

Increasing River Discharge to the Arctic Ocean

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Synthesis of river-monitoring data reveals that the average annual discharge of fresh water from the six largest Eurasian rivers to the Arctic Ocean increased by 7% from 1936 to 1999. The average annual rate of increase was 2.0 ± 0.7 cubic kilometers per year. Consequently, average annual discharge from the six rivers is now about 128 cubic kilometers per year greater than it was when routine measurements of discharge began. Discharge was correlated with changes in both the North Atlantic Oscillation and global mean surface air temperature. The observed large-scale change in freshwater flux has potentially important implications for ocean circulation and climate.

The Arctic is expected to be disproportionately affected by global warming, and the Arctic in turn may exert strong feedback on global climate (1). Many of the linkages between the arctic system and global climate involve the hydrologic cycle, including atmospheric moisture transport from lower to higher latitudes (2). This transport of moisture is predicted to increase with warming (1); both theoretical arguments and models suggest that net high-latitude precipitation increases in proportion to increases in mean hemispheric temperature (3, 4). At the same time, freshening of the Arctic Ocean is expected to reduce North Atlantic Deep Water (NADW) formation and Atlantic thermohaline circulation (THC) (3–6).

Global surface air temperature (SAT) has increased $0.6^\circ \pm 0.2^\circ\text{C}$ over the past century (1). Thus, one might expect that net moisture transport into the pan-arctic drainage basin (Fig. 1) is already increasing. Are such changes detectable in historical data sets? Arctic river discharge is particularly useful for addressing this question, because it provides an integrative measure of the continental water balance. The pan-arctic drainage covers $22.4 \times 10^6 \text{ km}^2$ (7), an area ~ 1.5 times that of the Arctic Ocean. Consequently, the Arctic Ocean is the most land-dominated of ocean basins. Net precipitation (precipitation minus evaporation) over the pan-arctic drainage is recorded in river discharge, the majority of which is routed to the Arctic

Ocean through a handful of very large and well-monitored rivers (8).

Evidence of increasing arctic river discharge has been reported in several recent publications, with changes most evident during the low-flow period from November through April (7, 9–11). However, analyses of trends have emphasized different time periods and areas of the Arctic (12). Thus, it has been difficult to generalize about temporal trends in discharge to the Arctic Ocean. In particular, high interannual variation makes it difficult to discern trends over shorter time periods. Discharge records for downstream stations on major North American arctic rivers extend back only a few decades, whereas gauging of major Eurasian arctic rivers generally began in the 1930s. The longer records pro-

vide the best opportunity for detecting change. Here we identify long-term trends in discharge from major Eurasian rivers to the Arctic Ocean and evaluate their possible links to climate variability.

Total river inflow to the Arctic Ocean is dominated by contributions from Eurasia (Fig. 1). The six largest Eurasian arctic rivers (Yenisey, Lena, Ob', Pechora, Kolyma, and Severnaya Dvina) drain about two-thirds of the Eurasian arctic landmass and include three of the largest rivers on Earth. Over the period of record (from 1936 to 1999), aggregate annual discharge from the six largest Eurasian arctic rivers shows a significant positive trend (Fig. 2). The average annual rate of increase was $2.0 \pm 0.7 \text{ km}^3/\text{year}$. Thus, average annual discharge is now about $128 \text{ km}^3/\text{year}$ (0.004 sverdrup) greater than it was when routine measurements of discharge from the major Eurasian arctic rivers began in the 1930s. This amounts to an approximate 7% increase in discharge. Although long-term trends in discharge are difficult to detect in the individual rivers (fig. S1), the additive effect of discharge increases in these rivers results in a strong signal of change at the scale of the Eurasian Arctic as a whole (13).

