TRENDS IN RUSSIAN ARCTIC RIVER-ICE FORMATION AND BREAKUP, 1917 TO 1994

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Abstract: Long-term time series of river-ice observations for nine large rivers in Arctic and subarctic Russia are analyzed using the Mann-Kendall test for monotonic trend. Of eight data categories analyzed for each river, the timing of melt onset displays the highest incidence of change, with statistically significant negative (earlier) shifts of approximately 1 to 3 weeks found for the Pechora, Ob, Olenek, Indigirka, and Kolyma rivers. However, corresponding shifts in associated ice-breakup phenomena are not found, suggesting an increase in spring melt period and a transition to more thermally driven ice-breakup events. An observed general pattern of decreased ice cover in the 1950s, increased ice cover in the 1980s, and subsequent decrease during the 1990s is generally consistent with other studies of Siberian temperature trends. However, both interannual and regional variability is found. Earlier occurrence of autumn freezing is found for the Onega, Varzuga, Mezen, and Yenisei rivers, leading to an increase in the duration of winter ice cover for all but the Mezen. An opposite trend is found for the Indigirka and Kolyma rivers of far eastern Siberia. This regional contrast is attributed to North Atlantic modulation of western rivers.
[Key words: River ice, Mann-Kendall, Arctic Russia.]

INTRODUCTION

It is now generally accepted that Arctic thermohaline circulation and sea-ice production are sensitive to freshwater inputs from precipitation and terrestrial runoff. The Arctic Ocean is relatively small and enclosed, receiving nearly 10% of the world's river runoff into a basin occupying only 6% of the global ocean surface area (Steele et al., 1996). Associated freshening of surface waters is critical to the presence of a perennial sea-ice cover, which maintains the cold Arctic climate and present global energy balance (Aagard and Carmack, 1989; Weatherly and Walsh, 1996). Coupled ice-ocean modeling indicates that fresh water inputs of precipitation and runoff are required to maintain the stable Arctic halocline, and therefore decadal trends in river runoff can exert large changes in the ocean-climate system (Weatherly and Walsh, 1996). All but one major Arctic river and approximately 85% of the total terrestrial runoff to the Arctic Ocean are supplied by the Russian Federation (Aagaard and Carmack, 1989). For this reason, better knowledge of the volume, timing, and natural variability of Russian river discharge has been defined as a major priority in Arctic science (Forman and Johnson, 1996). From a biological standpoint, increases in river stage, velocity, temperature, and concentration of suspended materials associated with ice breakup exert important effects on primary production and food-web dynamics in rivers and estuaries (Scrimgeour et al.,

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1994), and associated flooding is a primary control on the exchange of sediment and organic carbon between Arctic floodplains and main-stem rivers (Smith and Alsdorf, 1998).

Numerous investigations have utilized the timing of surface water freezeup or breakup to infer information about climate (e.g., Palecki and Barry, 1986; Robertson et al., 1992; Ginzburg et al., 1992; Soldatova, 1992; 1993; Ginzburg and Soldatova, 1996). The occurrence of lake ice is primarily a function of air temperature (Morris et al., 1995), whereas river-ice formation and breakup are also influenced by water discharge, temperature, and local hydraulic conditions (Beltaos, 1997). Despite this complexity, good correlation is found between Eurasian air temperatures and river-ice cover (Ginzburg et al., 1992; Soldatova, 1993; Ginzburg and Soldatova, 1996). It is encouraging that this correlation exists even for regulated rivers such as the Volga (Soldatova, 1992). This paper presents long-term timing and duration anomalies for 72 river-ice observation records acquired from 1917 to 1994 for the Varzuga, Onega, Mezen, Pechora, Ob, Yenisei, Olenek, Indigirka, and Kolyma rivers of Arctic and subarctic Russia (Fig. 1). Twenty of these records are found to display statistically significant trend, as determined by the Mann-Kendall test. These records are presented and interpreted in the context of spring breakup regime and regional climate.

