University of New Hampshire
University of New Hampshire Scholars' Repository

Faculty Publications

Record Russian river discharge in 2007 and the limits of analysis

Alexander I. Shiklomanov
University of New Hampshire, Durham, alex.shiklomanov@unh.edu

Richard B. Lammers
University of New Hampshire, Durham, richard.lammers@unh.edu

Follow this and additional works at: https://scholars.unh.edu/faculty_pubs

Record Russian river discharge in 2007 and the limits of analysis

To cite this article: A I Shiklomanov and R B Lammers 2009 *Environ. Res. Lett.* **4** 045015

View the article online for updates and enhancements.

Record Russian river discharge in 2007 and the limits of analysis

A I Shiklomanov and R B Lammers

Water Systems Analysis Group, University of New Hampshire, Durham, NH, USA

Abstract
The Arctic water cycle has experienced an unprecedented degree of change which may have planetary-scale impacts. The year 2007 in particular not only was unique in terms of minimum sea ice extent in the Arctic Ocean but also was a record breaking year for Eurasian river inflow to the Arctic Ocean. Over the observational period from 1936 to 2006, the mean annual river discharge for the six largest Russian rivers was 1796 km^3 y^{-1}, with the previous record high being 2080 km^3 y^{-1}, in 2002. The year 2007 showed a massive flux of fresh water from these six drainage basins of 2254 km^3 y^{-1}. We investigated the hydroclimatological conditions for such extreme river discharge and found that while that year's flow was unusually high, the overall spatial patterns were consistent with the hydroclimatic trends since 1980, indicating that 2007 was not an aberration but a part of the general trend.

We wanted to extend our hydroclimatological analysis of river discharge anomalies to seasonal and monthly time steps; however, there were limits to such analyses due to the direct human impact on the river systems. Using reconstructions of the naturalized hydrographs over the Yenisey basin we defined the limits to analysis due to the effect of reservoirs on river discharge. For annual time steps the trends are less impacted by dam construction, whereas for seasonal and monthly time steps these data are confounded by the two sources of change, and the climate change signals were overwhelmed by the human-induced river impoundments. We offer two solutions to this problem; first, we recommend wider use of algorithms to 'naturalize' the river discharge data and, second, we suggest the identification of a network of existing and stable river monitoring sites to be used for climate change analysis.

Keywords: river runoff, hydrometeorology, reservoirs, discharge variability

1. Introduction and statement of problem

This paper has two purposes: (i) to investigate conditions for the record breaking 2007 river discharge to the Arctic Ocean from the large Russian Arctic rivers and (ii) to discuss the limits of analysis which can be performed when attempts are made to attribute river discharge changes to the broad-scale hydroclimatological signals.

The Arctic region has come under increasingly intense focus due to significant observed changes such as increases in land surface temperature, deeper permafrost active layer, shifting vegetation zones and declines in sea ice (ACIA 2005). The year 2007 in particular was unique in terms of changes associated with the Arctic hydrological cycle. September minimum Arctic Ocean sea ice shattered all historical records

(Stroeve *et al* 2008) and the Northwest Passage saw an ice-free path for the first time. Unusual freshening of the Arctic Ocean was also observed (Richter-Menge *et al* 2008). On Greenland the ice sheet melted at a record rate in 2007, 20% more than the average for period 1995–2006, and runoff was 35% greater than the 1995–2006 average (Mernild *et al* 2009). These changes, observed over the atmosphere, land and oceans, are indicative not only of the systemic changes taking place, but also of the capacity of researchers to observe these changes in an increasingly rapid manner.

One of the most important variables used for observing the hydrological cycle over the land surface is the flow of rivers. River discharge represents a powerful integrating tool and its monitoring can provide accurate and timely data on responses of the land surface to atmospheric forces. It is

also one of the most accurately measured components of the hydrological cycle (Shiklomanov *et al* 2006) and therefore can provide more reliable estimates of water cycle trends and variability. This is especially important for northern Eurasia where a significant increase in Russian river discharge to the Arctic Ocean was reported (Peterson *et al* 2002). This increasing freshwater flux to the Arctic Ocean has resulted in much speculation regarding a slowdown of the North Atlantic meridional overturning circulation and the possible implications for the climate of North America and Europe (Peterson *et al* 2006). The 2002 publication coincided with the United States National Science Foundation's Freshwater Integration (FWI) programme; together they initiated a flurry of research activity focused on the high latitude hydrological cycle. Much of the research centred on understanding and tracking the changes found in these Russian rivers.

Significant changes in the seasonality of discharge across the Eurasian pan-Arctic were well documented (Shiklomanov *et al* 2000, Lammers *et al* 2001, Yang *et al* 2004a, 2004b, Ye *et al* 2004). Less clear has been the understanding of major forces driving the changes, although a number of potential natural causes of the change were investigated (Berezovskaya *et al* 2004, 2005, McClelland *et al* 2004, Rawlins *et al* 2006, Adam *et al* 2007). Discharge of the largest Eurasian rivers was seriously affected by reservoir regulation and it is difficult to distinguish between climatic and anthropogenic effects (Shiklomanov and Veretennikova 1978). Several attempts to examine the influence of reservoirs on river discharge have been carried out over the last few years (McClelland *et al* 2004, Ye *et al* 2003, Adam *et al* 2007). The most comprehensive analysis clearly demonstrated the overwhelming reservoir impact on seasonal discharge of the three largest Russian pan-Arctic rivers—Yenisey, Lena and Ob (Adam *et al* 2007). Reservoirs can seriously confound the results of hydroclimatological analysis and this is not always taken into account (e.g. Rawlins *et al* 2006, Ye *et al* 2004).

