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Increasing river discharge in the Eurasian Arctic: Consideration of dams, permafrost thaw, and fires as potential agents of change

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[1] Discharge from Eurasian rivers to the Arctic Ocean has increased significantly in recent decades, but the reason for this trend remains unclear. Increased net atmospheric moisture transport from lower to higher latitudes in a warming climate has been identified as one potential mechanism. However, uncertainty associated with estimates of precipitation in the Arctic makes it difficult to confirm whether or not this mechanism is responsible for the change in discharge. Three alternative mechanisms are dam construction and operation, permafrost thaw, and increasing forest fires. Here we evaluate the potential influence of these three mechanisms on changes in discharge from the six largest Eurasian Arctic rivers (Yenisey, Ob', Lena, Kolyma, Pechora, and Severnaya Dvina) between 1936 and 1999. Comprehensive discharge records made it possible to evaluate the influence of dams directly. Data on permafrost thaw and fires in the watersheds of the Eurasian Arctic rivers are more limited. We therefore use a combination of data and modeling scenarios to explore the potential of these two mechanisms as drivers of increasing discharge. Dams have dramatically altered the seasonality of discharge but are not responsible for increases in annual values. Both thawing of permafrost and increased fires may have contributed to changes in discharge, but neither can be considered a major driver. Cumulative thaw depths required to produce the observed increases in discharge are unreasonable: Even if all of the water from thawing permafrost were converted to discharge, a minimum of 4 m thawed evenly across the combined permafrost area of the six major Eurasian Arctic watersheds would have been required. Similarly, sensitivity analysis shows that the increases in fires that would have been necessary to drive the changes in discharge are unrealistic. Of the potential drivers considered here, increasing northward transport of moisture as a result of global warming remains the most viable explanation for the observed increases in Eurasian Arctic river discharge. *INDEX TERMS:* 1655 Global Change: Water cycles (1836); 1803 Hydrology: Anthropogenic effects; 1833 Hydrology: Hydroclimatology; 1860 Hydrology: Runoff and streamflow; *KEYWORDS:* Arctic river discharge, global change

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1. Introduction

[2] The Arctic is a central component of the global climate system. Increasing temperatures in recent decades have been linked to a wide variety of changes in the Arctic [*Serreze et al.*, 2000]. At the same time, changes in the Arctic may have strong feedbacks on global climate [*Intergovernmental Panel on Climate Change* (*IPCC*), 2001]. Many of the linkages between the Arctic system and global climate involve the hydrologic cycle. For example, changes in the moisture content of Arctic soils influence uptake and release of greenhouse gases [*Gorham*, 1991; *McKane et al.*, 1997; *Oechel et al.*, 1993; *Stieglitz et al.*, 2000], and changes in freshwater inputs to the Arctic Ocean have the potential to alter global ocean circulation [*Broecker*, 1997; *Manabe and Stouffer*, 1994; *Rahmstorf*, 2002]. This second feedback recently became the focus of heightened attention after publication of records showing long-term increases in river discharge from Eurasia into the Arctic Ocean [*Peterson et al.*, 2002]. Discharge to the Arctic Ocean from the six largest Eurasian rivers

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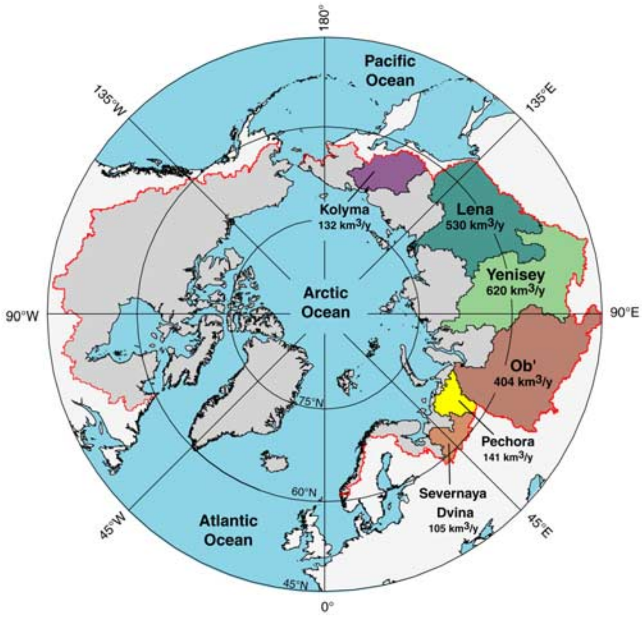

Figure 1. Watersheds and average annual discharge from the six largest Eurasian Arctic rivers. Boundary of the pan-Arctic watershed (red line) is shown.

(Figure 1) increased by ~128 km^3 y^{-1} from 1936 to 1999. This change in discharge was correlated with global surface air temperature. Furthermore, calculations of future discharge coupled to Intergovernmental Panel on Climate Change global warming scenarios suggested that additional freshwater contributions to the Arctic Ocean could significantly impact North Atlantic Deep Water formation within this century [*Peterson et al.*, 2002].

[3] Accurate projections of Arctic river discharge depend on identifying the specific mechanisms driving the changes. The projections of *Peterson et al.* [2002] assume increased net atmospheric moisture transport from lower to higher latitudes in a warming climate as indicated by many global circulation models [*IPCC*, 2001; *Manabe and Stouffer*, 1994; *Rahmstorf and Ganopolski*, 1999]. Yet uncertainty associated with estimates of precipitation in the Eurasian Arctic makes it difficult to confirm whether or not this mechanism was responsible for the changes in river discharge observed thus far [*Serreze et al.*, 2003; *Serreze and Etringer*, 2003; *Yang et al.*, 2001]. Three alternative mechanisms that have been suggested frequently to account for the long-term changes in river discharge are dam construction and operation, permafrost thaw, and increasing forest fires.

[4] Numerous large dams have been built in Russia and the former Soviet Union, including several in the watersheds of the major Eurasian Arctic rivers (L. K. Malik et al., Development of dams in the Russian Federation and NIS countries, 2000, at http://www.dams.org/kbase/studies/ru/). The influence of these dams on long-term discharge trends could be important, as dams have a major influence on watershed storage and flow regimes [*Vörösmarty et al.*, 1997]. All else being equal, filling of reservoirs near the beginning of a record would make discharge values lower early in the record and thus facilitate a positive trend in the data. Filling of reservoirs near the end of a record would work against any long-term increase in discharge. Similarly, controlling the seasonality of flow could have a positive or negative influence on long-term trends in annual discharge. Evaporation from reservoirs decreases discharge. However, increasing the proportion of water flowing to the Arctic Ocean during times of year when evaporative demand is low could result in higher annual values.

[5] Permafrost thaw is another obvious subject of enquiry because water stored in permafrost could become runoff after melting. While permafrost depths can reach several hundred meters, the upper 20 m of permafrost alone in the Northern Hemisphere contains 11,000–37,000 km^3 of frozen water, much of which is in the Eurasian Arctic [*Zhang et al.*, 1999, 2000]. These volumes of water are much larger than the excess 4160 km^3 of river water delivered to the Arctic Ocean between 1936 and 1999 [*Peterson et al.*, 2002]. Thus water stored in Eurasian Arctic permafrost has the potential to make major contributions to Arctic river discharge.