DATA AND METHODS

River-Ice Observations: 1917 to 1994

River-ice-thickness and seasonal-duration data from 49 stations in northern Russia have been recently compiled by the National Snow and Ice Data Center (NSIDC), University of Colorado at Boulder (Vuglinsky, 1999). Data were collected by the State Hydrological Institute of the Russian Federal Service for Hydrometeorology and Environmental Monitoring, and acquired through the Working Group VIII of the United States–Russia Agreement on Cooperation in the Field of Protection of the Environment and Natural Resources. Records for nine stations span periods greater than 50 years and were selected for trend analysis (Table 1). Most observations begin in the 1930s, with the earliest beginning in 1917. For each October to September hydrologic year of record, eight data classes were extracted: (1) start date of winter ice events; (2) start date of ice-cover formation; (3) start date of spring ice-cover events (i.e., melt onset); (4) start date of spring ice-drift events; (5) date of highest level of ice drift; (6) conclusion date of all ice events (i.e., ice disappearance); (7) total duration of continuous ice cover; and (8) total duration of all ice events between fall and spring of each hydrologic year. Hereafter these eight variables are referred to as "first ice," "ice cover," "melt onset," "first drift," "peak drift," "ice disappearance," "duration of cover," and "duration of events," respectively. With the exception of the Onega and Pechora rivers, records for these data categories were at least 95% complete for their respective rivers (Table 1).

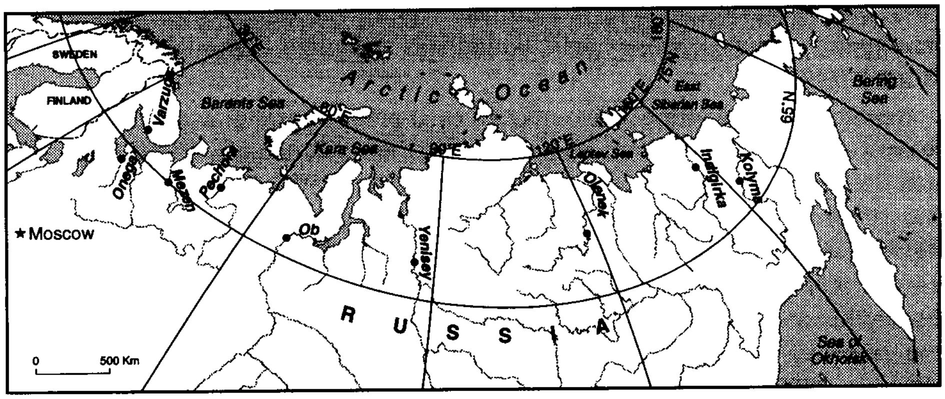

Fig. 1. Locations of nine river-ice observation stations used in this study. All records contain 50+ years of record.

Trend Analysis

Annual time series of river-ice occurrence and duration were analyzed using the non-parametric Mann-Kendall test for monotonic trend (Mann, 1945; Kendall, 1975; Maidment, 1993). A non-parametric test was preferred over a parametric test to avoid potential problems introduced by data skew. The Mann-Kendall test is also appropriate when a variety of stations are being tested in a single study or there is no prior hypothesis of a time of change (Hirsch et al., 1991). It has been used by several investigators to detect long-term trends in hydrologic time series (e.g., Hirsch et al., 1991; Burn, 1994; Lins and Slack, 1999). The Mann-Kendall statistic S is given by:

$$S = \sum_{t'-1}^{n-1} \sum_{t=t'+1}^{n} Z_k \tag{1}$$

where the ranked series Z_k is generated from each input time series y_t, $t = 1, \ldots n$ by comparing each value y_t', $t = 1, n\text{-}1$ with subsequent values y_t, $t = t'+1, t'+2 \ldots n$ and applying the following criterion:

$$\begin{aligned} Z_k &= 1 \quad \text{if } y_t > y_{t'} \\ Z_k &= 0 \quad \text{if } y_t > y_{t'} \\ Z_k &= -1 \quad \text{if } y_t > y_{t'} \end{aligned} \tag{2}$$

S therefore represents the number of all positive differences minus the number of all negative differences found in y_t. Because the test is based only on the ranks of the data, a correction must be made for the effect of data ties on the variance of S. Data ties occur when adjacent entries have the same date or duration; or when two more years of data are absent (missing values were replaced with the series mean). The correction is implemented as follows:

Table 1. River-Ice Observation Records Used in This Study[a]

