of the overall 20th century trends in mean annual river outflow to precipitation changes alone [*Pavelsky and Smith*, 2006]. What is difficult to reconcile with a “precipitation-only” mechanism, however, is the fact that the minimum flow

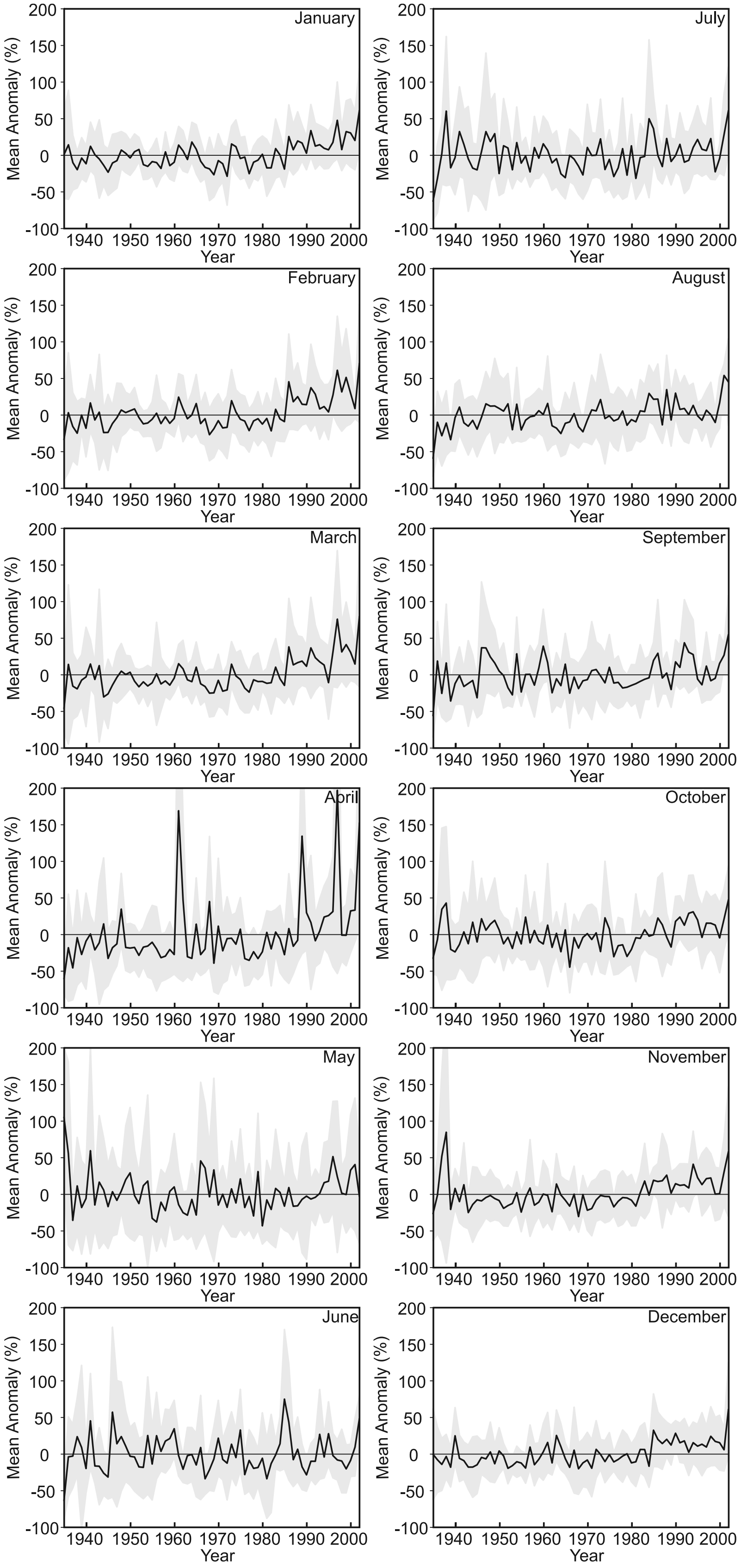

Figure 9. Monthly anomalies in minimum daily discharge expressed as a percent of mean minimum daily discharge and averaged for 12 stations with predominantly complete records, 1935–2002. Substantial positive anomalies since ~1985 in November through March suggest unprecedented recent increases in winter minimum flows, at least for this small subset of stations.

increases are not necessarily accompanied by overall flow increases. If precipitation alone is driving the overall discharge increases, then baseflow and surface runoff would both presumably rise. In contrast, we see that minimum flows have often risen faster than mean flow (Figures 2, 3, and 4 and Tables 2 and 3). For this reason we speculate that the overall discharge increases of the late 20th and early 21st century could be generated from a combined effect, i.e., increased precipitation together with less severe transient ground freezing during winter.

