Variability in river temperature, discharge, and energy flux from the Russian pan-Arctic landmass

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Variability in river temperature, discharge, and energy flux from the Russian pan-Arctic landmass

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[1] We introduce a new Arctic river temperature data set covering 20 gauges in 17 unique Arctic Ocean drainage basins in the Russian pan-Arctic (ART-Russia). Warm season 10-day time step data (decades) were collected from Russian archival sources covering a period from 1929 to 2003 with most data falling in the range from the mid-1930s to the early 1990s. The water temperature data were combined with river discharge data to estimate energy flux for all basins and over the Russian pan-Arctic as a whole. Tests for trend were carried out for water temperature, river discharge, and energy flux. Spatially coherent significant increases in the maximum decadal river temperature were found in the European part of the Russian pan-Arctic. Several other drainage basins showed significant changes, but there was no strong pattern either in the connections between variables or spatially. The trend in area averaged energy flux for the three largest drainage basins (Ob, Yenisey, Lena) combined was found to be significantly decreasing. We speculate that in the Yenisey basin, this decrease was due to large impoundments of river water. The lack of consistency between temperature and energy flux trends was due to the difference in timing between peaks in river temperature and river discharge. The mean area averaged energy flux from the Russian basins was 0.2 W m^{-2}. Using this mean we estimated the total energy flux from the entire Russian pan-Arctic, both gauged and ungauged, to be 82 EJ a^{-1}.

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1. Introduction

[2] Global land surface and ocean temperatures have been characterized by significant increases over the course of the last 100 years [*Hansen et al.*, 2006] and there is evidence of increased hydrologic cycle activity or acceleration [*Arctic Climate Impact Assessment*, 2005; *Intergovernmental Panel on Climate Change*, 2001; *Framing Committee of the Global Water Systems Project*, 2004]. There have also been increases in extreme precipitation, systematic reductions in snow cover and mountain ice, as well as more frequent and intense quasiperiodic events such as ENSO and the Arctic Oscillation over the last several decades [*Arnell and Liu*, 2001; *Groisman et al.*, 2005]. Such changes may have major social and ecological implications, thus it is important to gain a better understanding of the linkages and interconnections of the global water cycle [*Framing Committee of the Global Water Systems Project*, 2004].

[3] The Arctic has experienced warming air temperatures throughout most of the 20th century, with annual land-surface air temperatures (SATs) for the Arctic region (north of 60°N) indicating a significant warming trend of 0.09°C per decade from 1900 to 2003 [*Arctic Climate Impact Assessment*, 2005]. For this time period, SATs generally increased from 1900 to the mid-1940s, then decreased until the mid-1960s, and steadily increased from the mid-1960s onward. Between 1966 and 2003, northern Eurasia warmed 1°∼2°C on average [*Arctic Climate Impact Assessment*, 2005] with most regions of the Russian Arctic showing warming during all seasons [*Groisman et al.*, 2003].

[4] One important component of the changing system is that of the Arctic river system in Russia which supplies a large amount of the river discharge to the Arctic Ocean. There is evidence of increasing river discharge from the Russian pan-Arctic in recent decades [*Peterson et al.*, 2002; *McClelland et al.*, 2004], and in two studies of river discharge from small drainage basins (less than 50 000 km^2) distributed throughout the Russian pan-Arctic there was a consistent shift to earlier spring maximum discharge [*Shiklomanov et al.*, 2007] and increases in winter base flow [*Smith et al.*, 2007]. Research into Russian river discharge has benefited from the wealth of available data for the pan-Arctic region, including the R-ArcticNet database [*Lammers et al.*, 2001; *Shiklomanov et al.*, 2002]. However, we speculate about changes other than in river discharge likely to have occurred which may serve as an indicator of climate change: the thermal regime of large river systems, particularly for the Russian Arctic region.

[5] Water temperature is impacted by factors such as air temperature, land cover type, land use changes, human

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modifications (e.g., dams, industrial activities, municipal discharge), and it has an important influence on the quality and ecology of streams and rivers [*Webb and Nobilis*, 1997]. Most river temperature studies, to date, have been conducted on relatively small local or regional spatial scales, and only a limited subset of those have been in the Arctic or cold regions, including Alaska [*Kyle and Brabets*, 2001], Austria [*Webb and Nobilis*, 1997], and New Brunswick [*Caissie et al.*, 2001]. There has been some work moving to larger spatial scales in the Arctic. In a study of river temperature in 32 monitoring stations in 7 unique drainage basins around Cook Inlet in Alaska, *Kyle and Brabets* [2001] found river temperature increases affect fish quantity, well-being, and disease. These data were based on 32 time series covering 1 to 14 years of records (19 sites with 3 years or less) in basins ranging from 1.8 km^2 to 31 000 km^2. For larger drainage basins, *Yang et al.* [2005] looked at river temperature for five gauges on the Lena basin from 1950 to 1992 and concluded that there has been a consistent warming of stream temperature across the entire Lena basin during the early open water season (early to mid-June), coupled with an increase in peak discharge for the same period. River temperatures for the remainder of the open water season exhibited mixed results, with warming occurring in some subbasins, and cooling in others; some of this can be attributed to regulation by dams and spatial differences among gauging station locations, in addition to other factors.

[6] *Caissie* [2006] provides a recent review of the important role of river thermal regime, the processes involved in governing river temperature, models used, and the sources of variability, especially via human impacts. His survey indicated very little evidence of long-term changes to water temperature in large river systems due to climate change since almost all river basins investigated had some direct human changes to the river water or land cover in the basin. This is consistent with the recognition that few large drainage basins have remained unaltered [*Vorosmarty et al.*, 2004]. *Webb* [1996] reviewed the available river temperature data globally and showed very limited unbroken, long-term time series were available. He felt this was mainly due to the more recent recognition of water quality as an important issue and that the United Nations Environment Programme Global Environment Monitoring System (GEMS/Water) was limited owing to the poor coverage of stations globally and the wide spacing between data points. Reviewing the data holdings of GEMS/Water, a repository for global water quality including river temperature, for this paper indicates there has been a marked improvement in this database over the last 10 years in both spatial coverage and the amount of data. Thus, while there have been some local or regional studies on river temperature, including for portions of the Arctic, we are not aware of any continental-scale Arctic river temperature studies.

[7] In this paper we seek to identify any change in river temperature that may reflect climate change signals or direct human induced changes in the region and to estimate the continental-scale energy contributions by the Russian river drainage basins into the Arctic Ocean. We describe the Russian pan-Arctic region, the four data sets used in the analysis, the preprocessing of the raw data to get a "cleaned" version of the data, how we arrived at the time aggregated annual and climatological estimates, and finally how we spatially aggregated the results across drainage basins to arrive at a Russian pan-Arctic estimated energy flux. We finish by discussing the findings and suggesting further research to improve temperature and energy flux estimates.

2. Site Description

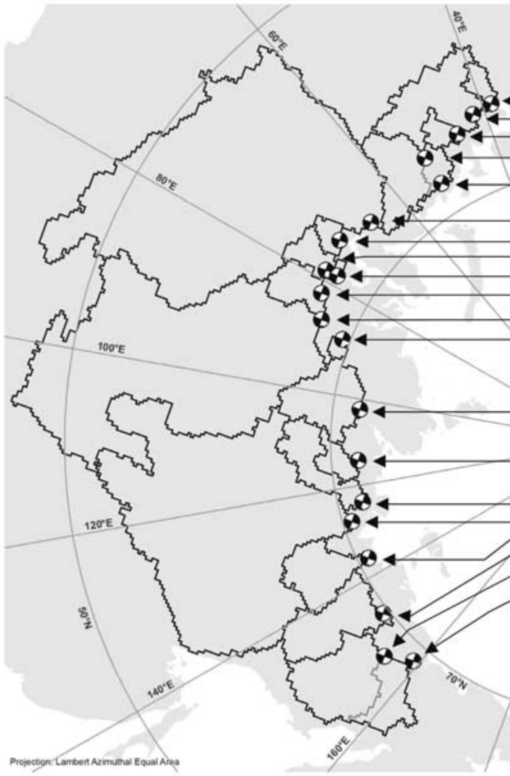
[8] The river temperature data comprise 20 stations located in the Russian pan-Arctic representing 17 large watersheds all draining northward into the Arctic Ocean (Figure 1 and Table 1). These stations cover 10,461,800 km^2 or 80.9% of the 12,925,000 km^2 of Russian north flowing rivers and in all cases these gauges are also the locations for the measurement of river discharge. These rivers freeze over during the winter yet they are large enough to have flow throughout the year. The drainage basins covered by the gauges extend from 38°E (Onega River Basin) to 171°E (Kolyma Basin) and from 72°N in the north (Khatanga River) to 46.5°N at the southern watershed boundary of the Yenisey. The basins range in gross drainage area from 19 800 km^2 (Norilka at Valek) to 2,950,000 km^2 (Ob at Salekhard). Basins in this region span several major land cover types from tundra to taiga forest to steppe. The basins have peak discharge in the Spring due to snowmelt across the region. On the basis of the permafrost map of *Brown et al.* [1998] thirteen stations have 100% of their upstream drainage area classified as having some permafrost and three stations have no permafrost at all (Table 1). Total glaciated area in these drainage basins is small with the Yana basin having the largest percentage coverage at 0.15% of the drainage area and the Ob having the largest total permanent ice cover of 870 km^2 (0.03% of drainage area).