Correspondence between Eurasian river discharge and the North Atlantic Oscillation (NAO) suggests that the rivers are responding to changes in large-scale hemispheric climate patterns (Fig. 3). This relationship is consistent with the report by Serreze *et al.* (14) that cyclone abundance and intensity in the North Atlantic have increased in parallel with the ramping-up of the NAO over the past few decades. Furthermore, Dickson *et al.* (15)



Fig. 1. Map of the pan-arctic watershed showing catchments and average annual discharge of the major Eurasian rivers that contribute water to the Arctic Ocean. Generalized NADW source locations in the Greenland-Iceland-Norwegian and Labrador seas are indicated by red dots.

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provide a spatial analysis of precipitation that indicates that high-NAO years are characterized by positive precipitation anomalies that are greatest in Scandinavia but extend across Siberia to the Lena River watershed. Whether the recent NAO trend is a response to global warming is unknown (15, 16).

Increases in discharge also correspond

to increases in global, pan-arctic, and Eurasian arctic SATs (14). Over the period of the discharge record, global SAT increased by 0.4°C, pan-arctic SAT increased by 0.6°C, and Eurasian arctic SAT increased by 0.7°C (17). Although temperature increases at these different scales are all interrelated, the most appropriate relationship for considering increased moisture trans-

port from lower to higher latitudes is between global SAT and river discharge (Fig. 3). Such a linkage has been predicted by several general circulation models (GCMs) and arctic hydrologic models (18–20).

Regression analysis of discharge against global SAT using annual data from 1936 to 1999 identified a positive relationship (Fig. 4). The slope in Fig. 4 (0.007 sverdrup/°C) provides an empirical estimate of a major component of the Atlantic hydrologic sensitivity parameter (HSP); the Atlantic HSP describes the amount of additional freshwater predicted to enter the Arctic Ocean/Atlantic Ocean north of 50°N per °C of global warming (21). Hydrologic sensitivity is the main control variable that determines the future response of THC. It is also one of the largest sources of uncertainty in predicting this response, because hydrologic sensitivity is, at the moment, poorly constrained by observations.

GCM predictions of future changes in global SAT are reasonably well constrained (1). Consequently, GCM estimates of global SAT provide a tool for projecting discharge trends into the future. The Intergovernmental Panel on Climate Change (IPCC) (1) projects a global SAT rise between 1.4° and 5.8°C by 2100. Thus, at a rate of 0.007 sverdrup/°C (Fig. 4), discharge from the six largest Eurasian arctic rivers alone would increase by 0.01 to 0.04 sverdrup (315 to 1260 km³/year) by 2100. This would represent an 18 to 70% increase in Eurasian arctic river discharge over present conditions. A comparable increase in Eurasian arctic river discharge (~35%) has been predicted by the NASA Goddard Institute for Space Studies GCM in response to a twofold increase in atmospheric CO₂ (~4°C global warming) (22, 23).

Changes in river discharge of this magnitude are potentially important with respect to NADW formation. Increases in discharge from other arctic rivers (24), net precipitation directly over the ocean, and meltwater from Greenland would provide additional freshwater forcing (25). Freshwater sensitivity experiments with a range of ocean and climate models predict a critical bifurcation point between 0.06 and 0.15 sverdrup of additional freshwater entering the northern Atlantic, after which NADW formation cannot be sustained (5, 6, 26–28). Although the extrapolation of arctic river discharge presented here should not be regarded as a prediction, it does highlight the potential importance of arctic river discharge as a feedback on Atlantic THC within the 21st century. Thus, it is particularly urgent now to increase our understanding of the coupled land, ocean, and atmospheric components of the arctic hydrologic cycle.