[34] Regardless of mechanism, the finding of widespread, year-round increases in river low flows raises the possibility of a profound but understudied impact of climate change in northern environments, namely a rising role of groundwater processes in the high-latitude water cycle. At the conceptual extreme, a shift from "aboveground" to "below-ground" storage of water would trigger far-reaching changes to nearly every aspect of the Arctic biophysical system, including its land cover, ecology, carbon cycling, gas exchange with the atmosphere, and human development [*Smith et al.*, 2007]. However, such dramatic scenarios are unlikely outside of permafrost terrain. More realistically, a gradual increase in soil infiltration, unsaturated zone storage, and groundwater movement will require some rethinking of how we model high-latitude hydrological processes, climate, and heat flux into permafrost, as well as practical concerns like bridge design and human water supply.

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References

Adam, J. C., and D. P. Lettenmaier (2007), Exploring the roles of precipitation and temperature changes on the variability of Eurasian Arctic river discharge, *J. Clim.*, in press.

Arnell, N. W. (2005), Implications of climate change for freshwater inflows to the Arctic Ocean, *J. Geophys. Res.*, *110*, D07105, doi:10.1029/2004JD005348.

Berezovskaya, S., D. Yang, and D. L. Kane (2004), Compatibility analysis of precipitation and runoff trends over the large Siberian watersheds, *Geophys. Res. Lett.*, *31*, L21502, doi:10.1029/2004GL021277.

Berezovskaya, S., D. Yang, and D. L. Kane (2005), Long-term annual water balance analysis of the Lena River, *Global Planet. Change*, *48*, 84–95.

Broecker, W. S. (1997), Thermohaline circulation, the Achilles heel of our climate system: Will man-made CO_2 upset the current balance?, *Science*, *278*, 1582–1588.

Brown, J., O. J. Ferrians, J. A. Heginbottom, and E. S. Melnikov (1997) (revised 2001), Circum-arctic map of permafrost and ground ice conditions, Natl. Snow and Ice Data Cent., World Data Cent. for Glaciol., Boulder, Colo. (Available at http://nsidc.org/data/ggd318.html.)

Burn, D. H. (1994), Hydrologic effects of climatic change in west-central Canada, *J. Hydrol.*, *160*, 53–70.

Burn, D. H., and M. A. H. Elnur (2002), Detection of hydrologic trends and variability, *J. Hydrol.*, *255*, 107–122.

Curry, R., and C. Mauritzen (2005), Dilution of the northern North Atlantic Ocean in recent decades, *Science*, *308*, 1772–1774.

Curry, R., B. Dickson, and I. Yashayaev (2003), A change in the freshwater balance of the Atlantic Ocean over the past four decades, *Nature*, *426*, 826–829, doi:10.1038/nature02206.

Dai, A., K. E. Trenberth, and T. Qian (2004), A global data set of Palmer Drought Severity Index for 1870–2002: Relationship with soil moisture and effects of surface warming, *J. Hydrometeorol.*, *5*, 1117–1130.

Déry, S. J., and E. F. Wood (2004), Teleconnection between the Arctic Ocean and Hudson Bay river discharge, *Geophys. Res. Lett.*, *31*, L18205, doi:10.1029/2004GL020729.

Déry, S. J., and E. F. Wood (2005), Decreasing river discharge in northern Canada, *Geophys. Res. Lett.*, *32*, L10401, doi:10.1029/2005GL022845.

Frauenfeld, O. W., T. Zhang, R. G. Barry, and D. Gilichinsky (2004), Interdecadal changes in seasonal freeze and thaw depths in Russia, *J. Geophys. Res.*, *109*, D05101, doi:10.1029/2003JD004245.

