A circumpolar perspective on fluvial sediment flux to the Arctic ocean

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A circumpolar perspective on fluvial sediment flux to the Arctic Ocean

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Quantification of sediment fluxes from rivers is fundamental to understanding land-ocean linkages in the Arctic. Numerous publications have focused on this subject over the past century, yet assessments of temporal trends are scarce and consensus on contemporary fluxes is lacking. Published estimates vary widely, but often provide little accessory information needed to interpret the differences. We present a pan-arctic synthesis of sediment flux from 19 arctic rivers, primarily focusing on contributions from the eight largest ones. For this synthesis, historical records and recent unpublished data were compiled from Russian, Canadian, and United States sources. Evaluation of these data revealed no long-term trends in sediment flux, but did show stepwise changes in the historical records of two of the rivers. In some cases, old values that do not reflect contemporary fluxes are still being reported, while in other cases, typographical errors have been propagated into the recent literature. Most of the discrepancy among published estimates, however, can be explained by differences in years of records examined and gauging stations used. Variations in sediment flux from year to year in arctic rivers are large, so estimates based on relatively few years can differ substantially. To determine best contemporary estimates of sediment flux for the eight largest arctic rivers, we used a combination of newly available data, historical records, and literature values. These estimates contribute to our understanding of carbon, nutrient, and contaminant transport to the Arctic Ocean and provide a baseline for detecting future anthropogenic or natural change in the Arctic.


1. Introduction

Concerns about global warming have stimulated a wide range of polar research. This research is motivated in part because climate change models predict greatest temperature changes in the future in polar regions [Houghton et al., 1996], and because polar systems may be particularly sensitive to change [Oppenheimer, 1998; Serreze et al., 2000]. Thus, polar ecosystems should provide early indications of anthropogenic influence on climate.

Examination of inputs from arctic rivers (Figure 1) to the ocean has been proposed as a means for tracking the effects of climate change because fluxes from rivers provide an integrative signal of processes occurring in their watersheds. Most attention has been paid to the flux of fresh water (Table 1), where relatively complete long-term data sets are available and changes in climate are expected to influence annual flux and/or seasonality of inputs [Aagaard and Carmack, 1989; Lammers et al., 2001; Shiklomanov et al., 2000]. Constituent fluxes in rivers, including nutrients, organic matter, and suspended sediments may also be sensitive to global change [Gordeev et al., 1996], but in general, constituent data sets have received less attention. In part, this lack of attention is because constituent data sets are relatively sparse compared to water discharge databases, and also because quality control problems have been identified in constituent data sets for some arctic rivers [Holmes et al., 2000, 2001; Zhulidov et al., 2000].

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Our overall objective is to provide a pan-arctic synthesis addressing sediment flux from large rivers toward the Arctic Ocean. We primarily focus on the eight largest rivers (by water discharge) in the pan-arctic watershed, namely the Yenisey, Lena, Ob', Mackenzie, Yukon, Pechora, Kolyma, and Severnaya Dvina rivers (Figure 1 and Table 1). Although the Yukon River does not discharge directly into the Arctic Ocean, it is included here because it makes major contributions of freshwater to the Arctic Ocean via prevailing ocean currents [Guay and Falkner, 1997; Jones et al., 1998]. We begin with a review and synthesis of available information on methods of sample collection and approaches to flux calculations that have been used for these rivers, and then present graphically the sediment data sets that we have been able to compile for each river from published and unpublished sources. Using these sediment concentration and flux time series, we investigate the reasons for sometimes conflicting flux estimates in the literature, including the use of different time periods of data and/or data from different sampling locations on a given river. Finally, to the extent that available data allow, we provide best estimates of current sediment transport in the lower reaches of these eight rivers and consider whether there is evidence that sediment flux has changed significantly over the period of record. We also briefly address sediment flux from 10 smaller Russian Arctic rivers.

2. Sediment Sampling and Flux Calculations

 Guidelines for suspended sediment sampling and flux calculations prescribed by the major government agencies in Russia, Canada, and the United States that are responsible for monitoring river discharge and water quality are discussed below. The accuracy of sediment flux estimates, of course, depends on a variety of factors from how carefully samples are collected to how well sampling frequency and distribution capture the variability of the system. In most cases, information on these factors is not available for individual arctic rivers. This makes it difficult to retrospectively assess error associated with sediment flux estimates for the different rivers. The descriptions below do, however, allow a broad comparison of similarities and differences between sampling and data handling approaches.

Table 1. Average Annual Water Discharge for the Eight Largest Rivers in the Pan-Arctic Watershed

<table>
<thead>
<tr>
<th>River</th>
<th>Gauging Station</th>
<th>Drainage Area Above Gauging Station, 10⁶ km²</th>
<th>Mean Annual Discharge, km³/yr</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yenisey</td>
<td>Igarka</td>
<td>2.44</td>
<td>580 (620)</td>
</tr>
<tr>
<td>Lena</td>
<td>Kysyur</td>
<td>2.43</td>
<td>528 (530)</td>
</tr>
<tr>
<td>Ob'</td>
<td>Salekhard</td>
<td>2.99</td>
<td>402 (404)</td>
</tr>
<tr>
<td>Mackenzie</td>
<td>Arctic Red</td>
<td>1.68</td>
<td>281 (307)</td>
</tr>
<tr>
<td>Yukon</td>
<td>pilot station</td>
<td>0.83</td>
<td>203 (205)</td>
</tr>
<tr>
<td>Pechora</td>
<td>Ust’ Tsil’ma</td>
<td>0.25</td>
<td>108 (141)</td>
</tr>
<tr>
<td>Kolyma</td>
<td>Kolymskoe</td>
<td>0.53</td>
<td>103 (132)</td>
</tr>
<tr>
<td>Severnaya Dvina</td>
<td>Ust’ Pingea</td>
<td>0.35</td>
<td>105 (105)</td>
</tr>
</tbody>
</table>

*Values are calculated using monthly discharge data as given in the R-ArcticNet database (www.r-arcticnet.sr.unh.edu) for the listed gauging stations. Values shown parenthetically include estimates of contributions from the entire watershed including nongauged areas.
that may contribute to differences between sediment flux estimates.