[6] Forest fires have been suggested as a potential mechanism behind the long-term changes in Eurasian Arctic river discharge because changes in vegetation following fires often lead to greater runoff. Loss or damage of vegetation causes a decrease in evapotranspiration, allowing a greater proportion of precipitation to become runoff [*Chapin et al.*, 2000]. This effect diminishes over time as the forest recovers. There are 620 × 10^6 ha of boreal forest in Russia [*Conard and Ivanova*, 1997]. The vast majority of this forest lies within the combined watershed of the six largest Eurasian Arctic rivers. Thus, as with permafrost thaw, increased fires in Russia's boreal forests have the potential to substantially alter river discharge.

[7] In this paper we consider the influence of dams, permafrost thaw, and fires with respect to the observed long-term changes in discharge from the six largest Eurasian Arctic rivers. Comprehensive long-term records of river discharge made it possible to evaluate the role of dams directly. Data on permafrost thaw and fires in the watersheds of the Eurasian Arctic rivers are less useful because temporal and spatial coverage is limited. We therefore use a combination of data and modeling scenarios to explore the potential of these two mechanisms as drivers of increasing Arctic river discharge.

2. Data Sets and Methods of Analysis

2.1. Dams

[8] The Russian Federal Service of Hydrometeorology and Environment Monitoring (Roshydromet) has been measuring river discharge at many stations within the Russian Arctic for much of the past century [*Lammers et al.*, 2001; *Peterson et al.*, 2002; *Shiklomanov et al.*, 2002]. Errors associated with the discharge estimates vary seasonally, with greatest uncertainty during the ice breakup period. However, estimates of discharge become increasingly well constrained from daily to monthly to annual averages. For example, on the Ob' River at Salekhard, errors in daily discharge estimates range from 26% in April to 5% in July, errors in monthly discharge estimates range from 18% in April to 3% in July, and the error in annual discharge estimates is 6% (A. I. Shiklomanov, manuscript in preparation, 2004). The long-term records of Eurasian Arctic river

Table 1. Dams With Reservoir Capacities >1 km^3 in the Watersheds of the Ob', Yenisey, Lena, and Kolyma Rivers[a]

	Dams	Reservoir Filling	Capacity, km^3	Surface Area, km^2
Ob' Watershed				
Irtysh River	Bukhtarminskoe	1956–1960	50	5490
Irtysh River	Shul'binskoe	1986–1989	2	255
Ob' River	Novosibirskoe	1956–1960	9	1070
Yenisey Watershed				
Yenisey River	Sayano-Shushenskoe	1976–1980	31	621
Yenisey River	Krasnoyarskoe	1966–1970	73	2000
Angara River	Irkutskoe	1956–1960	48	1466
Angara River	Bratskoe	1961–1965	169	5470
Angara River	Ust'-Ilimskoe	1971–1975	59	1873
Angara River	Boguchanskoe	under construction	59	2326
Kureika River	Kureiskoe	1986–1990	10	560
Khantayka River	Ust'-Khantaiskoe	1966–1970	24	2120
Lena Watershed				
Vilyuy River	Vilyuiskoe	1966–1970	36	2170
Kolyma Watershed				
Kolyma River	Kolymskoe	1986–1990	15	441

[a] Dams within each subwatershed are listed from upriver to downriver locations. The Severnaya Dvina and Pechora Rivers are not listed because there are no reservoirs with a capacity >1 km^3 within their watersheds.

discharge include substantial intervals both before and after construction of dams. Comparison of discharge data before and after dam construction made it possible to directly assess the influence of dams on discharge and to reconstruct records with the effects of dams removed ("naturalized flow").

[9] The former Soviet Union began building major hydroelectric dams (>1 km^3 reservoir capacity) in the watersheds of the largest Eurasian Arctic rivers in the mid-1950s (L. K. Malik et al., Development of dams in the Russian Federation and NIS countries, 2000, at http://www.dams.org/kbase/studies/ru/). There are now three major dams in the Ob' watershed, eight in the Yenisey watershed, one in the Lena watershed, and one in the Kolyma watershed (Table 1 and Figure 2). There are no major dams in the watersheds of the Pechora or Severnaya Dvina. Our data reconstructions take into account all of the dams listed in Table 1, with the exceptions of Ust'-Khantaiskoe and Kureiskoe. Ust'-Khantaiskoe dam is not included because it is on the Khantayka River, which enters below Igarka (the station used to estimate total discharge from the Yenisey River to the Arctic Ocean). Kureiskoe dam is not included because discharge records for the Kureika River are insufficient.

[10] Records from gauging stations at or near the dam sites (Table 2) were used to evaluate the influence of dams on discharge within the watersheds of the Ob', Yenisey, Lena, and Kolyma Rivers. The length and completeness of data sets were primary considerations when choosing particular gauging stations for analysis. Differences in average discharge before and after reservoir filling were calculated on a monthly basis for each of the stations listed in Table 2. These differences were then used to reconstruct discharge records at stations near the mouths of the Ob', Yenisey, Lena, and Kolyma Rivers: Ob' at Salekhard, Yenisey at Igarka, Lena at Kyusur, and Kolyma at Kolymskoye. Changes due to dam construction and operation are large relative to average discharge near the dam sites and become smaller as a percentage of average discharge down stream. This diminishing effect as a percentage of the total flow was accounted for by applying the absolute changes measured near the dam sites directly to the downstream discharge. For the periods during reservoir filling, data were reconstructed on a year-by-year basis relative to the predam averages to allow for large interannual changes in discharge due to the filling process. Differences were subtracted from downstream values in months showing excess discharge after reservoir filling and were added to the downstream values in months showing deficits in discharge after reservoir filling. Multiple dams were built on the Irtysh River (tributary of the Ob'), Angara River (tributary of the Yenisey), and main stem of the Yenisey River (Table 1). The newer dams were built successively downstream. In each of these cases, reconstructions were done using discharge data from gauging stations below the newest dams. Over time, the influence of older dams on discharge disappeared as new sites came on line to control flow.

Figure 2. Locations of major dams (reservoir capacity >1 km^3) in the watersheds of the six largest Eurasian Arctic rivers: 1, Bukhtarminskoe; 2, Shul'binskoe; 3, Novosibirskoe; 4, Sayano-Shushenskoe; 5, Krasnoyarskoe; 6, Irkutskoe; 7, Bratskoe; 8, Ust'-Ilimskoe; 9, Boguchanskoe; 10, Kureiskoe; 11, Ust'-Khantaiskoe; 12, Vilyuiskoe; and 13, Kolymskoe.