Frey, K. E., and L. C. Smith (2005), Amplified carbon release from vast west Siberian peatlands by 2100, *Geophys. Res. Lett.*, *32*, L09401, doi:10.1029/2004GL022025.

Frey, K. E., D. I. Siegel, and L. C. Smith (2007a), Geochemistry of west Siberian streams and their potential response to permafrost degradation, *Water Resour. Res.*, *43*, W03406, doi:10.1029/2006WR004902.

Frey, K. E., J. M. McClelland, R. M. Holmes, and L. C. Smith (2007b), Impacts of climate warming and permafrost thaw on the riverine transport of nitrogen and phosphorus to the Kara Sea, *J. Geophys. Res.*, *112*, G04S58, doi:10.1029/2006JG000369.

Gedney, N., P. M. Cox, R. A. Betts, O. Boucher, C. Huntingford, and P. A. Scott (2006), Detection of a direct carbon dioxide effect in continental river runoff records, *Nature*, *439*, 838–841, doi:10.1038/nature04504.

Georgievskii, V. Y., A. V. Ezhov, A. L. Shalygin, I. A. Shiklomanov, and A. I. Shiklomanov (1996), Assessment of the effect of possible climate changes on hydrological regime and water resources of rivers in the former USSR, *Russ. Meteorol. Hydrol.*, *11*, 66–74.

Groisman, P. Y., R. W. Knight, V. N. Razuvaev, O. N. Bulygina, and T. R. Karl (2007), State of the ground: Climatology and changes during the past 69 years over northern Eurasia for a rarely used measure of snow cover and frozen land, *J. Clim.*, *19*(19), 4933–4955.

Hirsch, R. M., R. B. Alexander, and R. A. Smith (1991), Selection of methods for the detection and estimation of trends in water quality, *Water Resour. Res.*, *27*, 803–813.

Hodgkins, G. A., R. W. Dudley, and T. G. Huntington (2005), Changes in the number and timing of days of ice-affected flows on northern New England rivers, 1930–2000, *Clim. Change*, *71*, 319–340, doi:10.1007/s10584-005-5926-z.

Kendall, M. G. (1975), *Rank Correlation Methods*, 4th ed., Oxford Univ. Press, New York.

Lammers, R. B., A. I. Shiklomanov, C. J. Vörösmarty, B. M. Fekete, and B. J. Peterson (2001), Assessment of contemporary Arctic river runoff based on observational discharge records, *J. Geophys. Res.*, *106*, 3321–3334.

Lawrence, D. M., and A. G. Slater (2005), A projection of severe near-surface permafrost degradation during the 21st century, *Geophys. Res. Lett.*, *32*, L24401, doi:10.1029/2005GL025080.

Liu, B., D. Yang, B. Ye, and S. Berezovskaya (2005), Long-term open-water season stream temperature variations and changes over Lena River Basin in Siberia, *Global Planet. Change*, *48*, 96–111.

Maidment, D. R. (Ed.) (1993), *Handbook of Hydrology*, McGraw-Hill, New York.

MacDonald, G. M., K. V. Kremenetski, L. C. Smith, and H. G. Hidalgo (2007), Recent Eurasian river discharge to the Arctic Ocean and the context of longer-term dendrohydrological records, doi:10.1029/2006JG000333, in press.

Macdonald, R. W. (2000), Arctic estuaries and ice: A positive-negative estuarine couple, in *The Freshwater Budget of the Arctic Ocean, Proceedings of the NATO Advanced Research Workshop on the Freshwater Budget of the Arctic Ocean*, edited by E. L. Lewis et al., pp. 383–407, Springer, New York.

Magilligan, F. J., and K. H. Nislow (2005), Changes in hydrologic regime by dams, *Geomorphology*, *71*, 61–78.

Magnuson, J. J., et al. (2000), Historical trends in lake and river ice cover in the Northern Hemisphere, *Science*, *289*, 1743–1746.

Manabe, S., P. C. D. Milly, and R. Wetherald (2004), Simulated long-term changes in river discharge and soil moisture due to global warming, *Hydrol. Sci. J.*, *49*, 625–642.