2. Data

Of all the river systems draining into the Arctic Ocean, those with the longest observational record are from Russia (Lammers *et al* 2001). The Russian Arctic drainage system contains three of the ten largest basins in the world based on area drained and the six largest watersheds in this region, covering 8.777×10^6 km^2. The significantly increasing river discharge has been well documented (Shiklomanov *et al* 2000, Lammers *et al* 2001, Peterson *et al* 2002, Richter-Menge *et al* 2006, 2007, 2009). In Russia the government agency responsible for the release of the river discharge data is Roshydromet. As with many observational monitoring programmes the observed river discharge data are usually released at least one full year after they are collected and processed. This creates a significant delay in the ability of researchers to detect and diagnose changing conditions. However, through our collaboration with the State Hydrological Institute in St Petersburg, Russia, we have had an opportunity to collect some early release data for the major pan-Arctic rivers. Some of these data are published online

in ArcticRIMS (http://RIMS.unh.edu) and are used for regular updates of Arctic hydrological conditions in yearly 'State of the climate' reports (Richter-Menge *et al* 2007, 2008, 2009).

Several other ArcticRIMS data sets were used in this analysis. To analyse long-term variability and the 2007 climate conditions, gridded daily precipitation from monthly station records disaggregated over 1980–2008 (Serreze *et al* 2003) and gridded mean daily air temperature from NCEP over 1948–2008 were used. The International Permafrost Association (IPA) digital permafrost map (Brown *et al* 1998) was used to estimate the permafrost area for subbasins. Percentage of permafrost for subbasins was defined on the basis of classification of different permafrost types: continuous—100%, discontinuous—70%, sporadic—30% and isolated—5%. To aggregate gridded data for river basins and subbasins the simulated topological river network with resolution 25 km × 25 km from ArcticRIMS was used.

To analyse the long-term trends we used the commonly employed least squares linear regression analysis. Additionally, statistical significance was determined using the Mann–Kendall test (Mann 1945, Kendall 1975), a rank-based, nonparametric test for monotonic trend. A nonparametric test was preferred over a parametric test to avoid potential problems introduced by data skew. Mann–Kendall is commonly used to detect long-term trends in hydrological time series (e.g. Hirsch *et al* 1991, Shiklomanov *et al* 2007).

3. Hydroclimatological analysis of 2007

Over the historical record from 1936 to 2006, the mean annual river discharge for the six largest Russian rivers was 1796 km^3 y^{-1} and the previous record high was 2080 km^3 y^{-1}, in 2002. The year 2007 showed a massive flux of fresh water from the Russian land surface of 2254 km^3 y^{-1} (figure 1), an increase of 25% over the long-term mean. This was greater than the total annual flow from the Ob basin, the eighth largest basin in the world by drainage area (Vörösmarty *et al* 1997), and was approximately equal to the total estimated mean annual Greenland runoff (Mernild *et al* 2009).

The partitioning of the annual river discharge into the six contributing drainage basins showed record high flows in 2007 in the Pechora and Yenisey basins and very high flows in the Ob, Lena and Kolyma. Only the Severnaya Dvina had flow near the long-term mean. Except for the Kolyma, contributions of individual rivers to the 2007 record river discharge were very consistent with the contributions of the river basins to the long-term discharge change (computed on the basis of linear trends over 1936–2006; figure 1 inset). This suggests that the 2007 river discharge record reflected the patterns of the long-term changes observed in the Eurasian pan-Arctic over the 1936–2007 period and the year 2007 was an anomaly in magnitude without major structural changes between basins. The last period (1980–2007) demonstrates an unprecedented rate of change in river discharge to the Arctic Ocean. The mean annual slope of the linear trend line over the period is about ~10 km^3 y^{-1} (figure 1), or almost four times higher than over the entire observational period from 1936 to 2007. An increased level of fresh water input from Eurasia accompanied
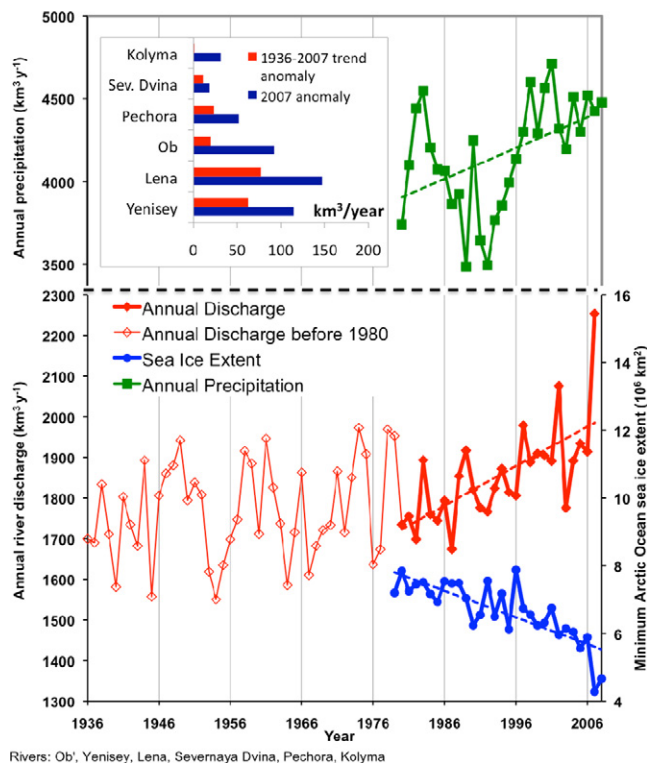
Figure 1. Annual time series of spatially aggregated river discharge over the downstream monitoring sites of the six largest Russian basins (Severnaya Dvina, Pechora, Ob, Yenisey, Lena, Kolyma), grid cell precipitation, and aggregated Arctic Ocean sea ice coverage. River discharge and precipitation data from ArcticRIMS (http://RIMS.unh.edu), sea ice cover from NSIDC (http://nsidc.org/data). Inset: contributions of each drainage basin to the 1936–2007 trend (black bars) and the 2007 anomaly (grey bars).

by increasing discharge from North American Arctic rivers during the last 10 years (Déry *et al* 2009) is evidence of an intensifying water cycle in the pan-Arctic.