Table 2. Gauging Stations Used to Evaluate the Influence of Major Dams on Discharge Within the Watersheds of the Ob', Yenisey, Lena, and Kolyma Rivers

	Gauging Station	Years of Discharge Record	Average Discharge at Station, km^3 yr^{-1}
Ob' Watershed			
Irtysh River	Omsk	1936–1999	28
Ob' River	Kolpashevo	1936–1990	125
Yenisey Watershed			
Angara River	Boguchany	1936–1988	108
Yenisey River	Bazaiha	1936–1989	91
Lena Watershed			
Vilyuy River	Khatyrik-Khomo	1936–1990	46
Kolyma Watershed			
Kolyma River	Ust' Srednekan	1936–1998	23

[11] Our approach for data reconstruction does not fully account for the influence of climate change because changes in average discharge at the upstream stations used for analysis (Table 2) are attributed to dams alone. However, effects of climate change on the much larger watershed area downstream of the stations used for analysis are represented in our "naturalized" discharge records. Furthermore, any long-term changes in discharge that might be attributed to climate change above the dams are dwarfed by the dramatic stepwise changes in discharge caused by the dams. Thus differences between the original and reconstructed discharge records overwhelmingly reflect the influence of dams.

[12] The reconstructed discharge data for the Ob', Yenisey, Lena, and Kolyma Rivers were summed with the original discharge data from the Pechora and Severnaya Dvina Rivers (which have no large dams) to get reconstructed monthly values for the six largest Eurasian Arctic rivers combined. These data were compared to the original combined discharge data for the six rivers to evaluate the affect of dams on seasonality. Finally, regressions of annual discharge versus year for the reconstructed and original combined data were compared to evaluate the effect of dams on long-term changes in discharge from the six largest Eurasian Arctic rivers.

2.2. Permafrost

[13] Although active layer thickness is being measured at many locations across Russia, temporal and spatial coverage remains insufficient for robust analysis of long-term trends at the scale of the Eurasian Arctic drainage. As an alternative approach to evaluate the potential contribution of permafrost thaw to long-term increases in river discharge, we (1) examined the empirical relationships between permafrost coverage and runoff trends in the Severnaya Dvina, Pechora, Ob', Yenisey, Lena, and Kolyma Rivers and (2) calculated annual and cumulative thaw depths that would be required to generate the observed increases in discharge.

[14] Data on permafrost coverage were tabulated from a prerelease of the International Permafrost Association digital permafrost database and provided by the Water Systems Analysis Group at the University of New Hampshire (http://www.watsys.unh.edu/). Permafrost was categorized as continuous (90–100%), discontinuous (50–90%), isolated (10–50%), and sporadic (0–10%). Categories expressed as percentages of watershed area for each of the six largest Eurasian Arctic rivers are presented in Table 3.

[15] Potential contributions from thawing permafrost to increasing river discharge depend on the area of permafrost being thawed and the water content held in the permafrost. Considering these key variables, annual and cumulative thaw depths required to generate the observed increases in discharge were calculated for three different scenarios. In the first scenario, all classes of permafrost were allowed to thaw. In the second scenario, all classes of permafrost except continuous were allowed to thaw. In the third scenario, only isolated and sporadic permafrost areas were allowed to thaw. The total land areas encompassed by scenarios 1, 2, and 3 are 6.5×10^6, 2.9×10^6, and 2.1×10^6 km^2, respectively. However, taking into account that permafrost does not completely cover the land area for any permafrost category, the effective permafrost areas for scenarios 1, 2, and 3 are 4.3×10^6, 0.9×10^6, and 0.4×10^6 km^2, respectively. These values were derived assuming 95% permafrost coverage in continuous areas, 70% permafrost coverage in discontinuous areas, 30% permafrost coverage in isolated areas, and 5% permafrost coverage in sporadic areas. It was assumed for all calculations that that water/ice content is 25% of permafrost by volume and that all water in thawed permafrost becomes river discharge. Water content of permafrost can range from nearly 0 to 100%, but averaged over a large area such as considered in this paper, 25% water content is probably an overestimate [*Zhang et al.*, 1999, 2000]. Assuming that all water in thawed permafrost is available for discharge is also an

Table 3. Permafrost Extent in the Six Largest Eurasian Arctic Rivers[a]

River	Watershed Area, 10^6 km^2	Permafrost: All Classes, %	Continuous Permafrost, %	Discontinuous Permafrost, %	Intermittent and Sporadic Permafrost, %
Severnaya Dvina	0.36	0	0	0	0
Pechora	0.32	40	12	4	24
Ob'	2.99	30	2	5	23
Yenisey	2.58	90	34	11	45
Lena	2.49	100	80	11	9
Kolyma	0.65	100	100	0	0

[a] Data were provided by the Water Systems Analysis Group at the University of New Hampshire (http://www.watsys.unh.edu/).

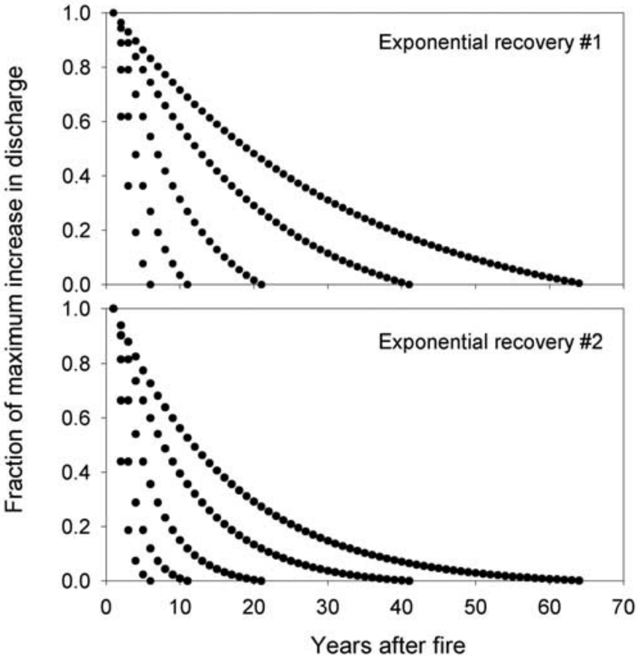

Figure 3. Exponential discharge recovery curves used in the fire-discharge model. The basic exponential equation e^{-kt} has been modified to force discharge through zero after 5, 10, 20, 40, or 64 years (see text for details).

overestimate. However, this assumption allows us to assess the maximum potential of permafrost as a water source.

2.3. Fires

[16] Long-term records of fires in Russia have been maintained in regions designated by the "Russia Forest Fund" [*Korovin*, 1996]. These regions, however, do not include vast forested areas in Siberia [*Conard and Ivanova*, 1997]. Fire-scar chronologies in some forests of central Siberia and the far east of Russia indicate substantial increases in fire frequency [*Arbatskaya and Vaganov*, 1997; *Cushman and Wallin*, 2002], but these changes do not necessarily equate with increases in annual burn areas because of increases in fire suppression efforts [*Conard and Ivanova*, 1997]. Only in recent years has satellite imagery allowed comprehensive analysis of fires in Russia [*Conard et al.*, 2002]. We therefore modeled the fire-discharge relationship to estimate increases in annual area burned that would have been required to generate the observed increases in discharge. Present burn rates were used as a benchmark for evaluating whether or not the required changes in burn rates would have been possible.