3. Data Sets

[9] Four data sets were used to generate the time and space aggregated temperature and temperature flux time series covering the important Russian drainage basins at the downstream (closest to the Arctic Ocean) gauging sites. These were a Russian river temperature data set, an ice thickness and duration data set giving dates of river thaw and freeze, and two pan-Arctic river discharge data sets. The first data set was newly digitized for this project and is discussed below. The second data set [*Vuglinsky*, 2000] was obtained from the National Snow and Ice Data Center (NSIDC) and consists of dates for several ice conditions such as the start of ice melt, start of spring ice drift, start of frazil ice, start of ice flow drift, and start of ice cover formation. The third and fourth sets of data originate from two established University of New Hampshire (UNH) river discharge data products at daily and monthly time steps. The river temperature and river discharge values for each station were collected at the same location on each river. An additional data set for air temperature was also used.

3.1. River Temperature Data

[10] The Arctic River Temperature data discussed in this paper (ART-Russia) represents a data gathering effort which is both unique and independent from the important GEMS/Water programme [*United Nations Environment Programme*, 2006], and the ART-Russia data set has a



ID	Station Name	River Temperature LM	River Temperature MK	Discharge LM	Discharge MK	Energy Flux LM	Energy Flux MK
18	Onega at Porog	M	M				
16	Severnaya Dvina at Ust-Pinega	M	M				
19	Mezen at Malonisogorskaya	M					
20	Pechora at Ust-Tsilma	X, M	M	M	M	X	X
17	Pechora at Oksino	M	M	—	—	—	—
12	Ob at Salekhard						
13	Nadym at Nadym						
11	Pur at Urengoy						
14	Pur at Samburg						
15	Taz at Sidorovsk						
10	Yenisey at Igarka					X	X
9	Norilka at Valek					X	
4	Khatanga at Khatanga			—	—	—	—
3	Anabar at Saskulakh	X, M	M				
5	Olenek downstream of Buurs mouth			D	D		
6	Lena at Kusur						
7	Yana at Ubileinaya	M	M			X, M	
8	Indigirka at Vorontsovo						
1	Kolyma at Srednekolymsk						X, M
2	Kolyma at Kolymskoye		D				

Slope key. Light/dark colors for significant changes with sign of change depending on variable (e.g. dark cell in temperature field is for a positive slope, or warming)

	Temperature	Discharge	Energy
Light	- Cooler	+ More Water	- Less Energy
Dark	+ Warmer	- Less Water	+ More Energy

X = Mean value; M = Maximum value;
D = Timing of Maximum; — = No values available;
LM = Least Squares Regression; MK = Mann-Kendall Regression; $\alpha = 0.95$
Units based on: Temperature °C y^{-1}, discharge $km^3\ y^{-1}$, energy flux PJ y^{-1}.

Figure 1. Locations of river temperature gauging stations along the northern Russian pan-Arctic. A total of 20 stations in 17 watersheds cover 85.3% of the Russian Arctic Ocean drainage system. Figure includes table showing significant trends in mean value, maximum value, and day of maximum for water temperature, river discharge, and energy flux using both linear regression and Mann-Kendall tests.

Table 1. Summary of Monitoring Stations[a]

Identification	Code	Short-hand	Name	Gauge Location, Decimal Degrees: Latitude	Gauge Location, Decimal Degrees: Longitude	Drainage Area at Gauge, km^2	Summer River Width, m: Min.	Summer River Width, m: Max.	Summer Mean River Depth, m: Min.	Summer Mean River Depth, m: Max.	Area with Permafrost (% of Drainage Basin)
18	70842	Oneg	Onega at Porog	63.82	38.47	55700	–	232	–	11.4	0
16	70801	Sevr	Severnaya Dvina at Ust-Pinega	64.13	41.92	348000	725	1036	6.7	11.3	0
19	70844	Mezn	Mezen at Malonisogorskaya	65.00	45.62	56400	270	359	3.0	3.6	0
20	70850	PchU	Pechora at Ust-Tsilma	65.42	52.28	248000	786	1170	6.7	11.3	43
17	70827	PchO	Pechora at Oksino	67.63	52.18	312000	–	–	–	–	42
12	11801	Ob	Ob at Salekhard	66.63	66.60	2950000	2000	2550	11.6	13.4	27
13	11805	Nadm	Nadym at Nadym	65.62	72.67	48000	850	1281	1.0	3.0	100
11	11571	PurU	Pur at Urengoy	65.97	78.35	80400	571	1400	1.8	4.5	100
14	11807	PurS	Pur at Samburg	67.00	78.22	95100	1148	1363	1.7	5.9	100
15	11808	Taz	Taz at Sidorovsk	66.60	82.28	100000	649	717	3.6	7.4	100
10	9803	Yen	Yenisey at Igarka	67.43	86.48	2440000	1500	1830	22.9	28.8	89
9	9455	Nor	Norilka at Valek	69.42	88.32	19800	358	384	3.0	4.6	100
4	3802	Khat	Khatanga at Khatanga	71.98	102.47	275000	975	1040	11.6	13.4	100
3	3801	Anab	Anabar at Saskulakh	71.97	114.08	78800	370	1080	0.53	7.6	100
5	3811	Olnk	Olenek 7.5 km down of Buurs mouth	71.85	123.65	198000	800[b]		2.2	10	100
6	3821	Lena	Lena at Kusur	70.68	127.39	2430000	2400[b]		10	25	100
7	3861	Yana	Yana at Ubileinaya	70.77	136.08	224000	800[b]		3	7	100
8	3871	Indk	Indigirka at Vorontsovo	69.57	147.53	305000	379	452	6.7	9.4	100
1	1801	KolS	Kolyma at Srednekolymsk	67.47	153.69	361000	879	1310	4.9	8.4	100
2	1802	KolK	Kolyma at Kolymskoye	68.73	158.72	526000	1650[b]		4.2	7	100

[a]River width and depth from Hydrological yearbooks [*Roshydromet*, 1973a, 1973b, 1973c, 1973d, 1973e]. Min., minimum value; Max., maximum value; dashes, unknown. Permafrost area from *Brown et al.* [1998]. Total area was summed over each permafrost class, continuous, discontinuous, sporadic, and isolated patches. This represents an overestimate of actual permafrost area.

[b]Mean values.

larger number of gauges for the Russian pan-Arctic, tends to have longer time series for these sites, and has 10-day mean values averaged from daily data rather than monthly point samples. GEMS/Water does have some monitoring stations upstream of the primary Russian gauges within the Ob and Yenisey basins. The river temperature data for our study was collected by Roshydromet from the large Siberian rivers and some of the most important uses were for the prediction of the dates of river freeze and ice out which are important for navigation.

[11] Three versions of the river temperature data are used in this paper. The first version represents all the raw data obtained from Russia after errors were fixed or removed. This version, described below in this section, we name T_0 and it represents the most complete version of the data currently available. A second version of the river temperature data was created to perform consistent analysis of ice-free mean temperature values. This data set, named T_1, began with T_0 and had some years removed owing to missing data and some individual data values removed or added at the beginning and/or end of the ice-free seasons. The third set, named T_2, was generated from T_1 in order to perform energy calculations. For T_2 all river temperature values during the winter period were set to 0°C and any years without river discharge had river temperature removed.

[12] For systematic monitoring of rivers in Russia, river temperature was recorded twice each day at 8am and 8pm from the water surface at or near the same location where river stage height was taken. According to the manual [*USSR State Committee on Hydrometeorology and Environmental Control*, 1978] this location was selected on the basis of detailed water temperature observations along the river cross section such that the daily measurement location gave representative values. These values were taken at the same time as water stage values and, occasionally, more extensive sets of measurements at several points along the river cross section were taken in conjunction with multiple river discharge measurements. Water temperature was measured with a water thermometer having an accuracy of 0.1°C. When the temperature was less than 0.5°C a microthermometer with an accuracy of 0.01°C was used. Measurements of temperature typically were not made during the winter months when the rivers were frozen. Temperature values were assembled at the regional Roshydromet offices [*Shiklomanov et al.*, 2002], averaged, and published as part of the Russian national hydrological yearbooks. Water temperature data were averaged for three periods of approximately 10 days in length (beginning of month to the 10th, 11th to 20th, and the 21st to the end of the month). This gave intervals between each decadal mean value of 8 to 11 days depending upon the length of the month and whether or not there was a leap year (although in practice no values were available for February). For the purposes of this paper we use the term 'decade' to describe exclusively these approximately 10-day intervals. Incompleteness of water temperature data in the data set was a result of both deterioration in the publication of the data during the 1990s and actual gaps in observations. A collaborative effort between scientists at the State Hydrological Institute (SHI), St. Petersburg, Russia and UNH created a digitized version of the decadal time aggregated data. This raw version of the river temperature is referred to as T_0.