2.1. Russian Arctic Rivers

The vast majority of sediment flux estimates for Russian arctic rivers are derived from data collected by the Russian Federal Service for Hydrometeorology and Environmental Monitoring (Roshydromet). In various papers, data have been attributed to sources such as the Leningrad (St. Petersburg) Hydrometeorological Service, Hydrological Year Books, and State Hydrological Institute (SHI). In each case, however, the database appears to be the same. The different names correspond to different years of the record, and/or identification of the data source with differing degrees of specificity. Sampling programs for suspended sediments were started between 1935 and 1966 for different rivers.

Methods of measurements of sediment concentration and discharge have been developed at the Laboratory of Sediments and Erosion within SHI. Guidelines for sampling from large Russian rivers call for daily collection of a single sample at a specific depth during low flow and twice daily

<table>
<thead>
<tr>
<th>Reference</th>
<th>Yenisey</th>
<th>Lena</th>
<th>Ob</th>
<th>Mackenzie</th>
<th>Yukon</th>
<th>Kolyma</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Shamov [1949]</td>
<td>11.0</td>
<td></td>
<td></td>
<td>13.4</td>
<td></td>
<td>4.6b</td>
</tr>
<tr>
<td>2. Lopatin [1952]</td>
<td>11.0</td>
<td>13.4</td>
<td></td>
<td>4.6b</td>
<td></td>
<td>6.8b</td>
</tr>
<tr>
<td>3. Samoilov [1952]</td>
<td>11.0</td>
<td></td>
<td>12.0b</td>
<td>13.5b</td>
<td></td>
<td>6.8b</td>
</tr>
<tr>
<td>4. Doronina [1962]</td>
<td></td>
<td></td>
<td>11.8</td>
<td></td>
<td>6.8b</td>
<td></td>
</tr>
<tr>
<td>5. Lisitzin [1966]</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>6.8b</td>
<td></td>
</tr>
<tr>
<td>7. Lisitzin [1972]</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>6.8b</td>
<td></td>
</tr>
<tr>
<td>14. Thomas et al. [1986]</td>
<td></td>
<td>15</td>
<td></td>
<td>6.8b</td>
<td>6.8b</td>
<td>6.8b</td>
</tr>
<tr>
<td>16. Hirst et al. [1987]</td>
<td></td>
<td>15</td>
<td></td>
<td>6.8b</td>
<td>6.8b</td>
<td>6.8b</td>
</tr>
<tr>
<td>17. Hill et al. [1991]</td>
<td></td>
<td>15</td>
<td></td>
<td>6.8b</td>
<td>6.8b</td>
<td>6.8b</td>
</tr>
<tr>
<td>18. Telang et al. [1991]</td>
<td></td>
<td>15</td>
<td></td>
<td>6.8b</td>
<td>6.8b</td>
<td>6.8b</td>
</tr>
<tr>
<td>22. Gordeev et al. [1996]</td>
<td></td>
<td>15</td>
<td></td>
<td>6.8b</td>
<td>6.8b</td>
<td>6.8b</td>
</tr>
<tr>
<td>23. Rachold et al. [1996]</td>
<td></td>
<td>15</td>
<td></td>
<td>6.8b</td>
<td>6.8b</td>
<td>6.8b</td>
</tr>
<tr>
<td>25. AMAP [1997]</td>
<td></td>
<td>15</td>
<td></td>
<td>6.8b</td>
<td>6.8b</td>
<td>6.8b</td>
</tr>
<tr>
<td>27. Carson et al. [1998]</td>
<td></td>
<td>15</td>
<td></td>
<td>6.8b</td>
<td>6.8b</td>
<td>6.8b</td>
</tr>
<tr>
<td>32. Are and Reimnitz [2000]</td>
<td></td>
<td>15</td>
<td></td>
<td>6.8b</td>
<td>6.8b</td>
<td>6.8b</td>
</tr>
<tr>
<td>33. Rachold et al. [2000]</td>
<td></td>
<td>15</td>
<td></td>
<td>6.8b</td>
<td>6.8b</td>
<td>6.8b</td>
</tr>
<tr>
<td>34. Brabets et al. [2000]</td>
<td></td>
<td>15</td>
<td></td>
<td>6.8b</td>
<td>6.8b</td>
<td>6.8b</td>
</tr>
<tr>
<td>36. Rachold et al. [2000]</td>
<td></td>
<td>15</td>
<td></td>
<td>6.8b</td>
<td>6.8b</td>
<td>6.8b</td>
</tr>
</tbody>
</table>

References are in chronological order, and superscripts indicate relationships among the listed references. Lack of superscript indicates an original estimate calculated using data collected by Roshydromet (Russian rivers), Environment Canada (Mackenzie River), or the USGS (Yukon River), except where indicated by footnote. Where ranges are reported data are from multiple references, gauging stations, or time periods.

- References are in chronological order, and superscripts indicate relationships among the listed references. Lack of superscript indicates an original estimate calculated using data collected by Roshydromet (Russian rivers), Environment Canada (Mackenzie River), or the USGS (Yukon River), except where indicated by footnote. Where ranges are reported data are from multiple references, gauging stations, or time periods.
- According to A. P. Lisitzin (personal communication.), data from Russell [1890], Lopatin [1950], and Samoilov [1952] were used to derive this estimate.
- Although no source information is given by Lisitzin [1972], he reports the same sediment flux values in a later publication [Lisitzin, 1974], and cites Zalogin and Radionov [1969], Shubaev [1969], and Moore [1969] as the source of the estimates.
- Reported in original manuscript in short tons (1 metric ton = 1.102 short tons).
- From unpublished manuscript [Lewis, 1988].
- Was intended to read 142 Mt/yr as reported in an unpublished manuscript by J. P. M. Syvitski, but got mistyped.
- Estimate derived using combination of data from Roshydromet and Moscow State University.
- Bed load transport adds another 4 Mt/yr of sediment to the Mackenzie delta.
- Sum of model estimates for major delta channels.
collection of a single sample during high flow. During periods when suspended sediment concentrations are less than 100 g/m³, two samples are combined and processed as one. When sediment concentrations are less than 50 g/m³, single samples collected daily over a 5–10-day period are combined for processing. If concentrations are below 50 g/m³ for longer periods of time, sampling is stopped until water discharge begins to increase. From these samples, an average concentration for the river is calculated using an equation that relates the particular sampling location to the river cross section as a whole. The equation is derived and periodically checked by sampling across the river at several points to fill in large gaps in the historical databases. The information that we do have indicates that sediment rating curves are routinely used on the Ob' River at Salekhard. In addition, estimates for the Lena and Kolyma made by Magritsky [2001] used sediment rating curves to fill in large gaps in the historical databases.