[17] Published data on the time and shape of discharge recovery after fires show substantial variability. We therefore conducted a sensitivity analysis that included a wide range of possibilities. Recovery times of 5, 10, 20, 40, and 64 years were considered for scenarios where excess discharge due to fire decreased linearly (linear recovery scenario) or exponentially (exponential recovery scenarios 1 and 2) back to baseline. The shapes of the exponential recovery curves are shown in Figure 3. Maximum increases in annual discharge of one third and two thirds after fire were considered for all scenarios. These increases were applied in year 1 of each model run. Excess discharge due to fire then declined according to the specifications of the different recovery scenarios.

[18] Discharge increases of one third and two thirds for the first year following each fire were chosen to capture the range of possibilities that could reasonably represent the aggregate response in Russia's boreal forest. There are no published studies of the fire-discharge relationship in Russia's boreal forests, but studies in Canada's boreal forests report maximum annual increases in discharge between 33 and 82% for moderate to severe fires [*Bayley et al.*, 1992; *Lamontagne et al.*, 2000; *Schindler et al.*, 1980]. Certainly, the full range of discharge responses following fires is wider: Changes in discharge after mild surface fires can be undetectable, whereas changes in discharge following severe fires can be >100% [*Helvey*, 1980]. However, the average response for forests over the whole Eurasian Arctic watershed has to fall between these extremes. We therefore used the Canadian results as a guideline for constraining maximum increases in discharge after fire but reduced the upper end of our range to better reflect the aggregate response of the very large forest area under consideration.

[19] Increases in discharge following new fires each year were summed with residual increases in discharge from previous years to account for the compounding effect of overlapping recovery periods. The model expresses the cumulative change in discharge rate (Q) resulting from an annual change in discharge rate (q) and a discharge recovery function ($f(t)$) as

$$Q = \sum_{j=1}^{n} \sum_{i=1}^{n} iqf_i(t_j). \tag{1}$$

The n term in equation (1) equals the total number of years over which effects of fire are being considered (in our case 64), and the $f(t)$ term in equation (1) is defined as

$$f_i(t_j)\begin{cases} 0 & t_j < t_i \\ g_r(t_j - t_i) & t_i \leq t_j \leq t_i + \delta, \\ 0 & t_j > t_i + \delta \end{cases}$$

where i and j identify discrete years within the total time period (functionally, t_i identifies the beginning of each new fire effect, while t_j identifies the years over which the fire effect lasts), δ represents the discharge recovery time, and g_r represents linear recovery (g_1) or exponential recovery (g_2):

$$g_1(t) = 1 - \frac{t}{\delta},$$

$$g_2(t) = (1+b)e^{-kt} - b; b = \frac{e^{-k\delta}}{1 - e^{-k\delta}}.$$

The basic exponential equation e^{-kt} has been modified in g_2 to force discharge through zero after time period δ. Values used for k in exponential recovery 1 scenarios lasting 5, 10, 20, 40, and 64 years were 0.4, 0.2, 0.1, 0.05, and 0.03125, respectively. Values used for k in exponential recovery 2 scenarios lasting 5, 10, 20, 40, and 64 years were 0.8, 0.4, 0.2, 0.1, and 0.0625, respectively.

[20] For all of the model runs our goal was to determine the annual increase in burn area that would drive

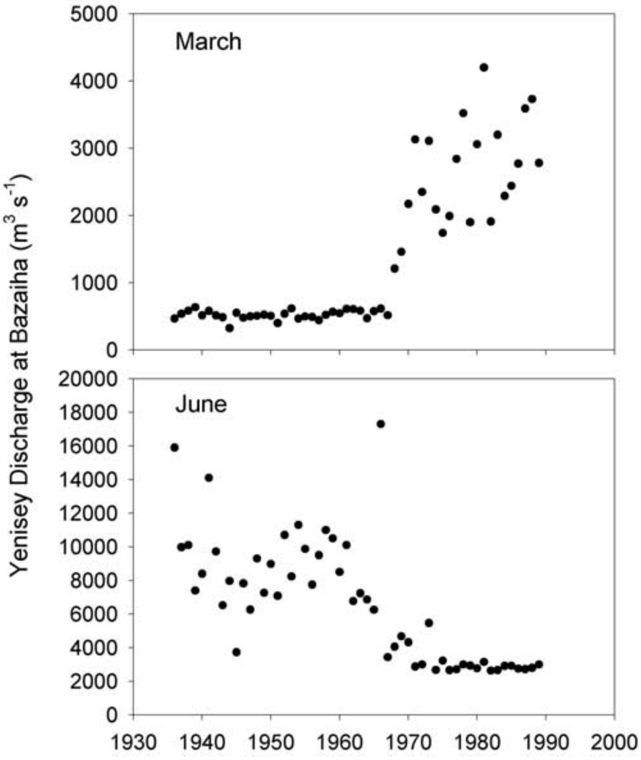

Figure 4. Time courses of March and June discharge at the Bazaiha gauging station on the Yenisey River. Stepwise changes in the data sets reflect regulation of flow after construction of the Krasnoyarsk dam.

discharge rates up by 128 km^3 y^{-1} over a 64-year period. This was achieved by running the model for 64 years using each of the discharge recovery scenarios and entering values for q iteratively until Q was equal to 128 km^3 y^{-1}. Annual increases in burn area (a) required to generate these q values were then calculated according to the equation $a = q/(dp)$, where d is equal to average annual discharge per unit area (2.03×10^{-6} km^3 ha^{-1} for the combined watersheds of the six largest Eurasian Arctic rivers) and p is equal to the maximum increase in discharge due to fire expressed as a fraction of one (set at either 0.33 or 0.66 for our analyses).

3. Results and Discussion

3.1. Influence of Dams on Discharge

[21] While our ultimate objective in this section is to evaluate the influence of dams on long-term trends in combined annual discharge from the six largest Eurasian Arctic rivers, we first address the influence of dams on seasonality of discharge. This analysis of seasonality provides insight about changes that underlie annual effects and provides an opportunity to assess the adequacy of data reconstructions.

[22] Operation of dams has dramatically changed the seasonality of discharge from the major Eurasian Arctic rivers. Control of flow during spring and early summer has reduced peak discharge, while release of water from the reservoirs has increased discharge during winter months (Figure 4). A month-by-month examination of annual changes in discharge between 1936 and 1999 comparing measured and reconstructed time courses (Table 4) shows that the influence of dams on the seasonality of discharge is strongest in the Yenisey River. The influence of dams on seasonality of discharge in the Ob' and Lena Rivers was less extreme but still very large. The single major dam on the Kolyma River had a relatively small influence on the seasonality of discharge. These findings contrast sharply with the conclusions of *Yang et al.* [2002] that shifts in the seasonality of discharge from the Lena River were primarily caused by climate change (dams were not considered in their analysis).