River	Station	Location	Area (km^2)	Record	No. years	Percentage
Varzuga	Varzuga	66 24 N, 36 38 E	7,940	1958 to 1992	58	98.5
Onega	Porog	63 49 N, 38 28 E	55,700	1930 to 1988	59	87.5
Mezen	Malonisogorskaya	65 00 N, 45 37 E	56,400	1932 to 1988	57	94.7
Pechora	Oksino	67 38 N, 52 11 E	312,000	1917 to 1988	71	72.2
Ob	Salekhard	66 38 N, 66 36 E	2,950,000	1937 to 1994	58	99.4
Yenisei	Igarka	67 26 N, 86 29 E	2,440,000	1936 to 1989	54	99.1
Olenek	Sukhana	68 37 N, 118 20 E	127,000	1937 to 1992	55	99.6
Indigirka	Vorontsovo	69 34 N, 147 32 E	305,000	1937 to 1992	56	98.4
Kolyma	Srednekolymsk	67 28 N, 153 42 E	361,000	1929 to 1988	60	95.4

[a] Watershed areas, record periods and length, and percentage of complete data also are shown.

$$Var(S) = \frac{n(n-1)(2n+5) - \sum_{i=1}^{n} t_i i(i-1)(2i+5)}{18} \qquad (3)$$

where t_i is the number of ties of order i. Note that untied values have $i = 1$. For $n > 40$ the standardized test statistic Z is obtained using a normal approximation:

$$Z = \begin{cases} \dfrac{S-1}{\sqrt{VarS}} & S > 0 \\ 0 & S = 0 \\ \dfrac{S+1}{\sqrt{VarS}} & S < 0 \end{cases} \qquad (4)$$

The null hypothesis (no trend) is rejected at significance level α if $|Z| > Z_{(1-\alpha/2)}$, where $(1-\alpha/2)$ is the value of the standard normal distribution with exceedance probability $\alpha/2$. This study used an exceedance probability of $p = .90$ ($\alpha = .2$) to establish trend. This corresponds to a critical value of $|Z| > 1.28$. Because the objective of this study is to establish the presence or absence of trend only, a slope estimator (e.g., Sen, 1968) was not used. Note that maximum available record lengths were analyzed. This offers the advantage of utilizing all data but has the disadvantage that some records begin or end on different years. Therefore, Z values must be interpreted in context of their respective time intervals, and not strictly compared with one another.

RESULTS

Departures from long-term averages in event timing and ice-cover duration are shown for all rivers in Figure 2. A positive timing anomaly reflects a later-than-average date of occurrence for a particular ice property on a given year. Negative anomalies indicate earlier-than-average occurrence. Positive- or negative-duration anomalies indicate hydrologic years with longer or shorter ice-cover periods, respectively. Considerable variability is found between years and also between different rivers for a given year. However, some visible trends can be seen in Figure 2. The date of melt onset displays a pronounced trend toward earlier occurrence each spring. Negative anomalies for autumn freezeup phenomena ("first ice" and "ice cover") also are common except in the 1980s. Total durations of ice cover are generally shorter in the 1940s and 1950s, longer in the 1970s, and decline again in the 1980s. Anomalies in the dates of first ice drift, peak ice drift, and ice disappearance do not display visible evidence of temporal trend.

Of the 72 records analyzed, 20 (28%) display trends significant at exceedance probabilities of $p = .90$ ($\alpha = .2$; $|Z| > 1.28$) (Table 2). Sixteen records (22%) display trend with $p = .95$ ($\alpha = .1$; $|Z| > 1.64$). Although the present study examines river-ice properties and not water discharge, these percentages are comparable with those of other Mann-Kendall analyses of hydrologic time series. In a similar study of the timing of the spring flood, Burn (1994) found that 44% and 30% of 84 rivers in west-central Canada display trend at .90 and .95 exceedance probabilities, respectively. Lins and Slack (1999) found that discharge quantiles for 28% to 49% of 395 stream gauges in the conterminous United States display Mann-Kendall trend at $p = .95$.

Records containing trends at $p = .90$ or higher are plotted in Figure 3. Corresponding magnitudes of time shift, calculated for the period 1917 to 1994 using ordinary least-squares regression, are shown in Table 3. As noted earlier, most records do not fully encompass this period, so values contained in Table 3 are approximate. From Figure 2 and Table 2, variables with the highest incidence of statistically significant trend are the "first ice," "duration of cover," and "melt-onset" categories. Of the eight variables tested, melt onset has experienced the highest incidence of change. Five of nine rivers tested reject the Mann-Kendall null hypothesis in this category, thereby establishing the presence of negative trend, or earlier occurrence. Trends are established with exceedance probabilities of $p = .99$ ($\alpha = .02$; $|Z| > 2.33$) for the Kolyma, Ob, and Pechora rivers, $p = .95$ for the Indigirka River, and $p = .90$ for the Olenek River. The two largest rivers of far eastern Siberia (Indigirka and Kolyma rivers) display trends toward later dates of autumn freezeup. The Onega and Yenisei rivers display the opposite effect. The Kolyma River has experienced decreased ice-cover duration, caused primarily by a strong negative shift in melt onset; the Pechora, Varzuga, and Yenisei rivers reflect increases. Little change is found in the springtime phenomena of ice breakup, peak ice drift, or ice disappearance.