3.2. Ice Conditions

[13] We used two time series from the Russian River Ice Thickness and Duration (RRITD) data set [*Vuglinsky*, 2000], the date of first observed ice drift (the first movement downstream of river ice during Spring break-up) in the spring and the first sign of stable ice cover in the fall. In the case of first sign of stable ice cover the ice must remain stable for more than 20 days after this date for it to be a valid date. This data set provided a valuable secondary source of information regarding the early and late season temperature data and allowed us to better define the near-0°C data points. As part of this research, each date was converted to the nearest decade (the 5th, 15th and 25th day of each month).

3.3. River Discharge Data

[14] The river discharge data were used in combination with river temperature to estimate the total heat flux from each of the river systems. For river discharge data we collected daily time series data for all temperature gauges from the Regional Integrated Hydrological Monitoring System for the Pan-Arctic Landmass (ArcticRIMS) data compendium [*Shiklomanov et al.*, 2002] (and http://ArcticRIMS.unh.edu). These data were averaged to match the 10-day time periods of the river temperature data (Figure 2). When 1 to 3 decadal values were missing from these data, we included interpolated river discharge from monthly time step R-ArcticNet data set [*Lammers et al.*, 2001].

[15] It is important to note these decadal river discharge data are quite different from other discharge data sets as we removed from the analysis all decadal values having no corresponding temperature value. Since no river temperature values exist for the winter period there will be a warm season bias giving very different results for time aggregated values and trends when compared to the full record of other studies.

3.4. Air Temperature Data

[16] Monthly gridded fields of air temperature at equal area 25 km × 25 km grid cell resolution were used to determine annual trends in air temperature for each gauge. The data were an updated version of C. J. Willmott and K. Matsuura (Arctic terrestrial air temperature and precipitation: Monthly and annual time series (1930–2000) version 1, available online at http://climate.geog.udel.edu/~(climate/2001), expanded to December 2004 and available at http://RIMS.unh.edu.

4. Methods

[17] Once the data sets were assembled we performed quality checks and began the selection procedure to choose which gauge-years were sufficiently complete to be used for annual calculations. Each individual gauge-year was evaluated independently from all other gauge-years and either retained or removed from the pool of acceptable data.

[18] Individual data points were added and/or removed to establish consistency between years. Some gauges had several decades of 0°C values during the cold season while others did not. Had we left in these multiple 0°C data values the calculations for mean annual temperature for that particular gauge-year would have been lower resulting in

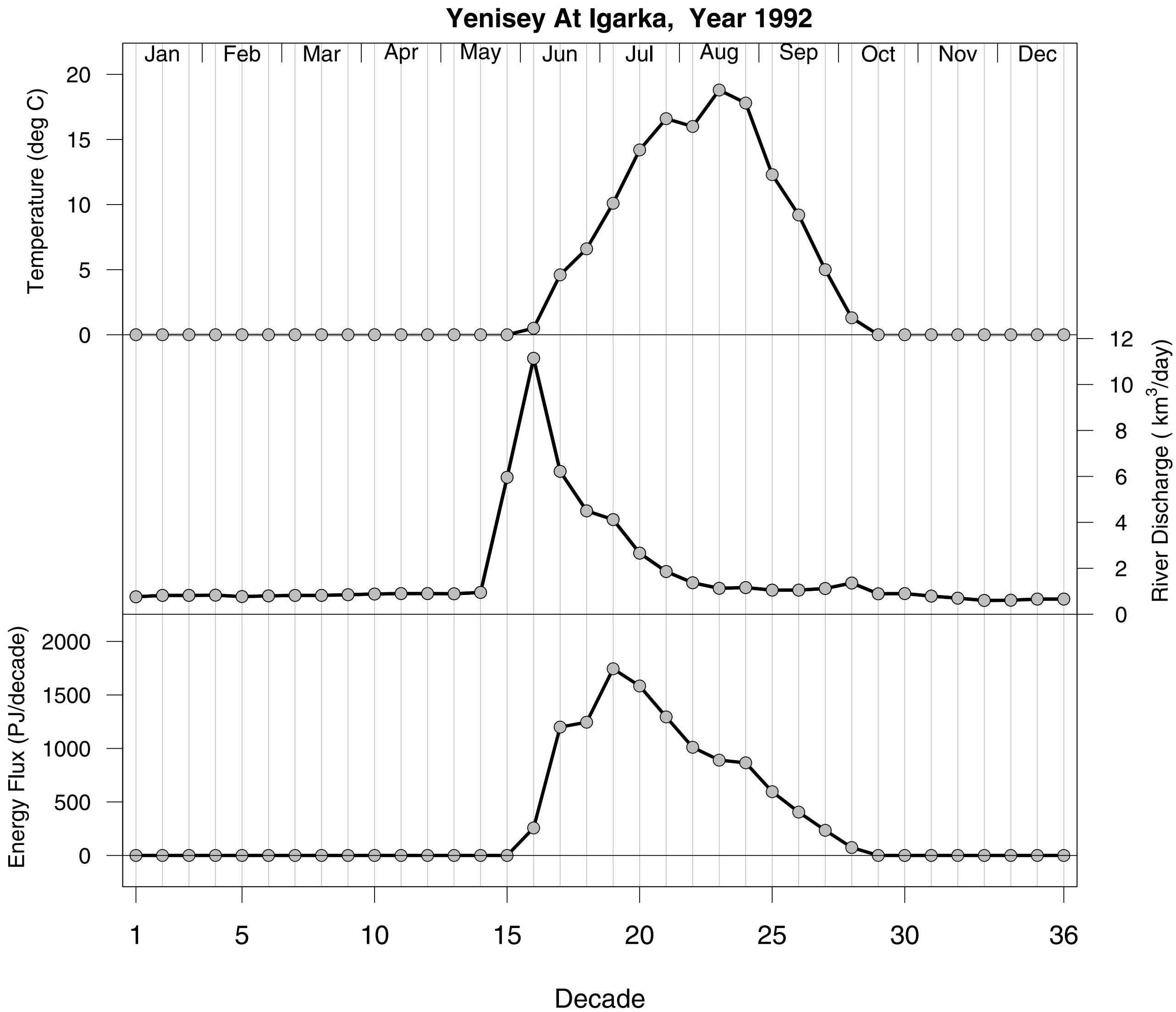


Figure 2. In most gauges and years, discharge tends to peak first and temperature tends to peak last while the energy flux typically will peak in between these two. This is illustrated for a single year of data, 1992, for the Yenisey drainage basin. (middle) River discharge peaks a month before (bottom) the energy flux, which in turn peaks approximately 40 days before (top) water temperature. The top curve also shows two versions of the temperature data T_1 (black line) and T_2 (gray line, values filled in at 0°C during the cold season). Decade refers to a period of approximately 10 days.

a downward bias relative to a similar gauge-year without extra 0°C values due to the inclusion of more low values. In other cases, where the time series did not have 0°C values at the ends of the warm season, we added temperature data points to avoid an upward temperature bias. Values were added only when the adjacent decadal temperature values were close to 0°C or we had additional information on ice conditions from the RRITD data.

[19] The next step was to generate a second subset of gauge-years to be used for energy flux calculations in which each decadal temperature value had a corresponding river discharge data point. The objective was to estimate total energy flux past the river gauge

$$E_{flux} = C_p \cdot \rho \cdot T_{\circ C} \cdot Q, \qquad (1)$$

where E_{flux} is the total decadal energy flux (PJ decade^{-1}), Cp is the specific heat of water (PJ kg^{-1} °C^{-1}), ρ is water density (kg km^{-3}), $T_{\circ C}$ is river temperature (°C), and Q is the total decadal river discharge (km^3 decade^{-1}). Although variable with respect to temperature specific heat and density were set to a fixed value of Cp = 4193 J kg^{-1} K^{-1} (corresponding to the T_0 data set mean value of 9.42 °C) and $\rho = 1 \times 10^{12}$ kg km^{-3}. Using the Celsius temperature scale means the E_{flux} is not an absolute energy flux, but relative to the freezing point of water. Decade is a period of approximately 10 days.