2.2. Mackenzie River

Discharge of water and water-borne constituents to the Mackenzie delta have been monitored by Environment Canada since the early 1970s, and nearly all of the published estimates of sediment flux to the delta rely on the Environment Canada database. The monitoring network is maintained through a partnership between the federal and provincial governments. Some references identify Environment Canada directly, whereas others identify specific departments and initiatives of Environment Canada. Published estimates of inputs to the Mackenzie delta were derived using data from stations (1) in the Mackenzie River just above the confluence with the Arctic Red River, (2) in the Arctic Red River below Martin-house, and (3) in the Peel River at Fort McPherson. Where references refer to sediment discharge from the Mackenzie, it sometimes is unclear whether or not contributions from the Peel and/or Arctic Red were considered.

Samples of suspended sediments generally were depth integrated, being taken from a single vertical in the river cross section where flow and depth were maximum. Samples also occasionally were collected from the surface.
using 20 l carboys. A limited comparison of surface versus depth integrated samples indicated that surface samples yielded results within 20% of those obtained from depth integrated samples [Brunskill et al., 1975], although studies elsewhere have shown that the difference can be greater. Collections primarily focused on the open water period from May to October each year. During this time period, the goal was to collect at least one sample per month. Difficulties associated with break-up and ice formation periods, however, resulted in less sampling during some months than others. In particular, data for May are scarce. During winter months, sampling through the ice was restricted to once or twice per year.

[12] Data on water discharge are more complete. Daily measurements of water level were generally recorded year-round. Flow was calculated from these data using a stage-discharge rating curve that was verified with direct flow measurements several times per year.

[13] Annual sediment discharge was estimated either directly or with sediment rating curves. Direct estimates involved calculation of monthly sediment discharge from average sediment concentration and water discharge for each month. Annual sediment discharge was then the sum of the monthly sediment discharges. In some instances, a seasonal mean concentration was used for months during which no concentration was measured. For the sediment rating curves, log(Concentration) was plotted against log(water discharge) using existing data. From this relationship, daily mean suspended sediment concentrations were derived. These data were then used along with daily water discharge to calculate annual sediment discharge. Most references for the Mackenzie do not give specific information on data analysis, and hence it is difficult to determine if one or both approaches were used. As a general trend, however, it appears that early estimates were derived directly, while later estimates rely more heavily on sediment rating curves. Carson et al. [1998] provide a rare example where data handling is clearly described and errors of measurement and calculation are frankly discussed. In their case, estimates are derived from a combination of the two approaches.

2.3. Yukon River

[14] In the upstream Canadian portion of the Yukon basin, suspended sampling began in 1970 by Environment Canada, whereas sampling was initiated by the United States Geological Survey (USGS) at selected sites in the US part of the Yukon in 1953 [Brabets et al., 2000]. However, suspended sediment sampling at the downstream-most sampling station (Pilot Station) did not begin until late in 1975. Periodic sampling by the USGS at Pilot Station continued until 1996, and approximately 70 suspended sediment measurements were made at Pilot Station during this period. The majority of data are from summer months, with few samples being collected during the period when the river is frozen over and none collected during May or November. No discharge or water quality sampling was done at Pilot Station from 1997 to 2000, but in 2001 the USGS NASQN program resumed sampling at Pilot Station.

[15] According to USGS guidelines, suspended sediment concentration measurements are made by collecting a series of depth-integrated verticals across the stream channel. Mean discharge-weighted suspended sediment concentration in the river cross section was then determined by taking the average concentration of these verticals. Mean suspended sediment concentrations determined in this way, as well as daily water discharge values, are available free of charge from USGS at http://water.usgs.gov/nwis.

3. Data

[16] Our objective here is to present the data used to generate the sediment flux estimates in Table 2 and to provide more recent data where available. In most cases, the data are presented in a far more fundamental form than available in previous publications. Examination of the data at this level of detail is meant to help resolve conflicting flux estimates, allow assessment of interannual variability, and facilitate estimation of contemporary fluxes.

[17] Water discharge monitoring on downstream reaches of arctic rivers began much earlier in the former Soviet Union than in North America (Figure 2). Gauging began in the 1930s on the Yenisey at Igarka, Lena at Kyusyur, Ob’ at Salekhard, Kolyma at Srednekolymsk, and Pechora at Ust’ Tsil’ma, and extends all the way back to 1881 for the Severnaya Dvina at Ust’ Pinea. For the Mackenzie River, discharge measurements began in 1972 at the village of Arctic Red (Tsigehtchic). Similarly, discharge measurements on the Yukon River at Pilot Station began in the mid-1970s.

[18] Consistent measurements of sediment flux at the downstream monitoring stations began much later than measurements of water discharge in Russian arctic rivers (Figure 2). The sediment flux record is fairly complete from the late 1960s through the mid 1990s for the Yenisey, Lena, and Kolyma rivers. In addition, there are a few years of coverage in the 1940s and 1950s for the Yenisey River. Coverage for the Ob’ River is most complete, extending from 1938 to 1996 with few gaps. Far fewer measurements of sediment are available for the Pechora and Severnaya Dvina rivers. Data for these rivers come from the 1950s and 1980s. Sediment data for Russian rivers cover all months, but summer months were sampled in more years than were low flow months (Figure 3).