DISCUSSION

From Figures 2 and 3, a shift toward earlier occurrence of the spring melt is the most robust trend identified in this study. It is the only data category in which more than half of the study rivers (5 of 9) exhibit statistically significant negative trends in date of occurrence, and four of these are significant at the 95% level. However, cor-

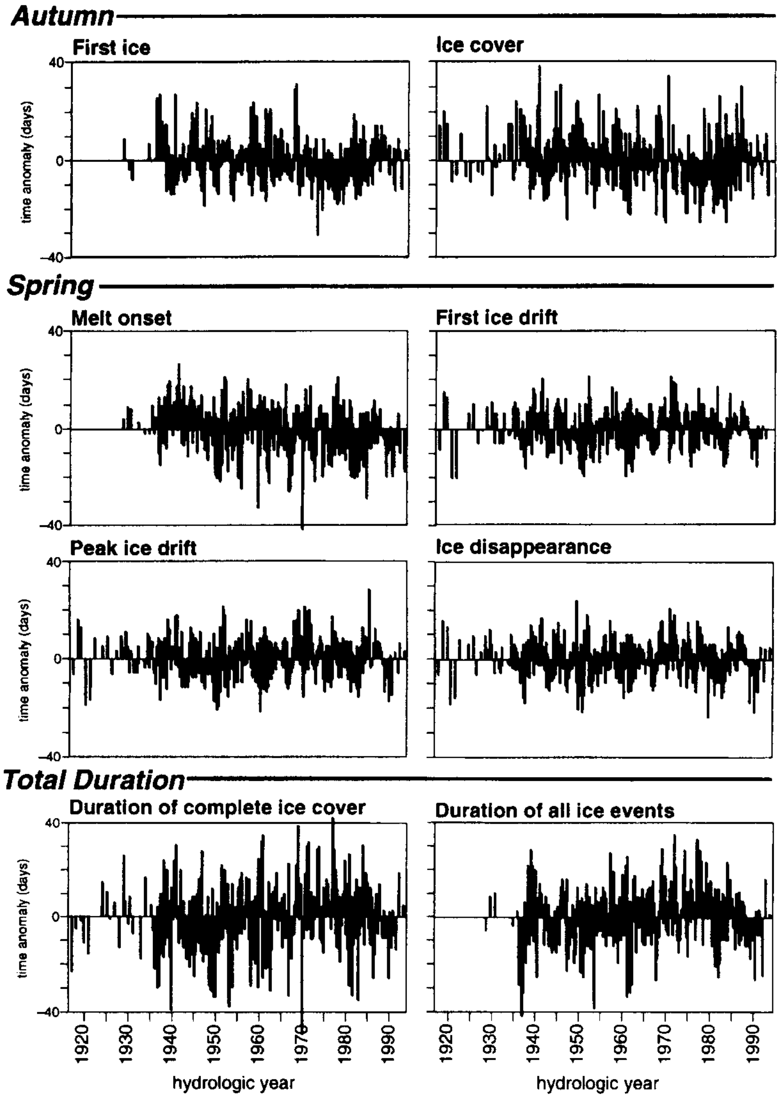

Fig. 2. Timing anomalies in the dates of occurrence of autumn and spring river-ice phenomena, and duration of ice cover for all rivers. Anomalies are computed as departures from the long-term mean for each record.

responding trends in associated spring breakup phenomena ("first drift," "peak drift," and "ice disappearance") are absent in all rivers but the Yenisei. This temporal divergence between melt onset and subsequent ice breakup suggests that while the actual timing of ice breakup and arrival of the spring flood has not changed significantly, the duration of precursor melting has increased.