[20] A third version of the river temperature data set was created, referred to as T_2, where all cold season decades within the T_1 data set were set at T = 0°C in order to provide data points for the full gauge-year (Figure 2). Such values were consistent on the basis of single point river tempera-

Table 2. Summary of River Temperature Data

		River Temperature Data (T_0)				Number of Data Points			
Identification	Short-hand	First Year	Last Year	Years in Range	Years With Data	Temperature (T_0)	Temperature (T_1)	Energy Flux (Using T_2)	Gauge Used for Figure 5
18	Oneg	1937	2003	67	55	1034	944	1440	√
16	Sevr	1936	2003	68	56	1017	1009	1728	√
19	Mezn	1940	2003	64	26	458	410	720	√
20	PchU	1936	2003	68	56	925	925	1836	√
17	PchO	1939	2003	65	28	448	465	36	-
12	Ob	1936	1998	63	61	943	710	1620	√
13	Nadm	1939	1998	60	55	732	536	828	√
11	PurU	1948	1990	43	42	551	439	324	-
14	PurS	1938	1991	54	54	685	635	1476	√
15	Taz	1951	1995	45	43	542	432	720	√
10	Yen	1936	2001	66	66	1026	907	2052	√
9	Nor	1963	2001	39	34	402	409	1044	-
4	Khat	1961	1992	32	32	398	415	108	-
3	Anab	1954	1996	43	39	437	431	1224	√
5	Olnk	1964	1992	29	27	334	331	900	√
6	Lena	1936	1995	60	58	769	719	1800	√
7	Yana	1943	1992	50	46	552	499	612	√
8	Indk	1939	1992	54	54	730	700	1800	√
1	KolS	1929	2001	73	70	960	810	1872	√
2	KolK	1965	2001	37	37	527	540	864	-
Mean		1945	1998	54	47	674	613	1150	
Sum						13,470	12,266	23,004	15

ture measurements for several Russian basins in the GEMS/Water database [*United Nations Environment Programme*, 2006]. The energy flux for these low cold season temperatures will be 0 PJ decade^{-1} in this study, but they will be useful for any researcher requiring a different reference temperature (M. Steele and P. Winsor, personal communication, 2006).

[21] Once the river temperature and river discharge data sets were unified at the decadal-scale energy flux was calculated and annual sums of energy flux (PJ a^{-1}) were determined. Climatologies, consisting of mean and standard deviation values at each decade across all gauges, were generated for temperature, discharge, and energy flux.

[22] For each station, summary statistics for temperature, discharge, and energy flux were determined. These statistics consisted of the annual decadal mean, the annual decadal maximum, and the timing (date) of the maximum. Tests for significance in the slope of the regression lines of these annual time series were carried out using both the commonly used least squares method and the nonparametric Mann-Kendall test [*Helsel and Hirsch*, 1992; *Lammers et al.*, 2001].

[23] Spatial aggregation of the annual mean temperature and discharge and the total energy flux were carried out using 15 of the 20 gauges across the Russian pan-Arctic and for the 3 largest basins only, Ob, Yenisey, and Lena (OYL). For the Russian-wide estimate three gauges were removed owing to duplicate gauges within a single basin (Kolyma at Kolymskoye, Pur at Urengoy, and Pechora at Oksino) where the gauge with the most data was preserved and 1 gauge was removed owing to potentially anomalous values (Norilka at Valek). The annual time series had a variable number of gauges for any given year depending upon the availability of data, which could introduce bias. To mitigate this potential problem, the data points in the OYL time series were used only when all three yearly data values were present.

[24] Annual mean air temperature trends were calculated for (1) local grid cell, the grid cell in which the observed river gauge was located and for (2) the upstream average representing the mean annual air temperature for the entire drainage basin up stream from the monitoring gauge. For each gauge air temperature trends were calculated from only those years covering the full range of available river temperature data. Therefore each gauge will have different years underlying the trends based on the river temperature start and end years from Table 2.

[25] Estimates of total energy flux to the Arctic Ocean from Russia were made by combining the observed energy flux at each gauge and creating a simple model for estimating the energy flux in the ungauged regions. River temperatures were derived from latitude based on a linear regression using the observed gauges. Local runoff for the ungauged regions were estimated from small regional watersheds from R-ArcticNet and extrapolated to the ungauged areas using the method of analogues [*Shiklomanov et al.*, 2000; *Korzoun et al.*, 1978]. Annual total runoff data from R-ArcticNet were used, with adjustments from monthly data, to make estimates of the warm season (ice free or ice mobile) time period. These calculations were made for each of the 5 sea basins using annual values.

5. Results

5.1. Data

[26] Twenty river temperature gauges made up the data set representing 17 unique drainage basins (Figure 3). The earliest year with data was 1929 (Kolyma at Srednekolymsk) and the average start year for all gauges was 1945 (Table 2). The latest date was 2003 for 5 gauges all in

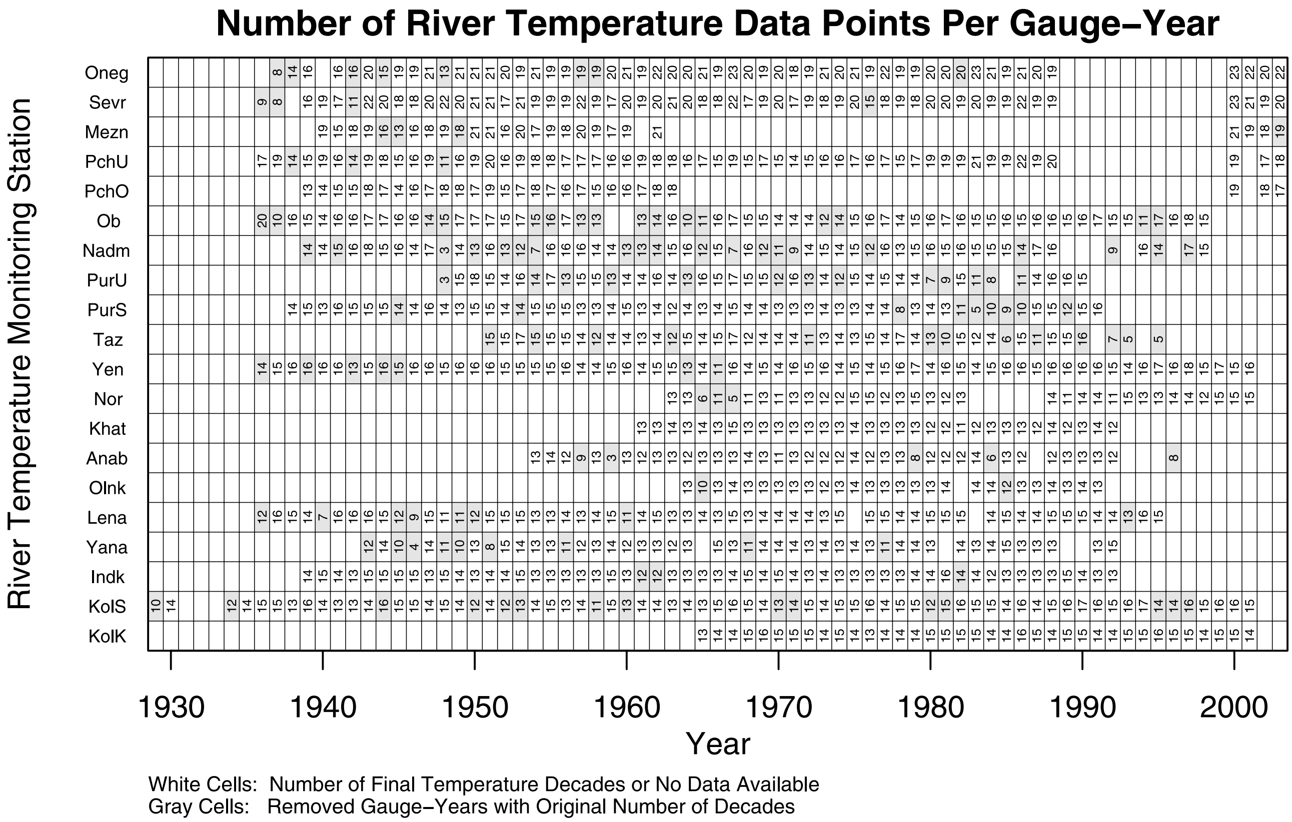


Figure 3. Distribution of data for all 20 monitoring stations from 1929 to 2003. Each cell in the matrix references a single year and contains the number of temperature data points of the original data set (T_0) before processing. Gray cells correspond to those years removed from further analysis. See Table 1 for full description of each monitoring station.

European Russia and a mean final year for all gauges of 1998. The gauge with the most number of years with data is Kolyma at Srednekolymsk with 70 years and the gauge with the least is the Mezen River with only 26 years with data (despite a range of data spanning 64 years). Individual data points per gauge ranged from 334 (Olenek) to 1034 (Onega) with a mean of 674 data points per gauge and a total of 13 470 data points in the initial data set (T_0) and 613 data points per gauge and 12 266 data points for the final cleaned data set (T_1).

[27] Individual decadal temperature in the raw data set ranged from 0°C at all stations to 25.3°C (Onega during the middle of July) with a mean of 9.42°C in the T_0 data set and 8.96 °C in T_1. These numbers reflect only those decades when data were available. Decadal river discharge ranged from 0 km^3 d^{-1} to 15.1 km^3 d^{-1} (Lena at Kusur; early June 1989) and the overall mean value was 0.32 km^3 d^{-1}. The largest single decadal energy flux from the data set (4152 P/decade^{-1}) was during the first decade in July 1956 on the Lena and coincided with a mean temperature of 15.4°C and a mean discharge of 6.43 km^3 d^{-1}. It is interesting to note that this mean coincided with neither the maximum temperature nor the maximum river discharge.