[19] Sediment measurements at downstream stations in the Mackenzie and Yukon rivers began simultaneous to water discharge observations and available data extend through the mid-1990s (Figure 2). Annual flux estimates in the Mackenzie River are reported by Carson et al. [1998] for the period 1974–1994, and the 1973 estimate comes from Davies [1974]. For the Yukon River, flux estimates for individual years have not been previously reported. Thus, sediment flux values for the Yukon River shown in Figure 2 were derived from a rating curve generated using USGS sediment concentration and discharge data and bias corrected using the smearing estimator [Duan, 1983].

[20] Sediment sampling was restricted to high discharge months (May through October) on the Mackenzie River (Figure 3), and monthly averages were generally derived.
from multiple samples collected throughout these months. However, sampling in May was sparse, presumably owing to complications associated with ice breakup. In fact, May samples were only collected during 4 years, and these samples were all collected in the final few days of the month. Yukon sampling also focused on the high discharge months, although no measurements were made in May, and August was sampled only in 2 years. Sediment measurements were also made during low flow periods of some years, but in contrast to those from the Mackenzie River, samples from the Yukon River at Pilot Station were never collected more frequently than once per month.

Variations in sediment flux from year to year are substantial in most of the arctic rivers, but are more extreme at some rivers than others (Figure 2). The Lena, Ob’, Kolyma, Mackenzie, and Yukon show the largest interannual variation, while the Yenisey, Pechora, and Severnaya Dvina have less variable sediment fluxes from year to year. In all cases, changes in annual sediment flux broadly track changes in annual water discharge. Long-term changes are not evident in the sediment flux data, with the exception of the Yenisey and the Kolyma rivers where single stepwise shifts have occurred. In the Yenisey, the shift is associated with construction of the dams, while in the Kolyma the shift is associated with use of data from a new gauge opened closer to the mouth.

Sediment flux in all the eight largest arctic rivers is highest in late spring/early summer, and increases in sedi-
ment flux during the spring are generally steeper than declines during the fall (Figure 3). These seasonal changes generally track water discharge. The one clear exception to the pattern is the Yenisey, where sediment flux drops off very rapidly after the summer peak. This is evident in both the predam and postdam data.

Sediment yield varies widely among the eight largest arctic rivers (Table 4). The Mackenzie and Yukon have much greater yields than the other rivers, and the Yenisey stands out with the lowest yield. These differences, at least in part, are linked to differences in sediment concentration among the rivers: plots of sediment concentration relative to water discharge (Figure 4) show that the Mackenzie and Yukon Rivers sort out distinctly from the Yenisey, Lena, and Ob’ Rivers. The relatively narrow ranges of discharge in the Kolyma, Pechora, and Severnaya Dvina make these rivers more difficult to categorize in this way. Nonetheless, changes in suspended sediment concentration over their limited ranges of annual water discharge suggest that the Severnaya Dvina should be grouped with the larger Russian rivers, the Kolyma with the North American rivers, and the Pechora somewhere in between.

4. Discussion

Long-term trends and explanations of conflicting sediment flux estimates are discussed for each of the eight largest arctic rivers below, and best contemporary estimates...
are identified. These topics are then addressed in the context of the pan-arctic watershed and global change.

### 4.1. Yenisey River

At ~620 km$^3$/yr water discharge and with a catchment area of over 2.5 million km$^2$, the Yenisey ranks among the largest rivers on Earth. Despite the massive size of the Yenisey River, its suspended sediment flux is low, with published estimates ranging from 4.2 to 14.5 Mt/yr (Table 2). By comparison, the Mississippi River, which has a lower annual water discharge (530 km$^3$/yr), now transports about 210 Mt/yr suspended sediment [Meade, 1996].

Although annual sediment flux in the Yenisey River is remarkably small, there remains a relatively large range of values in the literature (Table 2). A primary cause of these divergent estimates is related to changes associated with dam construction. In 1967, a huge dam was completed on the Yenisey River near Krasnoyarsk (the Krasnoyarsk Dam), and several additional dams were completed on the Angara River (a major tributary of the Yenisey) in the 1970s [Bobrovitskaya et al., 1996; Meade et al., 2000]. Although these dams are more than 2500 km from the mouth of the Yenisey, they trap a significant portion of the Yenisey’s sediment flux. For example, after the construction of the Krasnoyarsk Dam, sediment flux at Divnogorsk (just downstream of the dam) dropped from 6.3 to 0.2 Mt/yr [Lisitsyna, 1974]. The impact of these dams is clearly evident in average monthly sediment fluxes far downstream at Igarka, where sediment fluxes during the month of greatest discharge (June) dropped by half after dam construction (Figure 3). As a result, annual flux estimates made using pre-dam data are generally over 10 Mt/yr [Lisitsyna, 1974; Samoilov, 1952; Shamov, 1949], whereas the few published estimates using more recent data (Table 3) are less than 6 Mt/yr. Interestingly, although there is a clear separation between pre- and post-dam annual fluxes, there is a suggestion in the data that postdam fluxes may have increased from the late 1960s through the 1980s (Figure 2). Additional data will be required to determine if this trend has continued.

The mean of the postdam data shown in Figure 2 for the Yenisey River at Igarka is 4.7 Mt/yr. This is the best contemporary estimate of sediment flux available, though our confidence in this estimate is only fair (Table 4), in part because it appears that annual fluxes were gradually increasing from the early 1970s through the 1980s, and also because we have no data after 1994. Our value is close to the postdam mean of 4.2 Mt/yr reported by Bobrovitskaya et al. [1996] based on data from 1970 to 1987 (Table 3), but our estimate contains additional data for 1988, 1989, 1993, and 1994.