Maximum Eurasian river discharge in 2007 corresponded to minimum sea ice extent in the Arctic Ocean. The long-term variations of these climatic characteristics also demonstrated a good correspondence with negative correlation $r = -0.7$ (figure 1) suggesting that (a) both rivers and sea ice were responding to changes in large-scale hemispheric climate patterns (see Rawlins *et al* 2009) and (b) an increasingly ice-free summer in the Arctic Ocean contributed to wetter conditions on the land via atmospheric moisture transport from open sea areas.

The second statement can be checked through analysis of precipitation data. Basin aggregated precipitation for six river basins and river discharge over 1980–2007 showed a relatively weak correlation ($r = 0.42$) with correspondence in linear trends (figure 1). The mean runoff ratio (runoff/precipitation) aggregated over the six river basins was about 45%. This is relatively low for the pan-Arctic and was probably due to extensive dry land areas in southern parts of Ob and Yenisey basins which typically have a much lower effect on river discharge to the ocean than the wetter northern regions. To spatially investigate hydroclimatological characteristics of 2007 and compare them with the observed long-term variations

we used river discharge data for 15 gauges (one gauge each for Severnaya Dvina, Pechora and Kolyma and the three largest watersheds, Ob, Yenisey and Lena, disaggregated to 12 subbasins) along with spatially aggregated precipitation and air temperature for the drainage basins of these 15 sites.

Precipitation anomalies for 2007 (figure 2(b)) showed that much of the observed river discharge increase to the ocean for that year originates from runoff in the northern parts of the drainage basin despite the decreasing anomalies in the southern headwaters of the largest basins (figure 2(d)). The annual trends from 1980 to 2007 (figures 2(a) and (c)) demonstrate similar patterns to the 2007 precipitation and discharge anomalies which further supports the suggestion that 2007 was a higher magnitude expression of the ongoing pattern of change over the last 28 years. It is interesting to note that 2007 was the warmest year over the last 60 years in Yenisey, Lena and Kolyma basins covering about 90% of the total permafrost area in the six Eurasian basins (figure 2(f) and table 1). The warmer conditions of 2007 could therefore have intensified permafrost thaw giving an increased rate of runoff. Indeed, the runoff ratio (runoff/precipitation) in 2007 (figure 2(h)) was significantly higher than the long-term mean over 1980–2007 (figure 2(g)) for all subbasins located inside these three permafrost-dominated watersheds. All subbasins where the runoff anomaly exceeded the precipitation anomaly by more than 25 mm for 2007 (bold font in table 1) were located in the transition zone between non-permafrost and permafrost regions where permafrost degradation is expected to have a greater impact with global warming (Stanilovskaya *et al* 2008, Marchenko *et al* 2007). Thus, we conclude that increased precipitation across the northern part of the basin and probably more intensive permafrost thawing caused the 2007 record river discharge to the Arctic Ocean from the Eurasian pan-Arctic.

4. Limits of analysis

There is a tendency for researchers to explore ever deeper into the causes and effects of the patterns that we see. In the case of the findings in this paper we are tempted to move the analysis of river discharge anomalies to seasonal and monthly time steps. However, we must first ask whether we can more accurately attribute these changes to a finer temporal resolution. We feel it is not reasonable for this region and that annual time steps represent a limit on the observational data without the use of models to make significant adjustments to the data.