[23] A mix of the dam effects on the Ob', Yenisey, Lena, and Kolyma Rivers is reflected in the combined Eurasian Arctic river discharge data. The cumulative effects of annual changes in combined Eurasian Arctic river discharge between 1936 and 1999 are shown in Figure 5 for the measured and reconstructed records. Comparison of measured versus reconstructed discharge shows that much of the observed increase in winter discharge and decrease in summer discharge from 1936 to 1999 was due to dams (Figure 5). Furthermore, it is clear that without dams, increases in discharge over the period of record would have

Table 4. Annual Changes in Discharge Rates for Measured and Reconstructed (Dam Effects Removed) Monthly Data From 1936 to 1999 for Ob', Yenisey, Lena, and Kolyma Rivers[a]

	Ob'	Yenisey	Lena	Kolyma
Jan.	19[b] (16[b])	78[b] (13[b])	18[b] (1)	3[b] (0)
Feb.	22[b] (14[b])	95[b] (17[b])	23[b] (6)	4[b] (0)
March	24[b] (13[b])	105[b] (21[b])	24[b] (9[b])	4[b] (1[b])
April	29[b] (22[b])	120[b] (65[b])	21[b] (7[b])	3[b] (0)
May	27 (103[b])	−100 (20)	60 (57)	8 (10)
June	32 (114[b])	−5 (159)	49 (109)	−12 (8)
July	8 (64)	−75 (20)	85 (84)	−47[b] (−43[b])
Aug.	−73 (−45)	−76[b] (−26)	23 (22)	−10 (−7)
Sept.	−44 (−24)	−46[b] (−10)	−29 (−19)	6 (6)
Oct.	−4 (7)	−29 (−21)	−1 (0)	6 (4)
Nov.	22 (24[b])	61[b] (33[b])	16[b] (7)	2[b] (−1)
Dec.	20[b] (19[b])	67[b] (13)	16[b] (0)	3[b] (−1)

[a] Rates are in m^3 s^{-1} yr^{-1}. Reconstructed data are indicated by parentheses. The Severnaya Dvina and Pechora are not included because there are no major dams on these rivers. Value are derived from regressions of discharge versus year for each calendar month.

[b] For these regressions, $p < 0.05$.

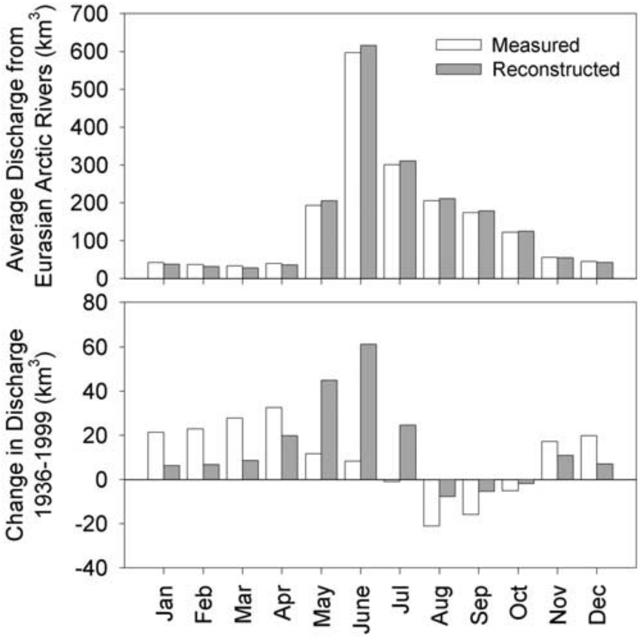

Figure 5. Average monthly discharge (1936–1999) and changes in monthly discharge over the period of record for measured and reconstructed data from the six largest Eurasian Arctic rivers.

been concentrated in the spring, the normal period of peak runoff.

[24] There are a variety of approaches for "naturalizing" streamflow data in regulated watersheds [*Hicks*, 1996; *Hicks et al.*, 1992; *Ye et al.*, 2003]. An analysis of dam effects in the Lena watershed by *Ye et al.* [2003] provides a unique opportunity to compare results using different approaches. *Ye et al.* [2003] analyzed the relationship between tributaries with and without dams and then used this information to reconstruct discharge at the outlet of the Lena basin. This approach produced very similar results to our own with respect to the sign, magnitude, and overall seasonality of dam effects. The only notable difference is that the peak in discharge as reconstructed by *Ye et al.* [2003] is a month later than the peak in our reconstructed discharge. This shift is probably the result of a time lag that is built into the analysis of *Ye et al.* [2003] for flow routing from the Vilyuiskoe dam to the mouth of the Lena River. We made no correction for time lags, though routing times can be up to 2 months in some parts of large Arctic river basins [*Arora and Boer*, 1999]. In contrast to the monthly data, time lags of this magnitude would not have an appreciable effect on the reconstructed annual discharge.

[25] While it is evident that dams had a marked effect on the seasonality of discharge, dam effects cannot account for the long-term increase in annual discharge. In fact, construction and operation of dams may have reduced discharge relative to what it would have been in the absence of dams (Figure 6). One explanation for this change is increased groundwater storage following dam construction. Filling of reservoirs forces river water into the surrounding ground (bank storage) and can be a large loss term depending on the geology of the region [*Jansen*, 1988]. Equilibration can take many years, and thus losses to groundwater could have affected discharge well beyond the time of reservoir filling. Another possibility is that evaporation from reservoir surfaces, and from water used for agricultural and municipal practices, accounts for the missing water. In this case a key question is the following: Where does the evaporated water precipitate back out of the atmosphere? If precipitation is on the Arctic Ocean, then this missing water should be included along with increasing discharge when considering potential effects on thermohaline circulation. On the other hand, if the missing water is redeposited within the watershed of the six combined Eurasian Arctic rivers, then it is already accounted for.

3.2. Permafrost Thaw as a Potential Agent of Change

[26] If water released from thawing permafrost was making a significant contribution to the observed increase in annual discharge from Eurasian Arctic rivers, we might expect that watersheds with the most permafrost (Table 3) would show the largest increase in runoff (discharge/watershed area). No such pattern is apparent (Figure 7). In fact, the watershed showing the largest change in runoff (Pechora) has only moderate permafrost coverage, and the watershed showing the second largest change in runoff (Severnaya Dvina) has no permafrost at all. At the other extreme, runoff did not increase from the Kolyma, the watershed with the greatest permafrost coverage.

[27] The results from the Severnaya Dvina make it clear that permafrost thaw cannot be the only driver of long-term changes in annual discharge from Eurasian Arctic rivers. Lack of correlation between permafrost extent and change in runoff among the other watersheds must be interpreted more cautiously. Differences in long-term temperature changes among watersheds could account for some of the observed variation in Figure 7. Surface air temperatures in the Ob', Yenisey, and Lena basins have increased significantly, whereas temperatures in the Severnaya Dvina, Pechora, and Kolyma basins have not (Table 5). Among the three watersheds showing long-term increases in temperature, changes in runoff correlate with permafrost extent (Figure 7).

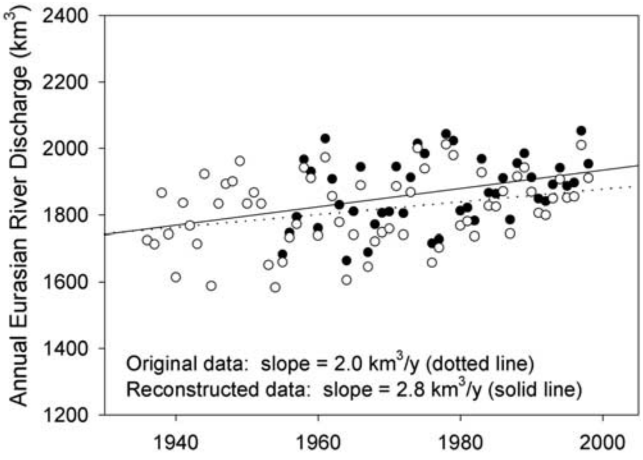

Figure 6. Comparison of combined annual discharge versus time for the original (open circles) and reconstructed (solid circles) data from the six largest Eurasian Arctic rivers.