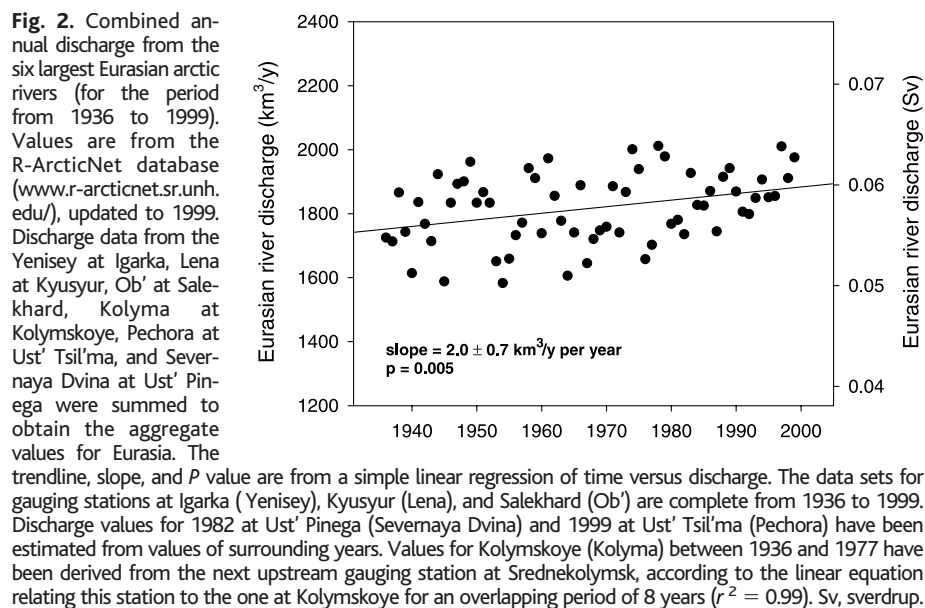


Fig. 3. Ten-year running averages of the Eurasian arctic river discharge anomaly, winter (December through March) NAO index, and global mean SAT for 1936 to 1999. "Anomaly" refers to variation from the long-term mean. NAO data were taken from www.cgd.ucar.edu/~jhurrell/nao.html, and temperature data are from www.giss.nasa.gov/data/update/gistemp/.

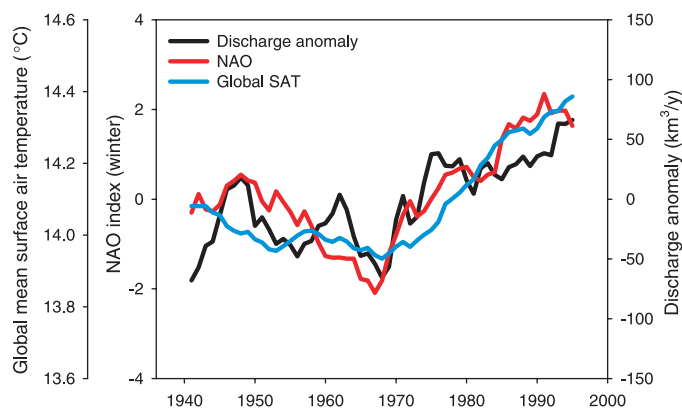
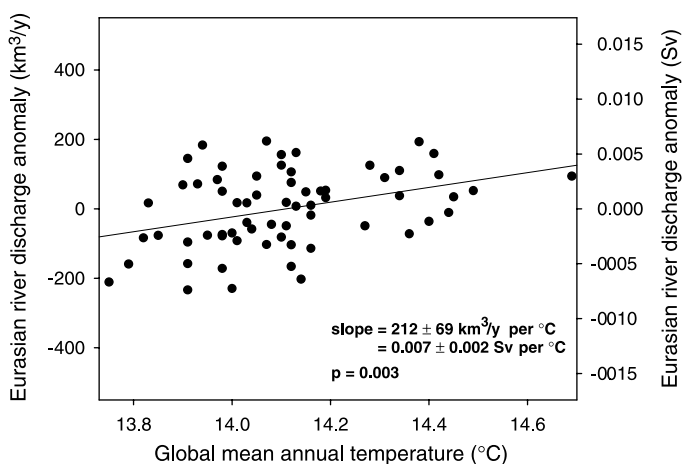


Fig. 4. Annual Eurasian arctic river discharge anomaly versus global surface air temperature (from 1936 to 1999).