5.2. Annual Means

[28] Annual means of the decadal temperature values (Table 3) were in the range 6.8°C (Anabar) to 10.5°C (Onega) and maximum decadal values ranged from 14.3°C (Norilka) up to 20.6°C (Severnaya Dvina). The timing of maximum temperature value had a narrow range covering July (end of decade 19, Kolyma at Srednekolymsk) to early August (beginning of decade 22, Norilka). The energy flux from the drainage basins (Table 3) was 3500 PJ a^{-1} (0.20 W m^{-2}) with the Lena having the largest total energy flux for any basin (15 000 PJ a^{-1}) and the Norilka had the largest area-normalized energy flux (0.62 W m^{-2}). These two basins also had the largest maximum decadal energy flux for all basins (2500 PJ a^{-1} for the Lena and 1.58 W m^{-2} for the Norilka). The timing of maximum energy flux ranged from early June (beginning of decade 16, Onega) to the middle of July (end of decade 20, Norilka). Most gauges had similar mean annual energy flux and the Norilka at Valek appeared to be an outlier.

5.3. Climatologies

[29] Long-term decadal mean values for temperature tended to be uniform throughout the summer with a peak of 15.9°C around 25 July (decade 21) and tails extending from late April to the middle of December (decades 11 to 35, Figure 4a). The standard deviation varied little between the middle of July and the beginning of October (decades 20 to 28) with values in the range of 2.5 to 3.2. The river discharge climatology showed the classic high-latitude, cold season, spring peak and long tail into the summer (Figure 4b). Mean long-term peak discharge was 1.97 km^3 d^{-1} which

Table 3. Water Temperature, River Discharge, and Energy Flux Trends for Each Monitoring Station

	Temperature (T_1)					Discharge				Energy Flux (Using T_2)						
												Total Value		Decadal Maximum		
Shorthand	Identification	Years	Decadal Value, °C	Decadal Maximum, °C	Timing of Maximum, decade	Years	Decadal Value, km^3 d^{-1}	Decadal Maximum, km^3 d^{-1}	Timing of Maximum, decade	Years	PJ a^{-1}	W m^{-2}	PJ	W m^{-2}	Timing of Maximum, decade	
Oneg	18	47	10.49	20.4	20.7	40	0.038	0.22	13.6	40	395	0.22	59	1.21	15.9	
Sevr	16	52	10.32	20.6	20.6	48	0.270	1.55	13.9	48	2696	0.25	454	1.49	16.2	
Mezn	19	22	9.50	19.1	20.4	20	0.052	0.40	14.1	20	484	0.27	97	1.97	16.3	
PchU	20	53	8.73	18.5	21.2	51	0.291	1.78	15.8	51	2810	0.36	541	2.49	17.8	
PchO	17	28	8.12	16.7	21.1	1	0.392	1.98	16.0	1	4294	0.44	986	3.61	16.0	
Ob	12	45	9.39	18.0	21.0	45	1.068	3.06	16.6	45	13129	0.14	1949	0.75	20.1	
Nadm	13	35	8.95	18.2	20.3	23	0.036	0.31	15.8	23	354	0.23	87	2.07	17.5	
PurU	11	29	9.49	19.2	20.1	9	0.072	0.31	16.7	9	782	0.31	150	2.12	18.0	
PurS	14	45	9.31	18.2	20.5	41	0.074	0.42	16.8	41	753	0.25	155	1.87	18.3	
Taz	15	30	10.08	19.3	20.5	20	0.087	0.47	16.8	20	1090	0.35	233	2.65	18.8	
Yen	10	59	9.76	18.5	21.2	57	1.586	9.80	16.2	57	14526	0.19	2366	1.11	17.8	
Nor	9	31	6.83	14.3	22.0	29	0.037	0.18	19.8	29	383	0.61	81	4.68	20.8	
Khat	4	32	7.77	15.5	21.1	3	0.217	1.10	17.0	3	2118	0.24	438	1.82	20.0	
Anab	3	34	6.81	14.4	20.6	34	0.040	0.62	17.1	34	305	0.12	106	1.53	18.3	
Olnk	5	25	7.62	16.1	20.7	25	0.091	1.09	16.6	25	838	0.13	235	1.36	18.5	
Lena	6	50	7.85	16.0	20.7	50	1.433	8.85	16.4	50	15118	0.20	2477	1.16	19.4	
Yana	7	37	8.28	15.7	20.1	17	0.086	0.64	18.7	17	1197	0.17	260	1.32	19.6	
Indk	8	51	8.77	15.8	20.1	50	0.138	0.69	18.9	50	2175	0.23	377	1.41	19.8	
KolS	1	55	9.25	17.2	19.9	52	0.194	1.28	16.6	52	2716	0.24	527	1.66	17.8	
KolK	2	37	8.91	16.4	20.0	24	0.274	1.83	16.5	24	3704	0.22	647	1.40	18.0	
Mean[a]		40	8.96	17.4	20.6	32	0.324	1.83	16.5	32	3493	0.20	611	1.25	18.2	
Std. Dev.		11	1.06	1.9	0.52	17	0.467	2.67	1.5	17	4796	0.11	755	0.92	1.4	

[a]Drainage area weighted mean shown for columns with units in °C and Wm^{-2}; otherwise, arithmetic mean is shown.

occurred at the beginning of June (decade 16). Variation was highest when mean discharge was high. The shape of the energy flux curve was asymmetrical with a peak of 622 PJ decade^{-1} at the end of June (decade 18) with a less pronounced decline in the summer than the discharge climatology (Figure 4c). Energy flux values tended to be above 0 from the end of April to the end of October (decade 12 to 30) and variance was proportional to magnitude.

5.4. Annual Trends

[30] Results of the regressions for both least squares and Mann-Kendall showed most of the significant changes occurred with the maximum decadal temperature and mean decadal energy flux (Figure 1 and Table 4). The 5 basins within the European part of Russia (stations 16 to 20) had spatially consistent trends toward warmer maximum decadal river temperatures. Temperature changes were also seen for the Anabar (decreasing mean and maximum), the Yana (increasing decadal maximum value), and the Kolyma at Kolymskoje (later timing of the maximum temperature, Mann-Kendall only). Only two stations showed significant changes in river discharge, the Pechora had increasing maximum discharge and the Olenek showed earlier timing of the maximum discharge. Significant increases in mean annual energy flux were seen in the Pechora, Norilka and Yana while the Yenisey and Kolyma at Srednekolymsk had decreasing trends. The Yana also showed increasing total energy flux, both total and decadal maximum values. Both the Yana and Kolyma at Srednekolymsk had significant changes in the maximum value of energy flux (decreasing and increasing respectively). The two Kolyma gauges were the only stations showing significant trends with the Mann-Kendall test and not the least squares approach. Slopes of the trend lines for temperature and energy flux each station are given in Table 4. Also calculated were annual air temperature trends for each individual basin, based on both local grid cell and upstream average temperatures (Table 4). Using local grid cell air temperature data, three stations showed significant increases: Taz, Norilka, and Kolyma at Kolymskoye. In analyzing average upstream air temperature trends, 7 of the basins had significant warming: Taz, Norilka, Kolyma at Kolymskoye (the same three as listed above), as well as the Nadym, Yenisey, Anabar, and Kolyma at Srednekolymsk.

[31] Several notes and caveats are appropriate regarding the annual trends discussed above. The Yenisey was the only drainage basin of the 3 large Siberian watersheds with any significant changes. The results for the Yana, which had significant trends for both temperature and energy flux, were based on 17 annual values. The Pechora at Ust-Tsilma showed the most significant trends for temperature, discharge, and energy flux. Inspection of the energy flux time series for this gauge showed a step function with a steep rise occurring over a four year period starting in 1980. The annual temperature and discharge time series suggest the high energy flux is due to a sustained high river temperature during the years in question. We do not know if these high temperatures are driven by regional air temperatures or by some human influence on the river temperature.