### 4.2. Lena River

Annual sediment fluxes in the Lena River at Kyusyur have ranged from 7.6 to 40 Mt/yr between 1962 and 2000, with a mean of 20.7 Mt/yr (Figure 2). Published estimates of average annual sediment flux in the Lena River at this...
station range from 11.7 to 26.1 Mt/yr (Table 2). Interestingly, with the exception of Lisitsyna [1974], all pre-1995 publications give estimates of <16 Mt/yr whereas post-1995 estimates generally exceed 16 Mt/yr (Table 2), suggesting that sediment flux in the Lena River might have increased over the past several decades.

However, there are no obvious long-term trends in the data presented in Figure 2, indicating that big changes have not occurred since the early 1960s. It remains possible, though, that sediment flux increased prior to 1962 when our data set begins. The earliest published estimates, such as those of Lopatin [1950, 1952] and Doronina [1962], use data collected prior to any that we have been able to access (Table 3). With access to these data and detailed information concerning how they were collected, it might be possible to determine if annual sediment flux has increased during the past several decades in the Lena River. However, given the great interannual variability apparent in the available data (Figure 2), such a conclusion in the absence of additional information is probably not warranted. In any case, the higher estimates seem to best represent contemporary conditions, and we consider the mean of annual fluxes shown in Figure 2 (20.7 Mt/yr) to be the best estimate of contemporary sediment flux in the Lena River (Table 4). Our confidence in this estimate is good. Although interannual variability is large, we have data from as recently as 2000 and thus have reasonable confidence that our estimate adequately represents current conditions. Moreover, a recent analysis by Magritsky [2001] yielded a similar estimate of average annual sediment flux at Kyusyur of 19.8 Mt/yr. To derive this estimate, Magritsky used a sediment rating curve to fill gaps in the sediment record between 1936 and 1992 (Table 3).

There are conflicting reports in the recent literature concerning how much of the sediment transported by the Lena River reaches the Laptev Sea [Are and Reimnitz, 2000]. For example, one recent publication states that only 10–17% of the sediment in the Lena at Kyusyur makes it through the Lena Delta [Alabian et al., 1995], whereas another paper persuasively argues that essentially all of the Lena’s suspended sediment reaches the Laptev Sea [Rachhold et al., 2000]. We do not know which of these views is correct, but a clear resolution is needed in order to adequately evaluate the impact of riverine sediment inputs to the Laptev Sea as well as to understand the sediment dynamics of the expansive Lena Delta.

### 4.3. Ob’ River

Although annual sediment flux in the Ob’ River at Salekhard varied from 5.7 to 25 Mt/yr between 1938 and 1996 (Figure 2), published estimates of average annual fluxes have all been within a surprisingly narrow range, 13.0–16.6 Mt/yr (Table 2), even though the years of data included in the estimates varied substantially (Figure 3). Similarly, the average of all annual sediment flux data for the Ob’ River shown in Figure 2 is 15.5 Mt/yr. The consistency of these estimates and the lack of apparent trend in the annual flux data (Figure 2) indicates that there have been no significant changes in annual sediment flux in the Ob’ River since at least the early 1940s. Thus, we consider 15.5 Mt/yr to be a good estimate of contemporary sediment flux in the Ob’ River (Table 4).

### 4.4. Kolyma River

Published average annual flux estimates for the Kolyma River vary by almost 350%, from 4.7 to 16.1 Mt/yr, with the earlier estimates tending to be the lowest (Table 2). Part of the explanation for this wide range of estimates may be that earlier data were collected at Srednekolymsk, whereas later data were collected farther downstream at Kolymskoye. However, according to the data in Figure 2, the average of sediment flux values at Srednekolymsk (1966–1976) are 6.4 Mt/yr, compared to 9.2 Mt/yr at Kolymskoye (1977–1994), not a large enough difference to account for the variation among estimates. Interannual variability at Kolymskoye is large (1.3–26 Mt/yr, Figure 2), and thus differences in estimates are likely due to the specific years that were used to make the estimates. Unfortunately, this cannot be determined for certain because, with the exception of Magritsky [2001], none of the published estimates of sediment flux in the Kolyma are accompanied by information on years of data included (Table 3). Magritsky [2001] reports a value of 6.23 Mt/yr at Srednekolymsk using data from 1966 to 1976, and a value of 10.8 Mt/yr at Kolymskoye using data from 1977 to 1989. These values are very similar to ours, with the difference in the Kolymskoye values being due to the inclusion of 1990–1994 data in our estimate. Ivanov and Piskun [1999] point out that water and sediment flux measurements made at Kolymskoye do not take into account flow through the Stadukhinskaya branch of the river. Thus they develop a model to estimate sediment flux downstream in the river delta, where gauging is not routinely done. Data on water discharge (collected on expeditions by the All-Union Arctic Institute in 1934, 1935 and 1937, Arktik project in 1953 and 1954, and Arctic and Antarctic Research Institute (AARI) in 1991) were used to design and regulate an “aerodynamic model” of the Kolyma delta. This model was then used to estimate the distribution of water discharges in the individual branches of the Kolyma delta on an annual basis. Finally, the model estimates of water discharges were used in conjunction with measured data on turbidity (collected on the same expeditions listed above) to derive sediment flux estimates for the individual branches of the Kolyma delta. These branch-specific fluxes were summed to estimate total sediment flux from the Kolyma. The estimate they finally arrived at is 10.1 Mt/yr, slightly higher than the average of annual fluxes measured at Kolymskoye (8.9 Mt/yr). Given that the estimate by Ivanov and Piskun [1999] includes contributions from the Stadukhinskaya branch of the river, we consider 10.1 Mt/yr to be the best estimate of contemporary sediment flux in the Kolyma River (Table 4).

### 4.5. Pechora River

Although the annual water discharge of the Pechora River is only about one-fifth of that of the Yenisey River, it apparently transports a similar amount of sediment (Figure 2). Published estimates of average sediment flux in the Pechora River at Ust’ Tsil’ma range from 6.5 Mt/yr [Lopatin, 1952] to 13.5 Mt/yr [Gordeev et al., 1996], and the
average of the data presented in Figure 2 is 9.4 Mt/yr. Based
on the data we have (Figure 2), it appears that annual
sediment flux in the Pechora may have increased in the late
1980s, but data are very limited so it is not possible to
determine with any certainty what the actual contemporary
average annual sediment flux may be. We consider the
mean of data presented in Figure 2 (9.4 Mt/yr) to be the best
estimate of contemporary sediment flux in the Pechora
River (Table 4), but have poor confidence in this estimate
for the reasons discussed above.