Mann, H. B. (1945), Non-parametric test against trend, *Econometrica*, *13*, 245–259.

Marc, V., J.-F. Didon-Lescot, and C. Michael (2001), Investigation of the hydrological processes using chemical and isotopic tracers in a small Mediterranean forested catchment during autumn recharge, *J. Hydrol.*, *247*, 215–229.

McClelland, J. W., R. M. Holmes, B. J. Peterson, and M. Stieglitz (2004), Increasing river discharge in the Eurasian Arctic: Consideration of dams, permafrost thaw, and fires as potential agents of change, *J. Geophys. Res.*, *109*, D18102, doi:10.1029/2004JD004583.

McClelland, J. W., S. J. Déry, B. J. Peterson, R. M. Holmes, and E. F. Wood (2006), A pan-Arctic evaluation of changes in river discharge during the latter half of the 20th century, *Geophys. Res. Lett.*, *33*, L06715, doi:10.1029/2006GL025753.

Pavelsky, T. M., and L. C. Smith (2006), Intercomparison of four global precipitation data sets and their correlation with increased Eurasian river discharge to the Arctic Ocean, *J. Geophys. Res.*, *111*, D21112, doi:10.1029/2006JD007230.

Peterson, B. J., R. M. Holmes, J. W. McClelland, C. J. Vörösmarty, R. B. Lammers, A. I. Shiklomanov, and S. Rahmstorf (2002), Increasing river discharge to the Arctic Ocean, *Science*, *298*, 2171–2173.

Prowse, T. D., F. J. Wrona, J. D. Reist, J. J. Gibson, J. E. Hobbie, L. M. J. Levesque, and W. F. Vincent (2006), Climate change effects on hydroecology of Arctic freshwater systems, *Ambio*, *35*, 347–358.

Rahmstorf, S. (1995), Bifurcations of the Atlantic thermohaline circulation in response to changes in the hydrologic cycle, *Nature*, *378*, 145–149.

Rahmstorf, S. (2002), Ocean circulation and climate during the past 120,000 years, *Nature*, *419*, 207–214.

Rawlins, M. A., C. J. Willmott, A. Shiklomanov, E. Linder, S. Frolking, and R. B. Lammers (2006), Evaluation of trends in derived snowfall and rainfall across Eurasia and linkages with discharge to the Arctic Ocean, *Geophys. Res. Lett.*, *33*, L07403, doi:10.1029/2005GL025231.

Rennermalm, A. K., E. F. Wood, A. J. Weaver, M. Eby, and S. J. Déry (2007), Relative sensitivity of the Atlantic meridional overturning circulation to river discharge into Hudson Bay and the Arctic Ocean, *J. Geophys. Res.*, *112*, G04S48, doi:10.1029/2006JG000330.

Rigor, I. G., R. L. Colony, and S. Martin (2000), Variations in surface air temperature observations in the Arctic, 1979–1997, *J. Clim.*, *13*, 896–914.

Rogers, M. W., M. S. Allen, and M. D. Jones (2005), Relationship between river surface level and fish assemblage in the Ocklawaha River, Florida, *River Res. Appl.*, *21*, 501–511.

Scrimgeour, G. J., T. D. Prowse, J. M. Culp, and P. A. Chamber (1994), Ecological effects of river ice break-up: A review and perspective, *Freshwater Biol.*, *32*, 261–275.

Serreze, M. C., D. H. Bromwich, M. P. Clark, A. J. Etringer, T. Zhang, and R. Lammers (2002), Large-scale hydro-climatology of the terrestrial Arctic drainage system, *J. Geophys. Res.*, 107, 8160, doi:10.1029/2001JD000919, [printed *108*(D2), 2003].

Shiklomanov, A. I., R. B. Lammers, and C. J. Vörösmarty (2002), Widespread decline in hydrologic monitoring threatens pan-Arctic research, *Eos Trans. AGU*, *83*, 13.

Shiklomanov, A. I., R. B. Lammers, M. Rawlins, L. C. Smith, and T. M. Pavelsky (2007), Temporal and spatial variations in maximum river discharge from a new Russian data set, *J. Geophys. Res.*, *112*, G04S53, doi:10.1029/2006JG000352.