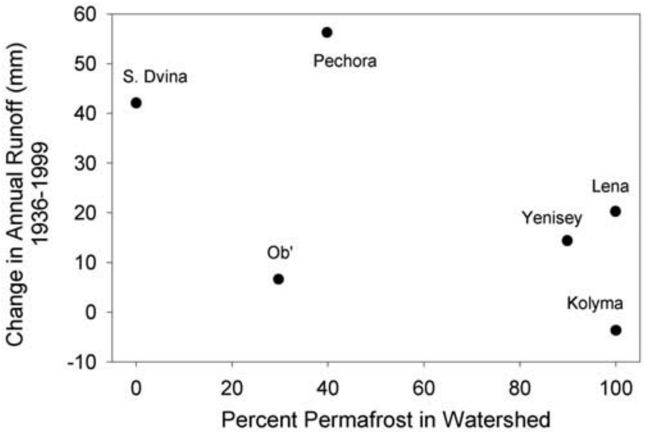

Figure 7. Long-term changes in runoff as a function of permafrost coverage in the watershed.

[28] To further refine our understanding of the permafrost-discharge relationship, we estimated the amount of permafrost that would have had to thaw and completely drain into rivers to drive the observed change in discharge. Our calculations indicate that annual thaw increments would have had to increase by 12, 58, and 130 cm from the beginning to the end of the 1936–1999 period, considering the areas of all permafrost types (scenario 1), all permafrost types except continuous (scenario 2), and sporadic and isolated permafrost only (scenario 3), respectively (Figure 8, top). While the amount of newly thawed permafrost required each year increases linearly, the depth at which thawing must occur is cumulative (Figure 8, bottom). As a consequence, relatively small amounts of water must be drained from extraordinary depths by the end of a 64-year period: Thaw depth would have had to increase by 4, 19, and 43 m from 1936 to 1999, considering scenarios 1, 2, and 3, respectively.

[29] Our assumption that 100% of the water from thawed permafrost becomes runoff has allowed us to examine the potential role of permafrost as a driver of increasing annual discharge from Eurasian Arctic rivers without unraveling the complex issue of groundwater storage. In reality, at least some of the water from thawed permafrost would be replaced annually. Net changes in moisture content after thawing can be much less than the volume of water stored in permafrost [*Stieglitz et al.*, 2000]. To the extent that this is the case, thawing of permafrost would have to be greater than that shown in Figure 8 to have a similar influence on discharge.

[30] Although it is difficult to extrapolate the existing observational data on active layer thickness to the combined watershed area of the six largest Eurasian Arctic rivers, it is reasonable to expect that widespread changes of the magnitude required to account for the observed increase in discharge would be apparent. Such changes are not evident in the observational data. Significant permafrost thawing has been observed in some areas of Siberia, but no widespread trends are apparent [*Brown et al.*, 2000]. Water from the thawing of permafrost in some areas could make a contribution to river discharge, but we conclude that it cannot be a major contributor to the observed long-term increase in Eurasian Arctic river discharge.

[31] We should note, however, that there is an indirect mechanism by which thawing of permafrost could contribute to increasing river discharge. By increasing the active layer depth and thus potentially lowering the water table, evapotranspiration might decrease, leading to increases in runoff. Further investigation will be required to evaluate the potential significance of this mechanism to river discharge increases in the Eurasian Arctic. However, again, the rivers with the greatest observed changes in runoff have little or no permafrost in their watersheds (Figure 7; Pechora and Severnaya Dvina), so this mechanism could apply only to a subset of the rivers.

3.3. Fires as a Potential Agent of Change

[32] Annual increases in fires that would be required to produce a 128 km^3 y^{-1} increase in Eurasian Arctic river discharge over 64 years depend on the magnitude of discharge increases after fire and the duration and shape of discharge recovery. Our scenarios demonstrate how required annual increases in burn area diminish as discharge recovery times becomes longer (Table 6). Likewise, smaller changes in burn area are required as estimates of maximum changes in discharge following fire increase. In contrast, moving from linear recovery to exponential recovery 1 and finally to exponential recovery 2 requires progressively greater annual increases in burn area to generate the 128 km^3 y^{-1} increase in discharge.

[33] The annual increases in burn area lead to long-term changes of as little as 4.4 Mha y^{-1} or as much as 111.7 Mha y^{-1} over 64 years depending on the specific scenarios and recovery times under consideration (Table 6). These rates are the equivalent of annually burning an additional 0.7% to 18% of Russia's boreal forest area at the end of a 64-year period as compared to the beginning. The upper end of this range is clearly unrealistic: Russia's forests are presently burning at a rate around 1–2% per year

Table 5. Average Surface Air Temperatures and Changes in Temperatures Between 1936 and 1995 for the Watersheds of the Six Largest Eurasian Arctic Rivers[a]

River	Long-Term Average Temperature, °C	Temperature Change 1936–1995, °C	Value of p
Severnaya Dvina	+1.0	+0.33	0.56
Pechora	−3.1	+0.52	0.43
Ob'	−0.4	+1.37	0.004
Yenisey	−5.2	+1.37	0.004
Lena	−9.9	+1.17	0.02
Kolyma	−13.1	−0.03	0.95

[a] Temperature changes and p values are from regressions of temperature versus year. Averages and changes in temperature were calculated using the database of *New et al.* [2000].

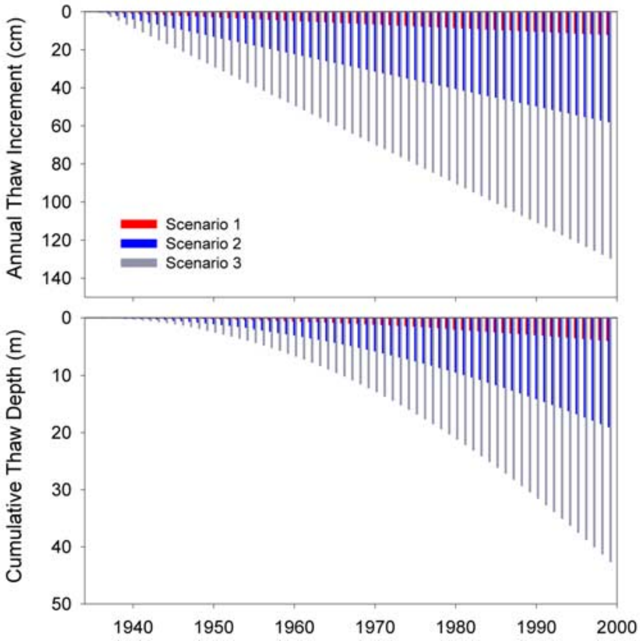

Figure 8. Permafrost thaw that would have been required to generate the observed long-term increase in Eurasian Arctic river discharge. (top) Amount of permafrost that would have had to thaw and completely drain into rivers in a given year and (bottom) cumulative depth of permafrost thaw. Scenario 1 means all permafrost areas are thawing, scenario 2 means all areas except continuous permafrost areas are thawing, and scenario 3 means only sporadic and isolated permafrost areas are thawing.