4.6. Severnaya Dvina River

[35] As with the Pechora River, only limited annual
sediment flux data are available for the Severnaya Dvina
River (Figure 2). In contrast to the Pechora, however, the
range of annual sediment fluxes in the Severnaya Dvina
River at Ust’ Pinega is rather low, 2.5–6.6 Mt/yr, with a
mean of 4.1 Mt/yr for the data presented in Figure 2. The
range of published estimates of average annual sediment
flux is also low, ranging from 3.8 Mt/yr [Gordeev et al.,
1996] to 5.8 Mt/yr [Lopatin, 1952]. We consider 4.1 Mt/yr
to be the best estimate of contemporary sediment flux in the
Severnaya Dvina River, and although data are limited, have
fair confidence in this estimate because interannual variabil-
ity is relatively low (Table 4).

4.7. Mackenzie River

[36] The literature on sediment flux in the Mackenzie
River is the most confusing of any large arctic river but at
the same time is also the most complete. The confusion
results from several factors. First, the range of published
estimates of annual sediment flux in Mackenzie is huge,
from 15 to 230 Mt/yr (Table 2). The earliest estimate
[Moore, 1969] is also by far the lowest (15 Mt/yr), and
this estimate was cited later by Lisitzin [1972]. According
to Moore [1969], the original source of this estimate was
the Department of Energy, Mines, and Resources, Ottawa,
Canada. The highest estimate (230 Mt/yr) comes from
Macdonald et al. [1998], who cite Hirst et al. [1987] as
the source of the estimate. However, data given by Hirst
et al. [1987] indicate that the average annual sediment flux
to the Mackenzie Delta (1973–1984) is 92 Mt/yr. It
should be noted, however, that Hirst et al. recognize this
estimate to be low, and prefer the estimate of 126 Mt/yr
reported by Lewis (C. P. Lewis, Mackenzie Delta sedimen-
tary environments and processes, unpublished manuscript,
1988).

[37] A second source of confusion comes from a typo-
graphical error by Milliman and Syvitski [1992], where
sediment flux in the Mackenzie was printed as 42 Mt/yr
instead of 142 Mt/yr as they intended (J. P. M. Syvitski,
personal communication, 2001). Although this typographi-

cal error has been identified and noted in some subsequent
publications [Macdonald et al., 1998], other manuscripts
have propagated the erroneous figure [Arctic Monitoring
and Assessment Program (AMAP), 1997; Meyeck and
Ragu, 1995; Walker, 1998].

[38] A third source of considerable variation in Mack-
enzie River sediment flux estimates results from different
years of data used to derive the estimates (Table 3). This is
particularly true for the earlier estimates, which often used
only a few years of data. For example, estimates by Davi-
[1974, 1975], Neill and Molland [1980], and Thomas et al.
[1986] all use four or fewer years of data, which given the
high interannual variability, leads to considerable differ-
ces in estimated fluxes.

[39] A final source of confusion relates to sampling
stations. Sometimes estimates of Mackenzie River sediment
discharge include contributions from the Arctic Red River
(a tributary of the Mackenzie River which enters just
downstream of the gauging station at the village of Arctic
Red), and/or the Peel River (not technically a Mackenzie
tributary but it does discharge into the Mackenzie Delta).
Given the relatively large contributions of these two rivers
(sediment transport is ~7 and 21 Mt/yr in the Arctic Red
and Peel rivers, respectively), it is important to be clear
whether their sediment fluxes are included in a Mackenzie
River annual flux estimate.

[40] Although all of these sources of confusion are sig-
nificant for the Mackenzie River, the paper by Carson et al.
[1998] does an exemplary job of clearly describing the
available data and documenting how sediment flux calcula-
tions were made. Moreover, sources of error and estimates
of uncertainty are highlighted. Carson et al. [1998] estimate
average annual sediment flux to be 103 Mt/yr for the
Mackenzie River. This estimate includes ~7 Mt/yr from the
Arctic Red River. The Mackenzie Delta also receives 21
Mt/yr from the Peel River. Thus, total average suspended
sediment flux to the Mackenzie Delta is estimated to be 124
Mt/yr. We consider the estimates of Carson et al. [1998] to
best represent contemporary sediment flux in the Mackenzie
River (Table 4), and most other papers published since the
mid-1990s report similar estimates (Table 2).

4.8. Yukon River

[41] Relatively few sediment flux estimates have been
published for the Yukon River. The earliest estimate comes
from Lisitzin [1966], who reported annual sediment flux to
be 88 Mt/yr. According to A. P. Lisitzin (personal commu-
nication, 2001), data from Russell [1890], Lopatin [1950],
and Samoilov [1952] were used to derive this estimate. The
same value is later reported by Lisitzin [1972, 1974],
Gordeev et al. [1996], and Gordeev [2000].

[42] The most commonly cited annual suspended sedi-
ment flux value for the Yukon River is 60 Mt/yr. Milliman
and Meade [1983] were the first to publish this estimate,
which they derived using data from Eagle (far upstream
from the mouth of the Yukon) and from estimates of con-
tributions from a major tributary, the Tanana River.
Meade and Parker [1985] report a value of 65 million tons
per year, but since this number comes from a USGS publi-
cation, the units are short tons, not metric tons as are
more commonly used. To convert from short tons to
metric tons, multiply by 0.907; thus, the estimate of annual
sediment flux in the Yukon River by Meade and Parker
[1985] is essentially identical to that reported by Milliman
and Meade [1983] and in fact the difference is simply due
to rounding (R. H. Meade, personal communication,
2001).