The most downstream monitoring gauge on the Yenisey at Igarka (drainage area 2.44×10^6 km^2) shows a clear example of these limits. The 'naturalized' hydrographs created using the hydrograph routing model, based on the work of Shiklomanov (1994), were applied to evaluate the effect of major impoundments on river discharge. The model routes observed daily hydrographs from unregulated upstream gauges in the downstream direction using a Duhamel integral approach (Kalinin *et al* 1969) and 'naturalizes' the river flow. This method provides more accurate hydrograph simulations than the approaches based on comparison of mean pre-dam and
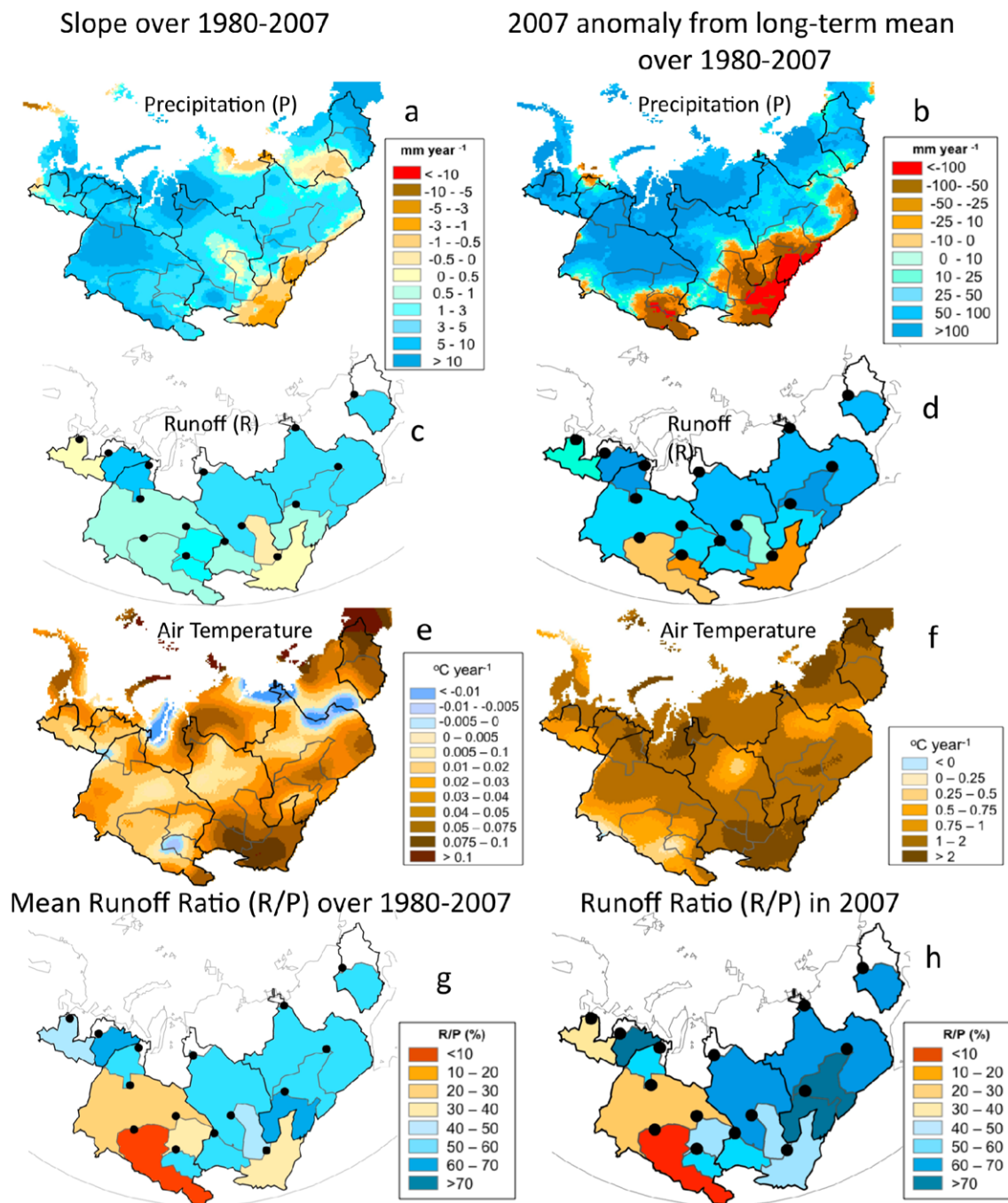
Figure 2. Maps of long-term trend (left column) and 2007 anomalies relative to the long-term trend (right column) of precipitation, river runoff, and air temperature along with runoff ratio (runoff/precipitation) for the long-term period (panel (g)) and for year 2007 (panel (h)). River runoff and P/R ratio calculated over 15 interstation regions as shown by black and grey border lines with circles representing the gauge locations. Colour scales are different in the left and right columns. A list of gauges is shown in table 1.

post-dam hydrographs (e.g. McClelland *et al* 2004, Yang *et al* 2004a, 2004b, Ye *et al* 2003) and it reduces the uncertainty associated with water balance modelling approaches for hydrograph simulation (e.g. Adam *et al* 2007) as it uses only observed river discharge which is the most accurately measured component of the hydrological cycle (Vörösmarty *et al* 2004, Shiklomanov *et al* 2006). The HRM was tested over the unregulated period (before 1957) and showed good results for all reconstructed gauges in the Yenisey basin. Figure 3

demonstrates observed and simulated ten-day hydrographs for representative pre-dam and post-dam years for two different gauges. Naturalized discharge was estimated beginning from the earliest reservoir filling in 1957 on the Angara at Irkutsk. The problem with data analysis arises when bar graphs are used to investigate month-to-month changes for the pre- and post-dam periods. With this common method of viewing the data, the differences between bars are minimized, and so is the perceived reservoir effect (figure 4).
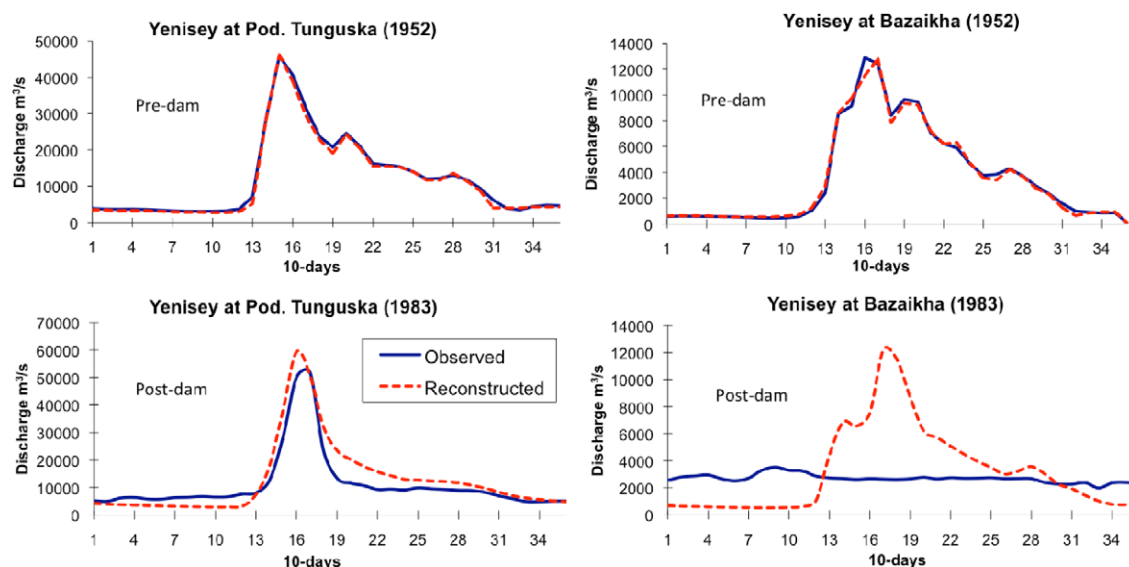
Figure 3. Ten-day observed and the HRM-simulated discharge hydrographs for two river gauges in the Yenisey basin. The two upper panels for a pre-dam year demonstrate the accuracy of the HRM simulations, and the lower panels show the effects of dam regulation at these two gauges. Drainage areas for these gauges are $1\,760\,000\ km^2$ (left panels) and $300\,000\ km^2$ (right panels).
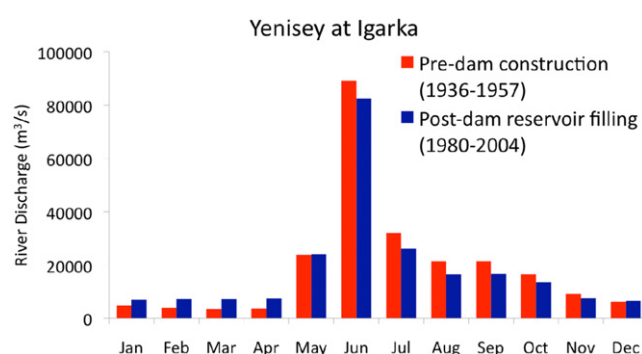