Smakhtin, V. U. (2001), Low-flow hydrology: A review, *J. Hydrol.*, *240*, 147–186.

Smith, L. C. (2000), Trends in Russian Arctic river-ice formation and breakup, 1917–1994, *Phys. Geogr.*, *20*, 46–56.

Smith, L. C., and D. E. Alsdorf (1998), Control on sediment and organic carbon delivery to the Arctic Ocean revealed with space-borne synthetic aperture radar: Ob's River, Siberia, *Geology*, *26*, 395–398.

Smith, L. C., Y. Sheng, G. M. MacDonald, and L. D. Hinzman (2005), Disappearing Arctic lakes, *Science*, *308*, 1429.

Smith, L. C., Y. Sheng, and G. M. MacDonald (2007), A first pan-Arctic assessment of the influence of glaciation, permafrost, topography and peatlands on Northern Hemisphere lake distribution, *Permafrost Periglacial Process.*, *18*, 201–208, doi:10.1002/ppp.581.

Sujono, J., S. Shikasho, and K. Hiramatsu (2004), A comparison of techniques for hydrograph recession analysis, *Hydrol. Process.*, *18*, 403–413.

Vellinga, M., and R. A. Wood (2002), Global climatic impacts of a collapse of the Atlantic thermohaline circulation, *Clim. Change*, *43*, 251–267.

Vörösmarty, C. J., L. D. Hinzman, B. J. Peterson, D. H. Bromwich, L. C. Hamilton, J. Morison, V. E. Romanovsky, M. Sturm, and R. S. Webb (2001), *The Hydrologic Cycle and its Role in Arctic and Global Environmental Change: A Rationale and Strategy for Synthesis Study*, Arctic Res. Consortium of the U. S., 84 pp., Fairbanks, Alaska.

Walvoord, M. A., and R. G. Striegl (2007), Increased groundwater to stream discharge from permafrost thawing in the Yukon River basin: Potential impacts on lateral export of carbon and nitrogen, *Geophys. Res. Lett.*, *34*, L12402, doi:10.1029/2007GL030216.

Woo, M.-K., and R. Thorne (2003), Streamflow in the Mackenzie Basin, Canada, *Arctic*, *56*, 328–340.

Wu, P., R. Wood, and P. Stott (2005), Human influence on increasing Arctic river discharges, *Geophys. Res. Lett.*, *32*, L02703, doi:10.1029/2004GL021570.

Yang, D., D. L. Kane, L. D. Hinzman, X. Zhang, T. Zhang, and H. Ye (2002), Siberian Lena River hydrologic regime and recent change, *J. Geophys. Res.*, *107*(D23), 4694, doi:10.1029/2002JD002542.

Yang, D., B. Ye, and D. L. Kane (2004a), Streamflow changes over Siberian Yenisei River Basin, *J. Hydrol.*, *296*, 59–80.

Yang, D. Q., B. Ye, and A. I. Shiklomanov (2004b), Discharge characteristics and changes over the Ob' River watershed in Siberia, *J. Hydrometeorol.*, *5*, 595–610.

Ye, B. S., D. Q. Yang, and D. L. Kane (2003), Changes in Lena River streamflow hydrology: Human impacts versus natural variations, *Water Resour. Res.*, *39*(7), 1200, doi:10.1029/2003WR001991.

Yoshikawa, K., and L. D. Hinzman (2003), Shrinking thermokarst ponds and groundwater dynamics in discontinuous permafrost near Council, Alaska, *Permafrost Periglacial Process.*, *14*, 151–160.

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

Zhang, T., J. A. Heginbottom, R. G. Barry, and J. Brown (2000), Further statistics on the distribution of permafrost and ground ice in the Northern Hemisphere, *Polar Geogr.*, *24*, 126–131.

Zhang, T., O. W. Frauenfield, R. G. Barry, A. Etinger, J. McCreight, and D. Gilichinsky (2005), Response of changes in active layer and permafrost conditions to hydrological cycle in the Russian Arctic, *Eos Trans. AGU*, *86*, Fall Meet. Suppl., Abstract C21C-1118.

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