5.5. Russian Pan-Arctic Energy Flux

[32] Annual time series for the Russian pan-Arctic aggregate of 16 representative gauges had an energy flux of 0.19 W m^{-2} but there was no significant trend (Figure 5a). However, the OYL subset of the 3 largest basins (Figure 5b) had a mean energy flux of 0.17 W m^{-2} and a significantly decreasing slope of -0.00053 W m^{-2} a^{-1} representing a

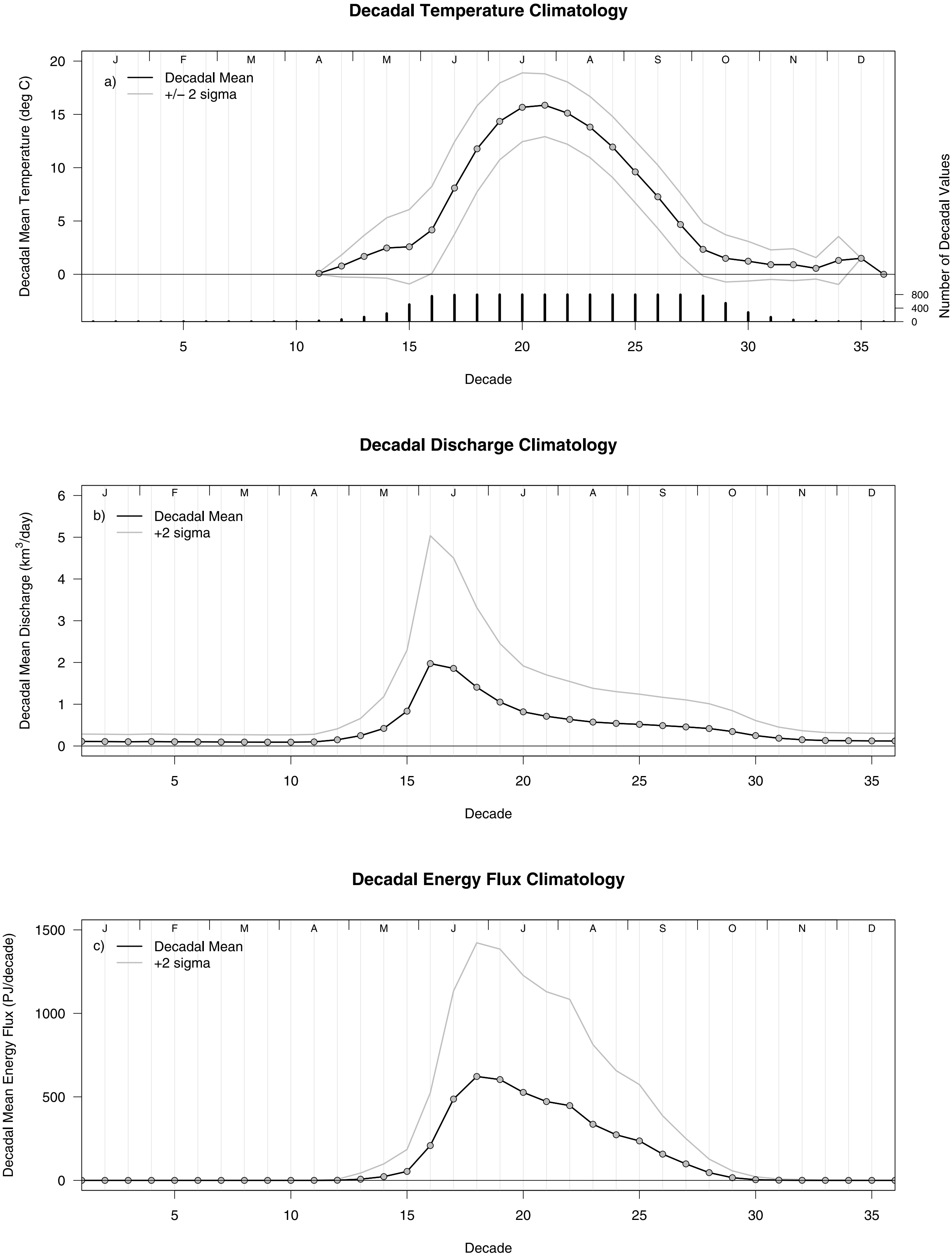


Figure 4. Long-term decadal (10 day) means (climatologies) for (a) river temperature, (b) river discharge, and (c) energy flux. Black lines and points are the climatologies with gray lines ±2 standard deviations for that decade. Bars below the river temperature graph show the number of contributing data points to each temperature decadal value. Months are shown at the top of each plot using the first letter of the month name.

Table 4. Least Squares Regression Results for River Temperature, Energy, and Air Temperature for Each Monitoring Station[a]

		River Temperature (T_1)				Energy Flux (Using T_2)				Air Temperature, Slope of Trend Line	
			Slope of Trend Line				Slope of Trend Line				
Short-hand	Identification	Years	Decadal Mean, °C a^{-1}	Decadal Maximum, °C a^{-1}	Timing of Maximum, decade a^{-1}	Years	Mean Value, PJ a^{-1}	Decadal Maximum, PJ a^{-1}	Timing of Maximum, decade a^{-1}	Local Grid Cell, °C a^{-1}	Upstream Average, °C a^{-1}
Oneg	18	47	0.0098	**0.0506**	0.0038	40	1.30	−0.10	−0.0273	0.004	0.010
Sevr	16	52	0.0068	**0.0397**	−0.0030	48	−5.47	−1.73	−0.0117	0.001	0.009
Mezn	19	22	0.0014	**0.0578**	−0.0166	20	−0.99	−0.31	−0.0413	0.008	0.009
PchU	20	53	**0.0190**	**0.0423**	−0.0140	51	**26.74**	2.55	−0.0051	0.002	−0.003
PchO	17	28	0.0101	**0.0668**	−0.0127	1	-	-	-	0.001	0.002
Ob	12	45	−0.0005	0.0078	−0.0087	45	−14.04	0.67	−0.0194	−0.007	**0.020**
Nadm	13	35	0.0182	0.0267	−0.0085	23	0.00	0.84	0.0404	0.005	0.007
PurU	11	29	−0.0026	−0.0013	0.0021	9	3.88	1.71	0.0077	0.016	0.019
PurS	14	45	0.0090	0.0340	0.0019	41	−0.28	0.04	0.0005	−0.006	0.001
Taz	15	30	−0.0108	−0.0199	−0.0072	20	5.10	2.14	0.0115	**0.036**	**0.037**
Yen	10	59	−0.0107	−0.0066	0.0041	57	**−51.67**	−1.21	−0.0072	−0.002	**0.017**
Nor	9	31	0.0060	0.0352	−0.0079	29	**2.74**	0.42	−0.0242	**0.045**	**0.044**
Khat	4	32	0.0219	−0.0403	−0.0312	3	-	-	-	0.020	0.025
Anab	3	34	**−0.0309**	**−0.0736**	0.0047	34	0.29	−0.08	−0.0246	0.016	**0.036**
Olnk	5	25	−0.0236	0.0147	−0.0281	25	−0.93	−1.35	−0.0290	0.017	0.021
Lena	6	50	0.0016	0.0075	−0.0106	50	7.53	−1.42	−0.0088	−0.006	0.011
Yana	7	37	0.0090	**0.0717**	0.0035	17	**34.04**	**9.17**	0.0228	0.000	0.011
Indk	8	51	−0.0024	0.0102	−0.0024	50	2.38	0.55	0.0072	0.001	0.011
KolS	1	55	−0.0086	0.0066	0.0109	52	−9.66	−3.32	0.0038	0.007	**0.011**
KolK	2	37	−0.0076	0.0110	0.0330	24	−32.30	−5.30	0.0265	**0.050**	**0.037**

[a]Significant linear regression slopes (α = 0.05) shown in bold. Positive slope in timing of maximum indicates later in year. Least squares regression results were not calculated for energy flux for basins 17 (PchO) and 4 (Khat) owing to insufficient number of years of data (1 and 3 years, respectively).

total decrease of 0.029 W m^{-2} from 1938 to 1992, a 17% decline relative to the mean for the entire period.

[33] We estimated Russian energy flux to the Arctic Ocean in two ways, a simple extrapolation of the mean energy flux to the entire land area and by applying a latitude correction to river temperature over each ungauged sea basin. Using the mean energy flux from the gauged basins (0.20 W m^{-2}, Table 3) and assuming this mean value is representative of the ungauged regions then we can estimate the total energy flux from the entire Russian pan-Arctic drainage area into the Arctic Ocean. Using an area of 12,925,000 km^2 we get a total flux of 8.16×10^{19} J a^{-1} or 82 EJ a^{-1}.

[34] A latitude-temperature regression and estimates of discharge were used to calculate the energy flux of the ungauged Russian Arctic (Table 5). Energy flux from the observed gauges was 63.6 EJ a^{-1} and ungauged energy flux was estimated to be 17.3 EJ a^{-1} for a total Russian energy flux to the Arctic Ocean of 80.9 EJ a^{-1}.

6. Discussion

[35] Before embarking on this research project our a priori assumption was that we would clearly see evidence of the observed warming that was taking place over the Russian pan-Arctic region [*Arctic Climate Impact Assessment*, 2005; *Hansen et al.*, 2006]. Rising air temperatures have been one of the important variables in global change research. The river discharge from the six largest Russian rivers (Severnaya Dvina, Pechora, Ob', Yenisey, Lena, and Kolyma) has been increasing over the past 70 years [*Peterson et al.*, 2002] (updated time series given by *Richter-Menge et al.* [2006].

[36] An important change we see is a consistent increase in the decadal maximum temperature for the drainage basins in the European part of Russia. However, this cohesive spatial pattern is not reflected in the energy flux except in the Pechora at Ust-Tsilma (table in Figure 1). We find significant energy flux trends in 5 of 17 drainage basins with 3 showing increased energy and 2 with a decrease in energy. We also see a significant decrease in the aggregated energy flux from the 3 largest Russian watersheds, Ob, Yenisey, and Lena which is counter intuitive to the air temperature trends.