Figure 4. Histogram of mean monthly values of river discharge at Yenisey–Igarka for the pre-dam construction period (1936–1957) and post-dam filling period (1980–2004).

We used separate plots to demonstrate changes and trends in annual, winter (November to April), spring (May and June) and summer–autumn (July to October) discharge associated with Yenisey at Igarka, a primary gauge for estimating discharge from the entire river basin (figure 5). There were some changes in annual discharge after dam construction related to both reservoir filling and annual regulation. The long-term annual trends do not change significantly as both the observed and naturalized annual discharge show significant positive trends over 1936–2004 (figure 5(a)). However, the winter, spring and summer–autumn time series (figures 5(b), (c) and (d) respectively) show large changes in trend as a result of dam construction and the region of influence of these major dams is seen all the way to Igarka. Both winter observed and naturalized data show significant positive trends but the slope of the naturalized discharge is 1/8 of the observed slope (figure 5(b)). Climate variation explains about 13% of the observed winter increase and impoundments account for 87% of the winter change. Spring runoff is less sensitive to

dam construction and operation than the other seasons due to the large unregulated northern part of the basin with large tributaries Nizhnyaya and Podkamennaya Tunguska (total drainage area is about $700\,000\ km^2$) playing an important role in the Yenisey spring flood at Igarka (Shiklomanov 1995). This northern part of the basin has a more dominant spring flow than the other region of the basin. Spring discharge exceeds 70% of annual discharge and the spring peak at Igarka is strongly controlled by runoff from this northern unregulated part of the Yenisey basin. There is no trend in observed spring runoff but naturalized records show an insignificant positive tendency over 1936–2004 suggesting small increases in snowmelt runoff over the basin (figure 5(c)). The observed negative trend over summer–autumn is significant but the naturalized runoff shows the opposite, increasing, tendency which is not statistically significant (figure 5(d)).

The naturalized records show that the increase in annual discharge of the Yenisey River accompanied a significant increase during winter and increasing tendencies during other seasons. This has caused us to re-evaluate the conclusions based on observed discharge records that the documented increase in annual discharge (Peterson *et al* 2002) was mainly due to winter–spring flow increase (Rawlins *et al* 2007, Yang *et al* 2004a, McClelland *et al* 2004). Our results for the effects of reservoirs on discharge and long-term trends in general do not contradict the results given by Adam *et al* (2007) although our estimates show a more significant influence of reservoirs on long-term trends in discharge during summer–autumn and winter periods.

Looking at an along river sequence of six gauges from the Angara River to Yenisey at Igarka we can see where the effect of reservoirs may completely overwhelm the natural long-term annual signal and severely limit hydroclimatological analysis (figure 6). Slopes of the lines between points represent the runoff trends for interstation drainage areas. The southern and

Table 1. Change in runoff, precipitation, air temperature and runoff ratio over 1980–2007 evaluated from the slope of the least squares linear regression and their anomalies in 2007 for 12 subbasins in the Yenisey, Lena and Ob watersheds and 3 river basins. For description of the interstation areas see Lammers *et al* (2001).