[43] The first estimate of Yukon River sediment flux made
using sediment data collected at a downstream station was
4.9. Other Rivers

because of limited data. Contemporary sediment flux in the Yukon River at Pilot Station of 62.8 million short tons per year (56.9 million Mt/yr). This value (60 Mt/yr) is probably the best estimate of data, as well as more recent estimates made by Meade using estimates made in the early 1980s by Meade using upstream and Omoloy Rivers. Stream reaches of the rivers. These additional inputs of discharge are consistently higher than ours. This difference for the rivers listed in Table 5, though his values for water discharge are 16 km³/y according to [2000]. Thus, Yukon River sediment flux estimates made in the early 1980s by Meade using upstream data, as well as more recent estimates made by Meade using data from Pilot Station, all are in the neighborhood of 60 Mt/yr. This value (60 Mt/yr) is probably the best estimate of contemporary sediment flux in the Yukon River at Pilot Station, although confidence in the estimate is only fair because of limited data.

5. Synthesis

According to the estimates given in Table 4, the combined average annual sediment flux of the eight largest arctic rivers is 249 Mt/yr. By comparison, estimates provided in other papers for these eight rivers yield combined flux estimates of 165 Mt/yr [Lisitzin, 1972], 175 Mt/yr [AMAP, 1997], and 178 Mt/yr [Walker, 1998]. In all cases, the majority of the difference between our estimate and the others comes from the Mackenzie River. In work by AMAP [1997] and Walker [1998], the Mackenzie values are erroneously low due to propagation of a typographical error from Milliman and Syvitski [1992]. The Mackenzie value given by Lisitzin [1972] is also unrealistically low.

The eight rivers that have been the focus of this paper contribute ~65% of riverine freshwater inputs to the Arctic Ocean, but are they equally significant in terms of sediment flux? This is a difficult question to answer, largely because there is only limited data for smaller arctic rivers which may contribute disproportionally large amounts of sediment. Whether or not this is the case is unknown due to propagation of a typographical error from Milliman and Syvitski [1992]. Gordeev et al. [1996] provide the most complete list of estimates, with values presented for 20 Eurasian arctic rivers. In addition, they give flux estimates for other, presumably ungauged, areas in the Eurasian arctic. Their estimate of total sediment flux in Eurasian arctic rivers is 115 Mt/yr, whereas our estimate from the sum of the 16 Eurasian arctic rivers presented in Tables 4 and 5 is 84 Mt/yr. Ungauged areas and extra rivers included in the Gordeev et al. [1996] compilation account for over half of the difference between our estimate and theirs. The remaining difference is due to higher estimates for some rivers given by Gordeev et al. [1996] as compared to our new estimates. Regardless of this difference, it is clear that many rivers make substantial contributions to the total sediment flux from Eurasia to the Arctic Ocean. In contrast, it is highly likely that the Yukon and Mackenzie rivers carry most of the river sediment from the North American Arctic because they drain the areas of tectonism and active alpine glaciation that are the great generators of

Table 5. Summary of Sediment Flux Data for Additional Russian Arctic Rivers

<table>
<thead>
<tr>
<th>River</th>
<th>Station</th>
<th>Average Annual Discharge, km³/yr</th>
<th>Period of Sediment Record</th>
<th>Years in Sediment Record</th>
<th>Average Annual Sediment Flux, Mt/yr</th>
<th>Sediment Yield, t/km²/yr</th>
</tr>
</thead>
<tbody>
<tr>
<td>Indigirka</td>
<td>Vorontsovo</td>
<td>50.4</td>
<td>1956–86</td>
<td>26</td>
<td>11.1</td>
<td>36.4</td>
</tr>
<tr>
<td>Taz</td>
<td>Sidorovsk</td>
<td>33.1</td>
<td>1969–75</td>
<td>4</td>
<td>0.7</td>
<td>7.0</td>
</tr>
<tr>
<td>Yana</td>
<td>Yubileynaya</td>
<td>32.2</td>
<td>1973–94</td>
<td>19</td>
<td>4.0</td>
<td>17.9</td>
</tr>
<tr>
<td>Olenek</td>
<td>Samburg</td>
<td>31.5</td>
<td>1968–94</td>
<td>21</td>
<td>1.1</td>
<td>5.6</td>
</tr>
<tr>
<td>Pur</td>
<td>Malonisogorskaya</td>
<td>28.3</td>
<td>1941–81</td>
<td>26</td>
<td>0.7</td>
<td>7.4</td>
</tr>
<tr>
<td>Mezen</td>
<td>Porog</td>
<td>20.4</td>
<td>1949–87</td>
<td>5</td>
<td>0.6</td>
<td>10.7</td>
</tr>
<tr>
<td>Onega</td>
<td>Saskylakh</td>
<td>15.7</td>
<td>1979–88</td>
<td>9</td>
<td>0.3</td>
<td>5.4</td>
</tr>
<tr>
<td>Anabar</td>
<td>Antsulak</td>
<td>13.3</td>
<td>1967–90</td>
<td>23</td>
<td>0.4</td>
<td>5.1</td>
</tr>
<tr>
<td>Aleyza</td>
<td>Andryushkin</td>
<td>1.5</td>
<td>1980–92</td>
<td>12</td>
<td>0.1</td>
<td>3.4</td>
</tr>
<tr>
<td>Omoloy</td>
<td>Namy</td>
<td>1.1</td>
<td>1979–84</td>
<td>4</td>
<td>0.04</td>
<td>3.7</td>
</tr>
</tbody>
</table>

*Annual discharge estimates are derived using the R-ArcticNet database, and water discharge stations correspond to sediment observation stations.