[37] This research leaves two questions unanswered: Why do we not see river temperature rising in concert with air temperature across the whole of the Russian pan-Arctic and why is the energy flux from the river systems not coupled closely to river temperature and river discharge?

6.1. Temperature

[38] Comparing annual air temperature trends at local and basin scales (Table 4) shows this is not a factor in the European Russia river temperature increases. Additionally, in those drainage basins where there are increases in air temperature there is no consistent coupling of the trends observed in the rivers. It is possible seasonal air temperature trends are a factor but these were not investigated here.

[39] What is causing the increased decadal maximum river temperature trends in European Russia? We do not know. Human impoundments are a possibility as they occur on many of the major river systems. The large reservoirs associated with the dams tend to shift some of the spring, summer, and fall discharge into the winter [*Yang et al.*, 2005]. While this does tend to significantly increase the winter discharge, the real effect in the warmer months is to

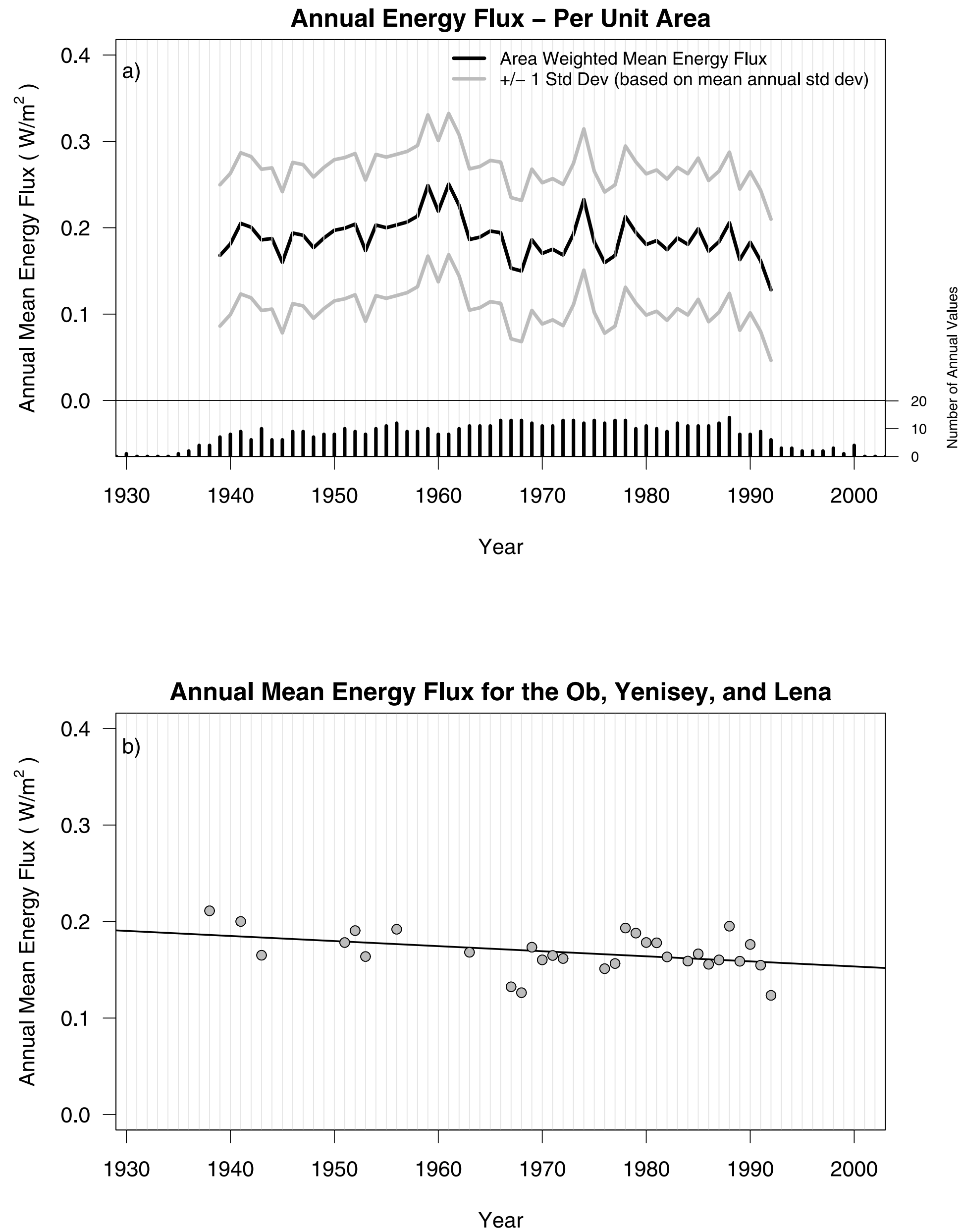


Figure 5. (a) Aggregate annual time series of energy flux per unit drainage area for 15 gauges. Annual weighted mean energy flux for all basins shown as a thick black line with ±1 standard deviation in gray. Total number of gauges contributing to each annual value shown at bottom. (b) Aggregate annual mean energy flux for the three largest Russian drainage basins, Ob, Yenisey, and Lena. Only years in which all three basins had values were used. Trend line shows a significant decrease in annual energy flux of -0.00053 W m^{-2} a^{-1}.

release cooler water from the reservoir, thus offsetting any warming of the rivers that may have occurred. As an example, the Yenisey basin (gauge 10) is the most heavily dammed of the major pan-Arctic Russian river systems and the water temperature in the Yenisey downstream of the Krasnoyarsk dam (55.46°N, 92.30°E, 1300 km south of Igarka) does not exceed 8°–10°C during the summer owing to water releases from a depth of 25–40 m [*Malik*, 1990].

[40] The complex interactions of many processes acting over drainage basins and river systems may also contribute to masking trends in river temperature. We see the cluster of warming trends which are primarily in drainage basins with no or little permafrost coverage (Tables 1 and 4). It is possible conduction of energy from meltwater into the permafrost layers may have a cooling effect, especially before the water enters the active streams. Additionally, increases in low flows have been observed [*Smith et al.*, 2007] suggesting changes to groundwater flux for many parts of the Russian Arctic. Such an influx of cooler water particularly in the summer months could reduce river

Table 5. Energy Flux to the Arctic Ocean From Russia for Ungauged Drainage Basins

Sea Basin or Aggregated Region	Ungauged Area, km^2	Mean Latitude, °N	Estimated Temperature,[a] °C	Estimated Runoff, mm a^{-1}	Warm Season Runoff, %	Warm Season Discharge, km^3 a^{-1}	Energy Flux, EJ a^{-1}
Barents	446,776	67.61	8.87	295.1	81	106.8	4.0
Kara	976,496	70.76	7.81	261.4	83	211.9	6.9
Laptev	430,438	72.79	7.13	194.5	94	78.7	2.4
E. Siberian	496,418	69.35	8.29	177.5	94	82.8	2.9
Chukchi	104,311	67.14	9.03	312.7	91	29.7	1.1
Sum	2,454,439					509.9	17.3
Total gauged area energy flux,[b] EJ a^{-1}							63.6
Total energy flux estimate, EJ a^{-1}							80.9

[a]Estimated temperature based on regression $T_{°C} = 31.6 - (0.3362 \times \text{Latitude})$ from observed gauges.
[b]Sum of total energy flux from 17 downstream gauges in Table 3.

temperatures. It is also possible evaporation from the river surface may act as a negative feedback to any water temperature increases. In all cases such assertions are speculative and each would require more extensive data collection and detailed simulations to gain a better understanding of the important processes.

[41] It is also possible that we may simply not see changes over large basins. While there is ample evidence of smaller watersheds displaying increases in river temperature [e.g., *Caissie*, 2006] or significant trends in upstream basins being reduced to insignificance at the basin outlet [*Yang et al.*, 2005] there are none that we know of for the large basins. Perhaps the largest drainage basins simply have too much spatial variability to capture any consistent trends.

6.2. Energy

[42] While we do see significant increases in river temperature, we do not see a pattern of increases in energy flux for the same gauges and this may be a result of the complex nature of a drainage system. Energy flux is a multiplicative combination of both the temperature and discharge (equation (1)). Maximum values in energy flux from the drainage basins occur when the two peaks of the uniform curve of the temperature signal and the asymmetric snowmelt dominated river discharge coincide. If the two peaks diverge, for example owing to earlier timing of the peak river discharge or a later peak of high river temperature then overall energy flux may go down. In the European part of Russia we see significant increases of the annual maximum temperatures in all four drainage basins. Two recent studies of small watersheds with areas less than 50,000 km^2 across the Russian pan-Arctic suggest a shift in the timing of daily maximum discharge to earlier in the spring [*Shiklomanov et al.*, 2007] and increases in trend for minimum discharge were strongest during May and November which *Smith et al.* [2007] interpret as a shortening of the cold season. Therefore we see increasing temperatures, but a shift to earlier peak river flow reduces the overall energy flux.