| Code | Name | Interstation drainage area (km^2) | Gauge coordinates | | Permafrost (%) | Runoff (mm y^{-1}) | | Precipitation (mm y^{-1}) | | Air temperature (°C) | | Runoff ratio (%) | |
			Lat.	Long.		Change 1980–2007	2007 anomaly	Change 1980–2007	2007 anomaly	Change 1980–2007	2007 anomaly	Change 1980–2007	2007 anomaly
1 801	Kolyma–Srednekolymsk	361 000	67.47	153.69	100	47.8	82.2	80.2	67.3	1.33	1.45	57	68
3 029	Lena–Krestovskoe	440 000	59.73	113.17	63	12.1	**47.2**	−16.3	**−79.5**	0.94	1.69	78	95
3 042	Lena–Tabaga	457 000	61.83	129.60	81	56.7	**104.4**	43.3	**−12.2**	0.96	1.62	56	94
3 821	Lena–Kusur	1 533 000	70.68	127.39	97	33.2	52.0	32.3	28.1	0.61	1.23	54	63
8 013	Angara–Irkutskaya GES	573 000	52.23	104.30	17	−6.0	**−15.5**	−63.8	**−86.5**	1.91	2.09	34	42
8 084	Angara–Boguchany	293 000	58.38	97.45	29	−20.8	**2.6**	3.8	**−43.9**	1.24	1.92	45	49
9 053	Yenisey–Bazaikha	300 000	55.98	92.80	33	7.4	28.9	79.3	23.5	1.77	1.95	55	58
9 803	Yenisey–Igarka	1 274 000	67.43	86.48	65	77.6	**90.7**	55.7	**64.1**	0.61	1.22	60	65
10 006	Ob–Barnaul	169 000	53.40	83.82	6.2	22.8	**−15.5**	50.7	**−53.6**	0.19	0.70	52	56
10 021	Ob–Kolpashevo	317 000	58.30	82.88	4.8	26.1	41.9	57.2	81.0	0.49	1.03	34	43
10 031	Ob–Belogor'e	1 435 000	61.07	68.60	21	9.2	28.4	142.2	139.3	0.48	1.14	21	21
11 048	Irtish–Omsk	769 000	55.02	73.30	0	5.2	−0.9	95.2	14.0	0.54	0.67	9	9
11 801	Ob–Salekhard	260 000	66.63	66.60	56	119.4	159.3	131.1	143.3	0.51	1.78	53	59
70 801	Severnaya Dvina at Ust–Pinega	348 000	64.13	41.92	0	−3.5	11.1	42.0	95.1	0.41	0.88	45	40
70 850	Pechora at Ust–Tsilma	248 000	65.42	52.28	26	90.1	**214.2**	111.7	**74.0**	0.46	1.51	63	82
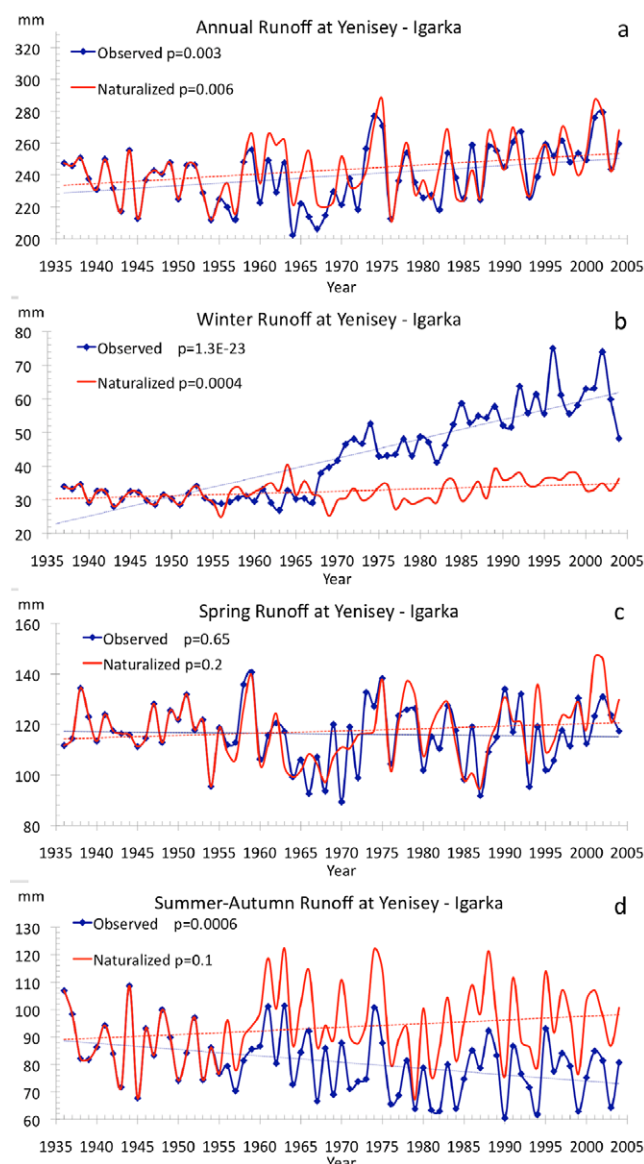
Figure 5. Time series of observed and naturalized (reconstructed) river discharge for Yenisey at Igarka over 1936–2004; (a) annual, (b) winter (November to April), (c) spring (May to June), (d) summer–autumn (July to October). Thin dashed lines show linear trends defined from least squares linear regression analysis and p-values represent the significance of the trend. The trend is considered significant if $p < 0.05$ ($\alpha = 95\%$).

central parts of the basin show decreasing trends in observed discharge and the northern regions of the basin show increasing discharge trend. This is consistent with our previous analysis for subbasins (figure 2). The naturalized discharge records show downward trends in the southern portion of the basin, no change or a slight increase in the central Yenisey and sharp increases in the north. The reservoirs Sayano–Shushenskoje (4) and Krasnoyarskoje (5) exert a considerable influence on annual river flow (figure 6). The naturalized trends have opposite signs through this part of the river and therefore annual runoff estimates are seriously influenced by dams. This in turn greatly limits their use in the raw observed form for assessing and quantifying any climate change signals.
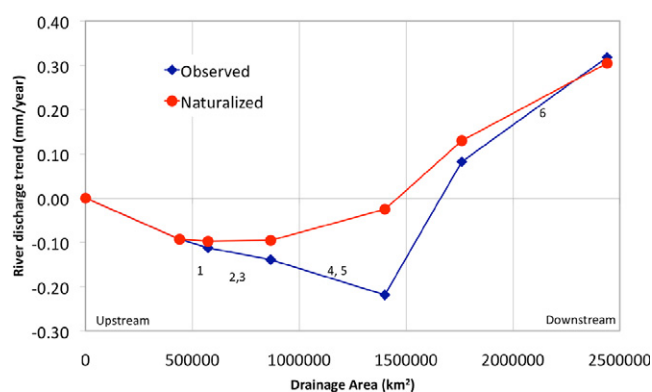

Figure 6. Observed and naturalized 1936–2004 annual slopes of the river discharge trend line at six sequential gauge locations along the Angara and Yenisey rivers. Each gauge from left to right is downstream of the previous gauges. Integers represent the locations of major dams from table 2. Dam No 7 in table 2 is downstream of Yenisey at Igarka and is not shown on the plot.