Ice breakup may be divided into over-mature, or "thermal," breakup events and pre-mature, or "mechanical" (also called "dynamic"), events (Prowse, 1994; Scrim-

Table 2. Standardized Z-Test Statistics for All 72 Time Series[a]

River	First	Cover	Melt	Break	Peak	Clean	Cdays	Idays
Indigirka	1.75	0.48	–1.75	0.53	0.64	1.10	0.11	0.04
Kolyma	1.82	0.81	–3.33	–0.82	–0.69	–0.91	–1.32	–0.73
Mezen	–0.50	–1.98	0.06	0.17	0.78	0.54	0.98	2.38
Ob	–0.28	–0.85	–4.07	0.58	1.04	0.60	0.69	0.41
Olenek	–0.45	–0.59	–1.37	0.62	0.69	–0.11	0.91	0.45
Onega	–1.65	0.36	–0.49	0.36	0.52	1.11	–0.35	1.12
Pechora	–0.86	–0.98	–2.56	0.28	–0.59	–0.86	1.34	1.15
Varzuga	–1.26	–2.40	–0.62	–0.95	–1.08	–1.03	1.88	0.25
Yenisei	–2.04	–1.92	–0.02	2.81	2.41	1.03	3.83	2.89

[a] Negative signs indicate negative trend (earlier occurrence), positive signs indicate positive trend (later occurrence). Bold entries are statistically significant at $p = .90$. Bold italicized entries are statistically significant at $p = .95$.

Table 3. Estimated Time Shifts (in Days) from 1917 to 1994 for Records Displaying Statistically Significant Trend

River	First ice	Ice cover	First melt	First drift	Peak drift	Duration of cover	Duration of event
Onega	–12.6						
Varzuga		–25.2				24.7	
Mezen		–14.6					11.4
Pechora			–23.9			7.9	
Ob			–22.5				
Yenisei	–7.9	–5.9		10.3	7.9	19.6	12.7
Olenek			–7.9				
Indigirka	5.1		–8.1				
Kolyma	4.2		–13.1			–4.1	

geour et al., 1994; Beltaos, 1997). Thermal breakup is characterized by ice that has thinned and weakened from thermal inputs prior to breakup, with little physical breakage taking place. Mechanical breakup occurs when a cool, highly competent ice cover is dynamically fractured by a flood wave before thermal processes have a chance to reduce significantly its thickness and strength. The historical records analyzed here do not provide direct observations of breakup dynamics. However, the observed increase in melt period suggests a transition to an increasingly thermal breakup regime. If so, fluxes of suspended sediment and organic debris may be reduced: Milburn and Prowse (1996) reported large increases in suspended sedi-

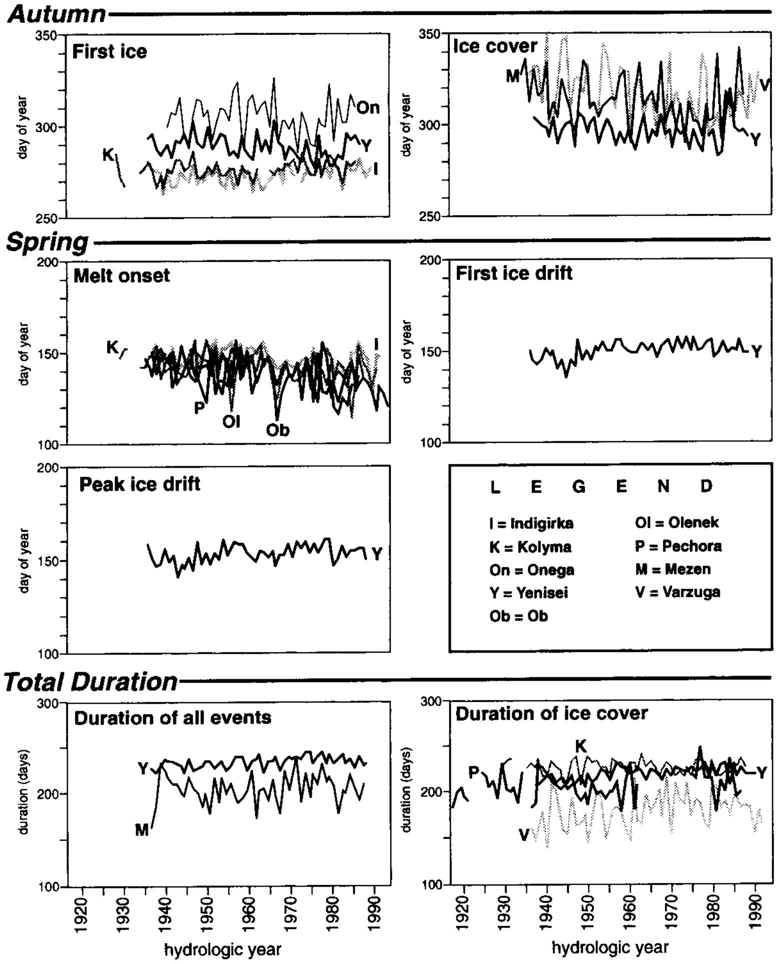

Fig. 3. Timing and durations for individual records displaying statistically significant trend. Five of nine rivers analyzed display strong negative trend in the "melt-onset" category.