[*Conard and Ivanova*, 1997; *Conard et al.*, 2002], and changes in burn rates must be less than total present rates. There are conditions, however, where required changes in burn rates drop below the 2% threshold for each recovery scenario. Assuming a peak increase in discharge of two thirds in the first year after each fire, values drop below the 2% threshold when discharge recovery times exceed 15, 23, and 35 years for the linear recovery, exponential recovery 1, and exponential recovery 2 scenarios, respectively (Figure 9). The recovery times required for each scenario to drop below the 2% threshold double if a maximum increase in discharge of one third in the first year after each fire is assumed.

[34] Out of the subset of conditions where required changes in burn rates between the beginning and the end of the record are below 12.4 Mha y^{-1} (2% of Russia's boreal forest area per year), are any of the combinations of discharge recovery times and shapes realistic? Results from studies in boreal forests of Canada [*Bayley et al.*, 1992; *Schindler et al.*, 1980] suggest that the answer to this question is no. The Canadian studies report discharge recovery times between 3 and 10 years following fires (Figure 9). Within this 3- to 10-year timescale for discharge recovery none of the scenarios that we examined can realistically produce changes in discharge that match those observed between 1936 and 1999.

[35] It is possible that average discharge recovery times for boreal forests fall outside the 3- to 10-year range defined by the Canadian studies [*Bayley et al.*, 1992; *Schindler et al.*, 1980]. Evaluations of the fire-discharge relationship in boreal forests are few relative to the vast region they represent, and discharge recovery times of 10–30 years have been reported for some temperate forests after disturbance [*Bormann and Likens*, 1979; *Burt and Swank*, 2002; *Swank and Douglass*, 1974]. On the other hand, unique hydrologic characteristics of boreal forests are consistent with relatively short discharge recovery times in comparison with temperate forests. First, the fraction of evapotranspiration coming from understory vegetation and the forest floor is much higher in boreal forests as compared to temperate forests [*Baldocchi et al.*, 2000]. Understory vegetation becomes reestablished relatively quickly and thus facilitates a rapid return of discharge to prefire levels. Second, whereas annual evapotranspiration is higher in evergreen conifer forests than in deciduous broad-leafed

Table 6. Increases in the Area of Russian Boreal Forest Burned Under Different Runoff Recovery Scenarios to Produce the 128 km^3 yr^{-1} Increase in Eurasian Arctic River Discharge Measured Over the Period From 1936 to 1999

	Annual Increase in Burn Rate, Mha yr^{-1}		Increase in Annual Burn Rate Over 64 Years, Mha yr^{-1}	
Runoff Recovery Scenarios Following Fire	Maximum Increase in Discharge of 1/3	Maximum Increase in Discharge of 2/3	Maximum Increase in Discharge of 1/3	Maximum Increase in Discharge of 2/3
Linear recovery				
5 years	1.015	0.507	64.9	32.5
10 years	0.571	0.286	36.6	18.3
20 years	0.316	0.158	20.2	10.1
40 years	0.182	0.091	11.6	5.8
64 years	0.137	0.068	8.7	4.4
Exponential recovery 1				
5 years	1.35	0.675	86.4	43.2
10 years	0.783	0.391	50.1	25.1
20 years	0.44	0.22	28.2	14.1
40 years	0.251	0.125	16	8
64 years	0.181	0.09	11.6	5.8
Exponential recovery 2				
5 years	1.746	0.873	111.7	55.9
10 years	1.074	0.537	68.7	34.4
20 years	0.616	0.308	39.4	19.7
40 years	0.349	0.175	22.3	11.2
64 years	0.245	0.122	15.7	7.8

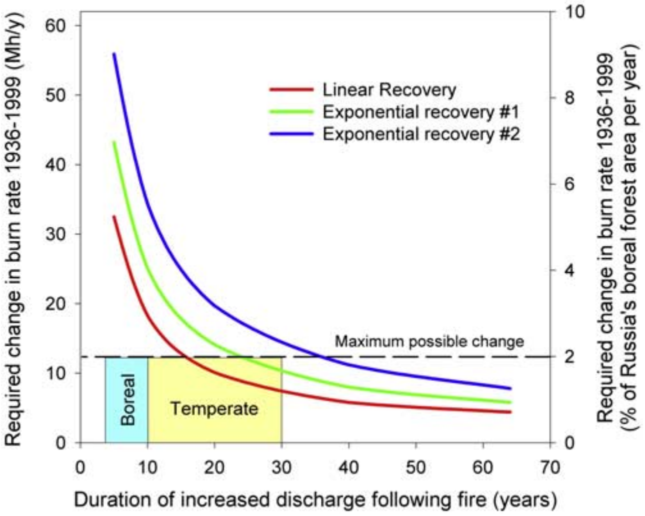

Figure 9. Changes in burn rates of Russian boreal forest that would have been required to produce the observed increase in Eurasian Arctic river discharge between 1936 and 1999, assuming a peak increase in annual discharge of two thirds in the first year following fire. Values are plotted as a function of discharge recovery time. Percentages on the right-hand *y* axis were calculated assuming 620 Mha of boreal forest [*Conard and Ivanova*, 1997]. The "maximum possible change" sets the historical burn rate at zero and thus reflects the present burn rate. The "boreal" and "temperate" windows show ranges of estimated discharge recovery times following fire for the two forest types.

forests of some temperate regions [*Meuser*, 1990; *Swank and Douglass*, 1974], this is unlikely in boreal regions because low temperatures inhibit year-round evapotranspiration [*Baldocchi et al.*, 2000]. As a consequence, evapotranspiration after a fire can return to or even exceed prefire values during succession through a deciduous phase in boreal regions. We therefore consider the relatively short discharge recovery times reported in the Canadian studies [*Bayley et al.*, 1992; *Schindler et al.*, 1980] to be typical of boreal forests in general.

[36] While increased recovery times reduce the change in annual burn rate required to generate the observed long-term trends in discharge, return of fires to previously burned areas has the opposite effect. Discharge from the previously burned areas increases, but overall discharge decreases relative to burning virgin regions because the amount of new area contributing excess water is less. This dynamic is not included in our scenarios, though fire return intervals in some of Siberia's forests are between 25 and 50 years [*Arbatskaya and Vaganov*, 1997; *Conard and Ivanova*, 1997; *Swetnam*, 1996]. Thus we have probably underestimated the changes in annual burn rates required to generate the observed discharge increases between 1936 and 1999.