There are temporal and spatial limits to the analysis that we can carry out while this drainage basin is undergoing simultaneous climate and human-induced changes. At annual time steps the trends are less impacted by dam construction, whereas for seasonal and monthly time steps these data are confounded by the two sources of change and the climate change signals are overwhelmed by the human-induced river impoundments. Spatially, different parts of the river system are especially influenced by impoundments which limit our ability to identify where the climate changes are taking place. This problem is not restricted to the Russian pan-Arctic but has global ramifications. Over the entire Earth humans have changed the natural signal expressed by the river systems (Vörösmarty *et al* 1997, 2004) and this limits our ability to assess climate change signals.

5. Conclusions and recommendations

River discharge from the large Russian basins in 2007 exceeded the previous record in 2002 by 10%. While that year's flow was unusually high, the overall spatial patterns were consistent with the hydroclimatic trends since 1980 indicating that 2007 was not an aberration but a part of the general trend. Annual discharge from Eurasia over 1980–2007 demonstrates an unprecedented increase with a rate of $10 \text{ km}^3 \text{ y}^{-1}$ or almost five times higher than that documented by Peterson *et al* (2002) over the 1936–1999 period. This suggests a significant acceleration of hydrological processes in the Eurasian pan-Arctic over the last three decades. Given the runoff projections based on Global Circulation Model simulations for this region (Shiklomanov and Shiklomanov 2003) we can expect further large fluxes of river discharge from these rivers in the future.

However there are limits on our ability to use observed river discharge to track and attribute these observed changes to specific periods within the year and to locations within the drainage basins. The engineering works placed in these river systems have relegated the climate change signal within the river discharge time series to a minor role. Our ability to detect

Table 2. Principal operating reservoirs in the Yenisey river basin. (Note: total capacity is full volume (storage) of the reservoir which includes dead storage and operating capacity (storage); operating storage is the volume of reservoir which can be regulated by the dam.)

ID	Name	River	Long-term discharge (km^3)	Total capacity (km^3)	Operating capacity (km^3)	Filling period (y)
1	Irkutskoje	Angara	60.4	48.1	46.4	1956–1960
2	Bratskoje	Angara	91.7	169.3	48.2	1961–1965
3	Ust–Ilimskoje	Angara	101.0	59.4	2.8	1971–1975
4	Sayano–Shushenskoje	Yenisey	46.7	31.3	15.3	1978–1984
5	Krasnoyarskoje	Yenisey	88.2	73.3	30.4	1966–1970
6	Kureiskoje	Kureika	19.4	18.5	11.2	1985–1987
7	Khantaiskoje	Khantaika	16.6	23.5	17.3	1966–1970

hydrological response to changes in climate system is limited for many large river basins. Having reliable 'naturalized' river discharge records is the best way to distinguish between human impact and climate variability.

How do we make assessments on the attribution of hydroclimatological changes in a timely way? Currently, we have available to us high temporal resolution nearly real time data from the large Russian basins which allow for rapid assessment of changes to the drainage systems. However, the majority of these monitoring sites are rendered unusable for assessment of climate change due to the human influenced signals. There are two solutions and we feel both are essential for understanding hydrological changes. The first is the need to couple the naturalization algorithms with operational data collecting capabilities. There will be additional error in the naturalized river flow estimates from the use of provisional data but these results would provide a rapid and important first look at the observed changes. The second solution is to use only river basins having minimal human-induced changes. This would require the creation of nearly real time data feeds for smaller upstream gauges in which impoundments and land cover change had a minimal effect on flow data. Such a data set could include basins which are not natural, provided they have not changed significantly during the time period of data collection (Pilon and Kuylenstierna 2000). This will serve to eliminate the most egregious influences on the hydrograph and the smaller drainage basin size would provide improved controls in terms of land cover and land use changes. We envision a hierarchical network in which many drainage basins can be used for inter-annual trend detection, a subset of the network would be used for seasonal and monthly time steps while a further more restrictive subset would be available for daily records. The recommendations of GCOS (Global Climate Observing System) for Global Terrestrial Observing Network (GT-NET) and the criteria for the WMO Reference Climatological Stations (RCS) can be applied to this reference basin network. The gauges used in Shiklomanov *et al* (2007) and Smith *et al* (2007) represent one example of such a monitoring network for long-term observational sites over relatively small basins the Russian pan-Arctic and can serve as a starting point for its creation. This coverage should be significantly extended and regularly updated to provide the scientific community with basic information for quantifying the role of climatic drivers in altered river discharge across the Eurasian pan-Arctic drainage basin.

References

Adam J C, Haddeland I, Su F and Lettenmaier D P 2007 Simulation of reservoir influences on annual and seasonal streamflow changes for the Lena, Yenisei, and Ob' rivers *J. Geophys. Res.* **112** D24114

Arctic Climate Impact Assessment Scientific Report 2005 (New York: Cambridge University Press) p 1042

Berezovskaya S, Yang D and Kane D L 2004 Compatibility analysis of precipitation and runoff trends over the large Siberian watersheds *Geophys. Res. Lett.* **31** L21502

Berezovskaya S, Yang D Q and Hinzman L 2005 Long-term annual water balance analysis of the Lena River *Glob. Planet. Change* **48** 84–95

Brown J, Ferrians O J Jr, Heginbottom J A and Melnikov E S 1998 Digital circum-Arctic map of permafrost and ground-ice conditions *International Permafrost Association, Data and Information Working Group, Comp. Circumpolar Active-Layer Permafrost System (CAPS), version 1.0* available from NSIDC User Services

Déry S J, Hernández-Henríquez M A, Burford J E and Wood E F 2009 Observational evidence of an intensifying hydrological cycle in northern Canada *Geophys. Res. Lett.* **36** L13402

Hirsch R M, Alexander R B and Smith R A 1991 Selection of methods for the detection and estimation of trends in water quality *Water Resources Res.* **27** 803–13

Kalinin G P, Kuchment L S and Koren V I 1969 Principles for elaboration of mathematical runoff models *Floods and Their Computation* (Paris: Les Crues Et Leur Évaluation) IASH