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- The Russian Federal Service for Hydrometeorology and Environment Monitoring (Roshydromet) monitors the discharge of Russian arctic rivers. We have compiled and digitized this database, which is available on our Web site (www.r-arcticnet.sr.unh.edu/) and from the National Snow and Ice Data Center (<http://nsidc.org>). The downstream stations from which the data in this paper come have been monitored almost continuously from 1936 to 1999, despite a general decline in the arctic hydrologic monitoring network that began in the mid 1980s (29). Roshydromet considers these stations to be of primary importance because of their proximity to the ocean. Stage height readings to the nearest centimeter were made daily, and cross-channel measurements of discharge for rating curve calibrations were made 25 to 30 times per year in each river. With these frequent calibrations, estimates of daily discharge from the rating curves were accurate to $\pm 5\%$.
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- HSP is defined in (4). In addition to river runoff, the Atlantic HSP includes meltwater from sea and continental ice and precipitation minus evaporation ($P - E$) over the ocean. The difference between basing hydrologic sensitivity on global or hemispheric temperature is small, because in greenhouse gas-induced warming, both hemispheres warm by similar amounts. When linking hydrologic changes to local temperature, such as for Greenland, one needs to take into account that local warming over Greenland could be twice the global mean; a $\sim 10\%$ accumulation increase per $^{\circ}\text{C}$ of local warming over Greenland, as found in Greenland Ice Core Project and Greenland Ice Sheet Project 2 ice core data, is then consistent with the slope shown in Fig. 4.
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- It is difficult to discern long-term trends for major North American arctic rivers, because discharge records from downstream gauging stations are relatively short (~ 25 to 35 years). Regression analyses of Mackenzie (at Arctic Red) and Yukon (at Pilot Station) discharge records produces slopes of $+0.6 \text{ km}^3/\text{year}$ and $-0.1 \text{ km}^3/\text{year}$ for the two rivers, respectively, but neither is a statistically significant result. However, temperature trends over North America that are similar to Eurasian trends over the past century support potential arctic-wide increases in river discharge (30).
- Modeling studies predict substantial increases in freshwater contributions from the Greenland ice sheet (31, 32). Although arctic glaciers and sea ice are much smaller in volume than the Greenland ice sheet, additional freshwater could be derived from their meltdown (33, 34). Finally, $P - E$ over the Arctic Ocean appears to have increased over the past century and is expected to continue to increase in the future (19).
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Supporting Online Material

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Fig. S1

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Soil Warming and Carbon-Cycle Feedbacks to the Climate System

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In a decade-long soil warming experiment in a mid-latitude hardwood forest, we documented changes in soil carbon and nitrogen cycling in order to investigate the consequences of these changes for the climate system. Here we show that whereas soil warming accelerates soil organic matter decay and carbon dioxide fluxes to the atmosphere, this response is small and short-lived for a mid-latitude forest, because of the limited size of the labile soil carbon pool. We also show that warming increases the availability of mineral nitrogen to plants. Because plant growth in many mid-latitude forests is nitrogen-limited, warming has the potential to indirectly stimulate enough carbon storage in plants to at least compensate for the carbon losses from soils. Our results challenge assumptions made in some climate models that lead to projections of large long-term releases of soil carbon in response to warming of forest ecosystems.

The acceleration of global warming due to terrestrial carbon-cycle feedbacks may be an important component of future climate change (1). Recent experiments with fully coupled, three-dimensional carbon-climate models suggest that carbon-cycle feedbacks could substantially accelerate (2) or slow (3) climate change over the 21st century. Both the sign and magnitude of these feedbacks in

the real Earth system are still highly uncertain because of gaps in basic understanding of terrestrial ecosystem processes (2, 3). For example, the potential switch of the terrestrial biosphere from its current role as a carbon sink (4, 5) to a carbon source is critically dependent upon the long-term sensitivity to global warming of the respiration of soil microbes, which is still a subject of debate (6–8). Here we present results from a long-term (10-year) soil warming experiment designed to explore this feedback issue in an ecosystem context.

We began our soil warming study in April 1991, in an even-aged mixed hardwood forest stand at the Harvard Forest in central Massachusetts (42.54°N, 72.18°W). Dominant tree

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