ment concentration during the 1987 and 1993 ice-breakup periods on the Liard River in northern Canada. These increases were attributed to high flow velocities and ice scour of bed and banks. However, maximum observed sediment concentration was nearly three times larger for the more mechanical event than for the more thermal event (1,067 mg/L in 1987 vs. 331 mg/L in 1993). The authors concluded that ice jamming and release associated with a mechanical breakup produces higher suspended sediment fluxes than does a thermal breakup (Milburn and Prowse, 1996). Similarly, ice scour of channel banks, riparian zones, and floodplain sediments is thought to produce a sharp pulse of organic material during breakup events (Scrimgeour et al., 1994).

Despite considerable interannual and regional variability, the aggregate-anomaly time series (Fig. 2) suggest a warming maxima around 1950, followed by cooler temperatures and a return to warm conditions beginning in the 1980s. This observation is in general agreement with mean May to September and cold-season temperatures in Siberia (Briffa et al., 1995; Fallot et al., 1997). In Figure 2, warmer temperatures from the 1930s to 1950s are reflected by positive time anomalies in ice cover and melt onset, and negative anomalies in peak ice drift, ice disappearance, and ice-cover duration. Cooler conditions in the 1970s and 1980s are associated with later occurrence of first ice and freezeup, earlier melt onset, and increased ice-cover duration. However, closer inspection of Figure 2 and Tables 2 and 3 suggests that trends vary regionally and may have opposite sign. This phenomenon was also noted by Ginzburg et al. (1992) and Soldatova (1993), although those studies present results for grouped collections of rivers, while the present study examines individual stations. In particular, the Yenisei and western Onega, Varzuga, and Mezen rivers display trends toward earlier occurrence of ice formation in the autumn, while the opposite trend is found for the Indigirka and Kolyma rivers of far eastern Siberia. A trend toward earlier melt onset is absent for western rivers but present in central and eastern Siberia. This contrast suggests that western Eurasia has experienced a change toward cooler autumns with no change in spring temperatures, while eastern Siberia is experiencing warmer spring and autumn seasons. The Yenisei River fits neither pattern, with ice cover experiencing earlier freezeup, later breakup, and increased duration.

A similar regional contrast between western and eastern Eurasia is observed in residuals between observed and modeled temperatures (Tao et al., 1996), with western Siberia more closely resembling the climatology of the North Atlantic region. Peng and Mysak (1992) compared North Atlantic sea-surface temperatures, Northern Hemisphere sea-level pressure anomalies, and Ob and Yenisei river discharge for warm (1951 to 1956) and cold (1971 to 1976) SST winters. Their analyses show a significant correlation between SST anomalies and river discharge, which are attributed to shifts in cyclone tracks associated with the SST variations. While these studies do not specifically address river ice, they provide strong evidence for a teleconnection between climatic conditions in the North Atlantic and western Siberia. Regional contrasts identified in this study may also reflect this effect.

CONCLUSIONS

The Mann-Kendall null hypothesis of no trend was rejected at the 90% level for nearly one-third of 72 ice-observation records for nine large rivers in Arctic Russia. Data categories in which three or more rivers display trend are "first ice," "ice cover," "duration of cover," and "melt onset," with approximately one- to three-week shifts in the latter found for five of nine rivers tested. Absence of corresponding trend in subsequent spring breakup phenomena suggests that river-ice covers are experiencing a longer period of melting each spring. This may indicate a transition toward a more thermal breakup regime, with a corresponding reduction in maximum sediment concentration during the spring flood. While general agreement is found between timing of river-ice cover and published Arctic temperature proxies, regional variability is also present, with the strongest contrast found between rivers of western and eastern Eurasia. This difference in part may result from temperature and precipitation modulation by the North Atlantic region.

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