Table 4 also made by Meade and published by Brabets et al. [2000]. The estimate was derived using data from about 70 sediment samples that were collected at Pilot Station between 1975 and 1996. According to R. H. Meade (personal communication), he calculated an annual sediment flux at Pilot Station of 62.8 million short tons per year (56.9 million Mt/yr). Due to uncertainties related to limited data availability, he then rounded the estimate to 60 million short tons per year (54 million metric tons per year) as reported by Brabets et al. [2000]. Thus, Yukon River sediment flux estimates made in the early 1980s by Meade using upstream data, as well as more recent estimates made by Meade using data from Pilot Station, all are in the neighborhood of 60 Mt/yr. This value (60 Mt/yr) is probably the best estimate of contemporary sediment flux in the Yukon River at Pilot Station, although confidence in the estimate is only fair because of limited data.
fluvial sediment. Data from smaller rivers in North America are needed to confirm this.

[48] Although sediment yields vary greatly among arctic rivers (Tables 4 and 5), distinct geographical patterns are evident. The Yukon and Mackenzie rivers contribute only 21% of the combined annual water discharge of the eight largest arctic rivers (Table 1), but transport 73% of the suspended sediments. In contrast, the Yenisey, Lena, and Ob' contribute 65% of the combined annual water discharge of the eight largest arctic rivers while transporting only 17% of the suspended sediments. Sediment yields in these three rivers have sometimes been considered anomalously low [Milliman and Meade, 1983], but in fact their yields are generally in line with what has been observed in other lowland rivers [Milliman and Syvitski, 1992].

[49] Variations in sediment concentration as a function of water discharge among the eight largest arctic rivers (Figure 4) also reflect geographical patterns. The drainage basins of the Mackenzie, Yukon, and Kolyma rivers share features of geology and climate that set them apart from the drainage basins of the Yenisey, Lena, Ob', Pechora, and S. Dvina rivers [Gordeev et al., 1996; Semiletov et al., 2000]. This division is broadly reflected in Figure 4, although the Pechora is an obvious exception. In any case, the distribution of rivers in Figure 4 reminds us that simply grouping rivers according to their continental affiliations can disguise functional differences.

[50] Although we have stated that we are addressing sediment flux to the Arctic Ocean, in fact we are using this phrase rather loosely. Instead, we are evaluating sediment flux in the downstream reaches of major arctic rivers, much of which may be retained in the marginal filter [Lisitsin, 1995]. The distribution of this sediment in deltas, estuaries, and the broad shelf of the Arctic Ocean is often unclear [Bauch et al., 2001]. As pointed out earlier, there is considerable disagreement about the proportion of Lena River sediment that reaches the Laptev Sea, with estimates ranging from 10 to nearly 100% [Alabyan et al., 1995; Are and Reimnitz, 2000; Rachold et al., 2000]. For the Mackenzie, it has been estimated that about half of the river's suspended sediment is transported through the extensive Mackenzie Delta [Macdonald et al., 1998], but it seems unlikely that a significant portion of the suspended sediment from the Yenisey and Ob' rivers is transported through their lengthy estuaries on annual timescales [Meade et al., 2000]. Still less likely is a significant contribution of sediment from the Yukon River to the Arctic Shelf. Thus, whereas the flux estimates provided in this paper allow assessment of sediment flux from a large percentage of the pan-arctic watershed, further research will be needed to determine how much of this sediment actually reaches the sea.

[51] Variation among published sediment flux estimates for individual rivers (Table 2) can largely be attributed to differences in the years of record included or use of data from different sampling stations. Because sediment flux is highly variable from year to year, establishing reliable average annual values requires integration over at least decadal time frames. Trends in sediment flux over time are not evident, and thus in most cases long-term averages of sediment flux provide best contemporary estimates. Notable exceptions are the Yenisey and Kolyma Rivers, where stepwise shifts accompanying dam construction and a change in sampling location, respectively, make it necessary to use only more recent flux data to represent present conditions.

[52] Long-term increases in water discharge have already been detected at the pan-arctic scale [Semiletov et al., 2000]. Given the dependence of sediment flux on water discharge, we would suspect that sediment flux might be increasing as well. The absence of identifiable long-term trends in sediment flux is likely linked to the variability in the data. Records of sediment flux are much shorter than those of water discharge, and frequently lack values for winter months when changes in water discharge are most evident. Longer-term data sets, and reduction in variation induced by sampling and data handling, will be needed to determine if long-term changes are indeed occurring.

[53] At present, it is unclear to what extent inconsistencies in sampling and data handling contribute to variations in the sediment data. A unique feature of arctic rivers that greatly complicates accurate determination of sediment flux is ice breakup. During the breakup period, suspended sediment sampling is very dangerous if not impossible, yet sediment fluxes may be substantial during these periods. We must somehow figure out a way to reasonably account for sediment fluxes during the breakup period. In the meantime, we must acknowledge this deficiency in current sediment flux estimates for large arctic rivers. A further confounding factor is that sample collection and flux calculation methods often vary among rivers and perhaps over time. Ideally, standard methods would be used throughout the pan-arctic catchment. Perhaps the closer cooperation emerging among arctic nations will facilitate standardization of sediment methods as well as protocols for other hydrologic and water quality parameters. At any rate, for sediment flux to be a useful metric of global change in the future, monitoring must continue and artifacts introduced by sampling and data handling must be minimized.

[54] Fluxes of water and waterborne constituents from arctic rivers to the ocean provide an integrative signal of processes occurring in their watersheds. Shifts in these fluxes over time give clues about natural and anthropogenic changes in the Arctic. Increases in water discharge may be linked to anthropogenic increases in greenhouse gases and associated climate change [Miller and Rusell, 2000]. Waterborne constituents, such as nutrients and suspended sediments, provide information about alterations in biogeochemical processes accompanying climate and land-use changes. Compared to water discharge, however, analytical challenges and shorter time series of constituent data have made interpretation of long-term trends more difficult [Holmes et al., 2000, 2001; Zhulidov et al., 2000]. Thus, for many of these constituents our current challenge is not so much to identify historical trends but instead to establish a reliable contemporary baseline against which to evaluate future changes. In this paper, we have established contemporary sediment flux estimates for the eight largest arctic rivers. Together these values provide a baseline for sediment flux at the pan-arctic scale. This large-scale perspec-
tive is essential for understanding the effects of global change on the Arctic System as a whole.

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