[37] Given the long discharge recovery times needed to support realistic changes in burn area, we conclude that increased fires are very unlikely to have significantly contributed to the observed increases in Eurasian Arctic river discharge between 1936 and 1999. A doubling in the area burned per year between the 1970s and the late 1990s in the boreal forest of western Canada demonstrates the potential for dramatic change [*Murphy et al.*, 2000]. Even a change of this magnitude, however, would not have been enough to generate the observed increase in Eurasian Arctic river discharge if runoff recovery times were <30 years: Assuming that Russia's boreal forest is burning at a rate of 2% per year at present (the upper end of recent estimates), a doubling would only amount to half of the maximum possible change shown in Figure 9.

[38] While the shape of a "typical" discharge recovery curve following fire is difficult to define, studies in both boreal and temperate forests show relatively fast discharge recovery in the early years after disturbance [*Bayley et al.*, 1992; *Bormann and Likens*, 1979; *Burt and Swank*, 2002; *Schindler et al.*, 1980; *Swank and Douglass*, 1974]. Thus discharge recoveries after fires in Russia's boreal forest are probably best approximated by the exponential recovery scenarios. The fact that our modeling approach provides low-side estimates of required increases in burn area makes it still less likely that increased burning has been a significant driver of the long-term changes in discharge.

[39] The potential influence of other land cover changes on river discharge from the major Eurasian Arctic watersheds would also be interesting to evaluate. In particular, timber harvest has been suggested as an important consideration. In Siberia, 410×10^6 m^3 yr^{-1} of wood, representing the cutting of ~4 Mha yr^{-1} of forest, were being harvested by the late 1980s [*Rosencranz and Scott*, 1992]. However, logging dropped off sharply after the collapse of the Soviet Union in 1991 and was still only at about one third of its previous level by 1998 [*Ovaskainen et al.*, 1999]. This temporal pattern does not match that of the Eurasian Arctic river discharge, which continued to rise in the 1990s [*Peterson et al.*, 2002].

4. Summary and Conclusions

[40] The 128 km^3 yr^{-1} increase in Eurasian Arctic river discharge between 1936 and 1999 cannot be explained by dams, permafrost thaw, or increases in fires. Construction of major dams and subsequent regulation of river flow in the watersheds of the Ob', Yenisey, Lena, and Kolyma has dramatically altered the seasonality of discharge but is not responsible for increases in annual discharge values. In fact, comparison of measured discharge to reconstructed records (dam effects removed) suggests that long-term increases in discharge actually would have been greater in the absence of dams. Both thawing of permafrost and increased fires may have contributed to the long-term changes in discharge, but neither can be considered a major driver. The lack of correlation between percent permafrost area and change in annual runoff in the six major Eurasian Arctic watersheds, including a relatively large increase in runoff from the Severnaya Dvina which has no permafrost, shows that thawing of permafrost does not provide an overarching explanation for changes in discharge. Furthermore, calculations show that the cumulative thaw depths required to produce 128 km^3 yr^{-1} of extra water over 64 years are unreasonable: Even if all of the water from thawing permafrost were converted to discharge, a minimum of 4 m thawed evenly across the combined permafrost area of the six major Eurasian Arctic watersheds would have been required. Similarly, sensitivity analysis shows that the

increases in annual area burned by fires that would have been necessary to drive the long-term changes in river discharge are unreasonably high. Required changes in annual burn rates vary widely among model scenarios, but considering relatively short discharge recovery times most likely for boreal forests, none of the scenarios can produce enough water to drive the observed change in discharge without greatly exceeding present burn rates.

[41] It might intuitively be expected that increases in evapotranspiration accompanying warming within the Arctic would work against the observed increase in river discharge. However, model simulations show that with most of the warming occurring in the long winter months, the impact on annual evapotranspiration (winter sublimation plus summer evapotranspiration) is significantly less than it would have been if the warming were uniformly distributed throughout the year [*Stieglitz et al.*, 2000]. In fact, these simulations show that enhanced annual evapotranspiration is easily accommodated by an associated increase in precipitation. Our ''naturalized'' streamflow data for the large Eurasian Arctic rivers corroborate these findings: Drying of the landscape implied by substantial decreases in summer discharge is largely an artifact of flow regulation following dam construction rather than an actual drying of the landscape. The absence of a strong drying effect has important implications for carbon sequestration and greenhouse gas emissions in the next century. Simulations have shown that warming without a concomitant drying in the soil moisture will most likely enhance carbon sequestration through increased soil nitrogen mineralization, enhanced net photosynthesis, and depending on region, a shift in species composition from low carbon to nitrogen (C/N) species to high C/N species [*McKane et al.*, 1997; *Stieglitz et al.*, 2000].

[42] Acceleration of the global hydrologic cycle as predicted by global circulation models in global warming scenarios [*IPCC*, 2001] remains the most plausible explanation for the long-term increases in discharge. In particular, increased net atmospheric moisture transport from lower to higher latitudes in a warming climate provides a robust mechanism for the observed increases in discharge. Annual precipitation data from the major watersheds of the Eurasian Arctic do not show clear long-term trends [*Serreze et al.*, 2003]. However, the required change may well be too small to detect: Mean annual precipitation onto the watersheds of the six largest Eurasian Arctic rivers would only have had to increase from 40.6 to 43.6 cm over 64 years to account for the observed increase in discharge (the average runoff/precipitation ratio for the six watersheds is 0.46). Coverage by precipitation gauges in Eurasia is sparse above 50°N, and quantification of snowfall is notoriously difficult [*Serreze et al.*, 2003; *Yang et al.*, 2001]. This uncertainty makes detection of such small changes in precipitation unlikely.

[43] While precipitation data from northern Eurasia alone are inconclusive, other lines of evidence certainly suggest that net atmospheric moisture transport to the Arctic is increasing. Analyses of combined precipitation data for the area between 55° and 85°N show a clear increase over the 20th century [*IPCC*, 2001; *Kattsov and Walsh*, 2000; *Serreze et al.*, 2000]. The observed trend represents an approximate 12% change in precipitation [*IPCC*, 2001]. When scaled to a 64-year period, this change is very similar to the 7% increase in Eurasian Arctic river discharge observed between 1936 and 1999. Further evidence of increasing net atmospheric moisture transport to the Arctic comes from oceanographic records of salinity [*Curry et al.*, 2003]. *Curry et al.* [2003] analyzed salinity along a transect in the Atlantic Ocean from 50°S to 60°N and found systematic freshening at both poleward ends of the transect over the past 4 decades. Salinity increased at lower latitudes over the same time period. These findings are particularly compelling because they show not only freshening in the north that is consistent with increased precipitation but also that the additional moisture is most likely coming from lower latitudes.

[44] Identifying the mechanisms behind increases in Arctic river discharge is of critical importance for projecting changes into the future. If changes are indeed coupled to increased atmospheric moisture transport in a warming climate, then there may be enough extra discharge within this century to significantly slow or even halt Atlantic thermohaline circulation [*Peterson et al.*, 2002]. On the other hand, the trajectory of future discharge could be very different under the control of another driver. This paper explores three alternative drivers that have been suggested frequently since the long-term changes in Eurasian Arctic river discharge were reported, and it finds each lacking. In contrast, understanding the relationship between global precipitation patterns and Arctic river discharge in a warming climate remains a high priority.

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