[43] We find a general pattern that appears to serve as a limit to the flux of area averaged energy from the river systems. As the difference between the decade of maximum temperature and maximum discharge increases (as the timing between the peaks of temperature and discharge diverge) we see a decrease in the maximum energy flux values (Figure 6). Greater divergence of the peak temperature and discharge creates a tendency toward lower energy flux from the basins.

6.3. Norilka

[44] In the spatially aggregated flux estimates we removed the Norilka from the analysis as it had one of the lowest total energy flux values (383 PJ a^{-1}) and the highest area averaged energy flux (0.61 W m^{-2}). There are four possible contributing factors as to why this basin was an outlier. First, the Norilka was the smallest watershed in our data set at 19,800 km^2 and the flux values may simply represent natural variability in basins of this small size. Second, the Norilka had the latest peak in maximum discharge of the 139 Russian drainage basins reviewed by *Shiklomanov et al.* [2007] with the peak discharge occurring at the end of July or early August. This had the effect of shifting maximum flows into the higher river temperature months thus magnifying the energy flux. Third, the Norilka is a highly naturally regulated basin as the gauge is located downstream of six large (relative to the drainage area) lakes in a highly mountainous region [*Defense Mapping Agency Aerospace Center*, 1982]. Fourth, the city of Norilsk, with its large heavy industry, is located very close to the monitoring station and, although we are not aware of any direct impoundments on the river, we cannot negate the possibility of significant alteration of the river hydrology which could have an impact on the degree of heating of the river water.

6.4. Time Sampling

[45] We would also like to comment on the time sampling for river temperature data. In a comparison of our decadal ART-Russia data set to the monthly point measurements of the GEMS/Water river temperature data (data supplied by Kelly Hodgson, UN GEMS/Water Programme Office, Burlington, ON, Canada) for the Lena at Kusur we found 6 of the 11 coincident years in GEMS/Water to underestimate peak decadal mean temperature by 1.0°C to 5.0°C. This is particularly important when carrying out calculations which are sensitive to the coincidence of the peaks of two curves (river discharge and temperature) to define energy flux. This illustrates the importance of having a greater than monthly sampling resolution when dealing with high temporally variable data such as river temperature.

7. Conclusions

7.1. Uses for This Data Set

[46] The data set provides a collection of time series covering a significant portion of the Russian pan-Arctic

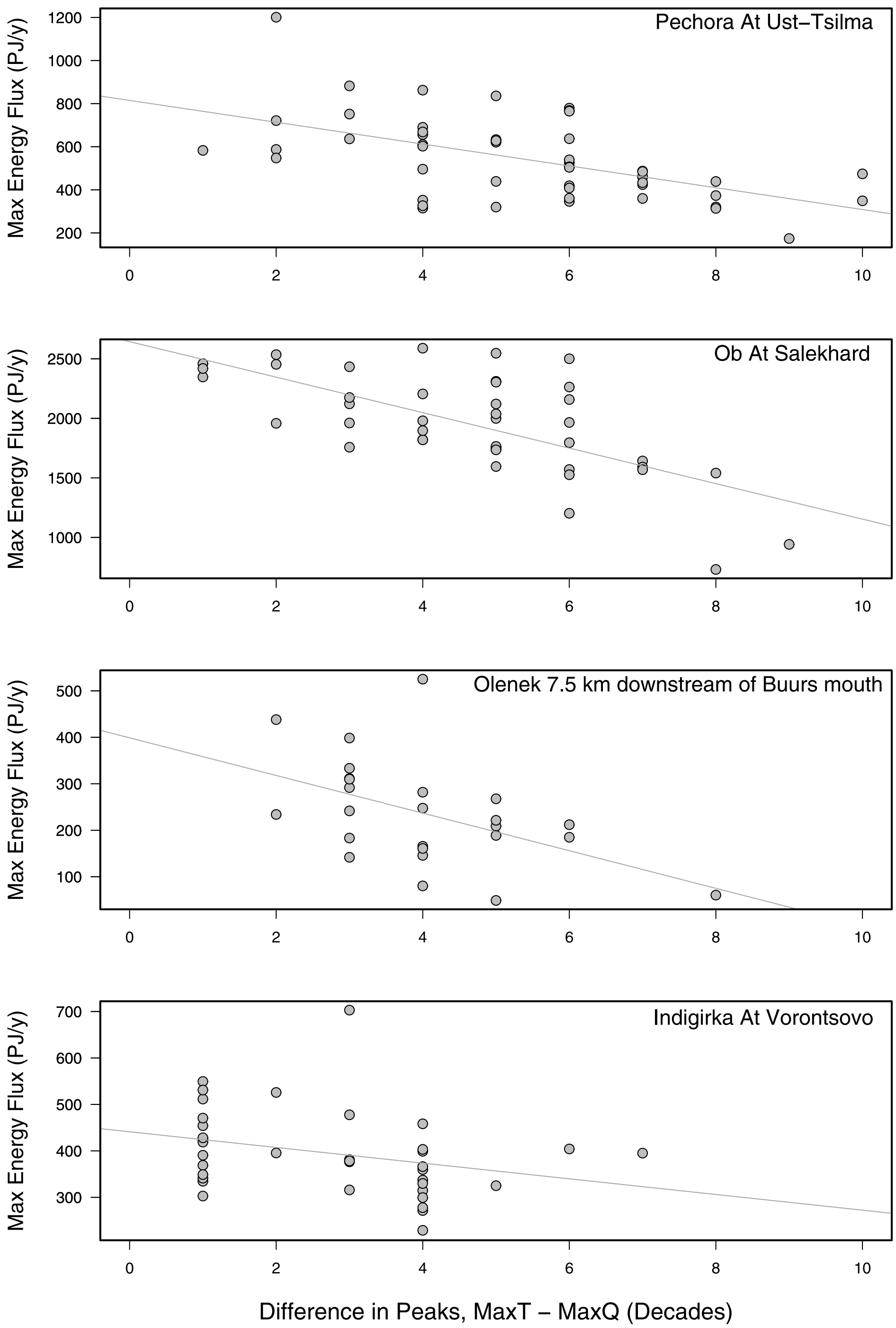


Figure 6. Maximum energy flux from the drainage basins appear to be limited by the difference in timing between the peaks in temperature and river discharge. For each gauge-year with a positive difference between maximum decadal temperature and maximum river discharge the annual maximum energy flux is shown for selected watersheds. Diagonal lines represent the linear regression line.

landmass and would be particularly useful to land surface energy balance modelers who now have another data set against which to validate their models. Much like river discharge data, the spatially integrated nature of drainage basin-wide data over such large domains avoids many of the validation problems encountered when comparing localized point data to gridded fields typical of land surface model output.

[47] River discharge temperature data are also particularly valuable for oceanographers as well as anyone who studies sea ice formation in the Arctic Ocean. This data set would serve as an important boundary condition to those models. Most ocean models do not use river temperature data as an input to drive their boundary conditions but rely solely on river discharge [e.g., *Maslowski et al.*, 2004] although, according to several ocean modelers contacted by us

(M. Steele, J. Finnis, and W. Maslowski), there is a movement to incorporate this variable explicitly. Where river temperature has been used in ocean models it has tended to be approximated owing to the limited availability of data. For example, *Harms et al.* [2000] used monthly climatological values in their runs with a maximum of 3.8°C in the month of August for the major Russian rivers, a value which we now know to be in the wrong month and over 10°C lower than our findings here would suggest. The cold season river discharge (where T = 0°C) is particularly important as the energy supplied to the ocean and atmosphere from the latent heat of fusion is equivalent to adding a parcel of water at 80°C.

7.2. Future Work

[48] Gauged networks of hydroclimatic variables tend to show a loss of gauges since the mid-1980s in Russia and a delay in the delivery of national agency-collected data to the research community [*Shiklomanov et al.*, 2002]. The ART-Russia river temperature data set shows similar features of a decline of available data after 1990 (Figure 3). For applications requiring more rapid acquisition of river temperature data we believe ongoing collection of this data is essential. One option to explore is the use of remote sensing of river [*Cherkauer et al.*, 2005, *Handcock et al.*, 2006] and lake [*Bussières and Schertzer*, 2003] temperatures in combination with near-real time in situ data acquisition for these high-latitude watersheds.

[49] We need to perform a more detailed investigation as to whether or not the human influences, specifically impoundments, are masking possible climate change signals in river temperature over these large regions. We would need to identify and collect river temperature data from several key tributaries in the principal drainage basins of the Russian pan-Arctic and compare the relative effects of impoundments similar to the analysis carried out by *Yang et al.* [2005] for the Lena basin.

[50] We did not find the strong water temperature signals for the entire Russian pan-Arctic which dominate the well-documented air temperature trends. Maximum river temperature in the European part of the Russian Arctic did increase. However, there is a possibility of such signals being masked by human modifications to the hydrological cycle which may be a negating factor in viewing the natural climate changes of the river systems. Additionally, the energy flux from these northern snowmelt dominated river systems is not a simple relationship with temperature as the flux of energy represents an interesting interplay between not only the magnitudes of water temperature and river discharge but also the relative timing of each their peaks.

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