Kendall M G 1975 *Rank Correlation Methods* 4th edn (London: Charles Griffin)

Lammers R B, Shiklomanov A I, Vörösmarty C J, Fekete B M and Peterson B J 2001 Assessment of contemporary Arctic river runoff based on observational discharge records *J. Geophys. Res.* **106** 3321–34

Mann H B 1945 Non-parametric test against trend *Econometrica* **13** 245–59

Marchenko S, Gorbunov A and Romanovsky V 2007 Permafrost warming in the Tien Shan Mountains, central Asia *Glob. Planet. Change* **56** 311–27

McClelland J W, Holmes R M, Peterson B J and Stieglitz M 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

Mernild S H, Liston G E, Hiemstra C A and Steffen K 2009 Record 2007 Greenland ice sheet surface melt extent and runoff *EOS Trans. Am. Geophys. Union* **90** 13–4

Peterson B J, Holmes R, McClelland J, Vörösmarty C, Lammers R B, Shiklomanov A, Shiklomanov I and Rahmstorf S 2002 Increasing Arctic river discharge: responses and feedbacks to global climate change *Science* **298** 2171–3

Peterson B J, McClelland J, Curry R, Holmes R, Walsh J and Aagaard K 2006 Trajectory shifts in the Arctic and sub-Arctic freshwater cycle *Science* **313** 1061–6

Pilon P J and Kuylenstierna J K 2000 Pristine river basins and relevant hydrological indices: essential ingredients for climate-change studies *WMO Bull.* **49** 248–55

Rawlins M A, Fahnestock M, Frolking S and Vörösmarty C J 2007 On the evaluation of snow water equivalent estimates over the terrestrial Arctic drainage basin *Hydrol. Process.* **21** 1616–23

Rawlins M A, Schroeder R, Zhang X and McDonald K C 2009 Anomalous atmospheric circulation, moisture flux, and winter snow accumulation in relation to record combined discharge from large Eurasian rivers in 2007 *Environ. Res. Lett.* **4** 045011

Rawlins M A, Willmott C J, Shiklomanov A, Frolking S and Vörösmarty C J 2006 Evaluation of trends in derived snowfall and rainfall across Eurasia and linkages with discharge to the Arctic Ocean *Geophys. Res. Lett.* **33** L07403

Richter-Menge J *et al* 2006 *State of the Climate in 2005* vol 87 ed K A Shein, chapter 5b (Arctic) BAMS, 102 p

Richter-Menge J *et al* 2007 *State of the Climate in 2006* vol 88 ed F Fetterer, chapter 5a (Arctic) BAMS, 135 p

Richter-Menge J *et al* 2008 *State of the Climate in 2007* vol 89 ed F Fetterer, chapter 5a (Arctic) BAMS, 179 p

Richter-Menge J *et al* 2009 *State of the Climate in 2008* vol 90 ed T C Peterson and M O Baringer, chapter 5 (Arctic) BAMS, 196 p

Serreze M C, Clark M P and Bromwich D H 2003 Monitoring precipitation over the terrestrial Arctic drainage: data requirements, shortcomings and applications of atmospheric reanalysis *J. Hydrometeorol.* **4** 387–407

Shiklomanov A I 1994 The influence of anthropogenic changes of global climate on the runoff in the Yenisei basin *Meteorology Hydrology* **2** 84–93 (in Russian)

Shiklomanov I A and Shiklomanov A I 2003 Climatic change and dynamics of river discharge into the Arctic Ocean *Water Resources* **30** 593–601

Shiklomanov I A, Shiklomanov A I, Lammers R B, Peterson B J and Vörösmarty C J 2000 The dynamics of river water inflow to the Arctic Ocean *The Freshwater Budget of the Arctic Ocean* ed E L Lewis *et al* (Dordrecht: Kluwer Academic) pp 281–96

Shiklomanov I A and Veretennikova G M 1978 Effect of reservoirs on the annual runoff of rivers in the USSR *Sov. Hydrol. Sel. Pap.* **17** 12–32

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

Shiklomanov A I, Yakovleva T I, Lammers R B, Karasev I Ph, Vörösmarty C J and Linder E 2006 Cold region river discharge uncertainty—estimates from large Russian rivers *J. Hydrol.* **326** 231–56

Smith L C, Pavelsky T M, MacDonald G M, Shiklomanov A I and Lammers R B 2007 Rising minimum flows in northern Eurasian rivers suggest a growing influence of groundwater in the high-latitude water cycle *J. Geophys. Res.* **112** G04S47

Stanilovskaya J, Ukhova J, Sergeev D and Utkina I 2008 Thermal state of permafrost in northern Transbaykalia, eastern Siberia *Proc. 9th Int. Conf. on Permafrost (University of Alaska Fairbanks, June–July 2008)* vol 1, pp 1695–700

Stroeve J, Serreze M, Drobot S, Gearheard S, Holland M, Maslanik J, Meier W and Scambos T 2008 Arctic sea ice plummets in 2007 *EOS Trans. Am. Geophys. Union* **89** 13–14

Vörösmarty C J, Sharma K, Fekete B, Copeland A H, Holden J, Marble J and Lough J A 1997 The storage and aging of continental runoff in large reservoir systems of the world *Ambio* **26** 210–19

Vörösmarty C J *et al* 2004 Humans transforming the global water system *EOS Trans. Am. Geophys. Union* **85** 513–14

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

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

Ye B, Yang D and Kane D L 2003 Changes in Lena River streamflow hydrology: human impacts versus natural variations *Water Resources Res.* **39** 1200

Ye H, Yang D Q, Zhang T, Zhang X, Ladochy S and Ellison M 2004 The impact of climatic conditions on seasonal river discharges in Siberia *J. Hydrometeorol.* **5** 286–95