View metadata, citation and similar papers at core.ac.uk
brought to you by CORE
provided by UNH Scholars' Repository

University of New Hampshire
University of New Hampshire Scholars' Repository

Faculty Publications

8-1-2000

Flux of nutrients from Russian rivers to the Arctic Ocean: Can we establish a baseline against which to judge future changes?

R. M. Holmes

B. J. Peterson

V. V. Gordeev

A. V. Zhulidov

M. Meybeck
Université de Paris

See next page for additional authors

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

Recommended Citation

Holmes, R.M., B.J. Peterson, V.V. Gordeev, A.V. Zhulidov, M. Meybeck, R.B. Lammers, and C.J. Vorosmarty (2000) Flux of nutrients from Russian rivers to the Arctic Ocean: Can we establish a baseline against which to judge future changes? Water Resources Research, 36:2309-2320.

This Article is brought to you for free and open access by University of New Hampshire Scholars' Repository. It has been accepted for inclusion in Faculty Publications by an authorized administrator of University of New Hampshire Scholars' Repository. For more information, please contact nicole.hentz@unh.edu.

Authors
R. M. Holmes, B. J. Peterson, V. V. Gordeev, A. V. Zhulidov, M. Meybeck, Richard B. Lammers, and Charles J. Vorosmarty

This article is available at University of New Hampshire Scholars' Repository: https://scholars.unh.edu/faculty_pubs/150

WATER RESOURCES RESEARCH, VOL. 36, NO. 8, PAGES 2309–2320, AUGUST 2000

Flux of nutrients from Russian rivers to the Arctic Ocean: Can we establish a baseline against which to judge future changes?

R. M. Holmes,[1] B. J. Peterson,[1] V. V. Gordeev,[2] A. V. Zhulidov,[3] M. Meybeck,[4] R. B. Lammers,[5] and C. J. Vörösmarty[5]

Abstract. Climate models predict significant warming in the Arctic in the 21st century, which will impact the functioning of terrestrial and aquatic ecosystems as well as alter land-ocean interactions in the Arctic. Because river discharge and nutrient flux integrate large-scale processes, they should be sensitive indicators of change, but detection of future changes requires knowledge of current conditions. Our objective in this paper is to evaluate the current state of affairs with respect to estimating nutrient flux to the Arctic Ocean from Russian rivers. To this end we provide estimates of contemporary (1970s–1990s) nitrate, ammonium, and phosphate fluxes to the Arctic Ocean for 15 large Russian rivers. We rely primarily on the extensive data archives of the former Soviet Union and current Russian Federation and compare these values to other estimates and to model predictions. Large discrepancies exist among the various estimates. These uncertainties must be resolved so that the scientific community will have reliable data with which to calibrate Arctic biogeochemical models and so that we will have a baseline against which to judge future changes (either natural or anthropogenic) in the Arctic watershed.

1. Introduction

Earth's temperature is predicted to rise 1°–3.5°C in the next century, with even greater increases in the Arctic [*Houghton et al.*, 1996]. This temperature increase is expected to impact numerous aspects of the Arctic system, including the extent of permafrost and ice-covered regions, the amount and distribution of precipitation, and the productivity and biogeochemistry of terrestrial and aquatic ecosystems [*Chapin et al.*, 1995; *Anisimov and Nelson*, 1996; *Hobbie et al.*, 1998; *Serreze et al.*, 2000]. All of these changes will affect river discharge and nutrient flux to the Arctic Ocean, which in turn may impact Arctic Ocean processes [*Aagaard and Carmack*, 1989; *Broecker*, 1997; *Anderson et al.*, 1998]. Because river discharge and nutrient flux integrate large-scale watershed processes, they should be early and accurate indicators of climate change in the Arctic.

Detection of future changes requires knowledge of current conditions. In this paper, we assess current (1970s–1990s) nutrient flux from Eurasia to the Arctic Ocean. We focus on Russian rivers because the majority of riverine input to the Arctic Ocean comes from Russia. Although several sources report nutrient concentrations and fluxes for Russian Arctic rivers [*Alekin and Brazhnikova*, 1964; *Tarasov et al.*, 1988; *Smirnov*, 1994; *Gordeev et al.*, 1996; *Gordeev and Tsirkunov*, 1998; M. Meybeck and A. Ragu, Rivers Discharges to the Oceans: An Assessment of Suspended Solids, Major Ions and Nutrients, book draft, United Nations Environment Programme, 1995] (hereinafter referred to as Meybeck and Ragu, book draft, 1995) (see also Global Environmental Monitoring System (GEMS-Water), United Nations Environment Programme, www.cciw.ca/gems/), there has been little critical evaluation of the published values. We will derive nitrate, ammonium, and phosphate flux estimates for 15 Russian rivers that enter the Arctic Ocean using a previously unavailable data set and compare our estimate to model predictions [*Seitzinger and Kroeze*, 1998] and to other data. We will conclude that in spite of the extensive data set, it is currently not possible to quantify riverine nutrient flux to the Arctic Ocean with sufficient confidence to establish a contemporary baseline. We will argue that the scientific community must soon resolve the remaining uncertainties so that we do not squander a powerful opportunity to detect the impact of climate change on the Arctic system.

[1]The Ecosystems Center, Marine Biological Laboratory, Woods Hole, Massachusetts.
[2]P. P. Shirshov Institute of Oceanology, Russian Academy of Sciences, Moscow.
[3]Centre for Preparation and Implementation of International Projects on Technical Assistance, Rostov-on-Don, Russia.
[4]Laboratorie de Géologie Appliquée, CNRS, Paris.
[5]Complex Systems Research Center, University of New Hampshire, Durham.

Copyright 2000 by the American Geophysical Union.

Paper number 2000WR900099.
0043-1397/00/2000WR900099$09.00

2. Description of Data Set

During the Soviet era the Russian water quality monitoring system was among the most extensive on Earth. However, prior to the 1990s, scientists (Russian and otherwise) were unable to access, analyze, or publish the official water quality data of the former Soviet Union (FSU), largely because of political and ideological reasons [*Zhulidov et al.*, 1998]. Such restrictions no longer exist, but many of the data remain inaccessible. For example, data are often stored in notebooks instead of digital form, and these notebooks are not necessarily centrally located but instead may reside in regional laboratories.

Owing to these complications, use of the Russian nutrient data has been limited, and their fate has been uncertain because recent economic and political instability in Russia has lead to closure of laboratories and the potential loss of data. In order to help preserve the data set of the FSU and to estimate

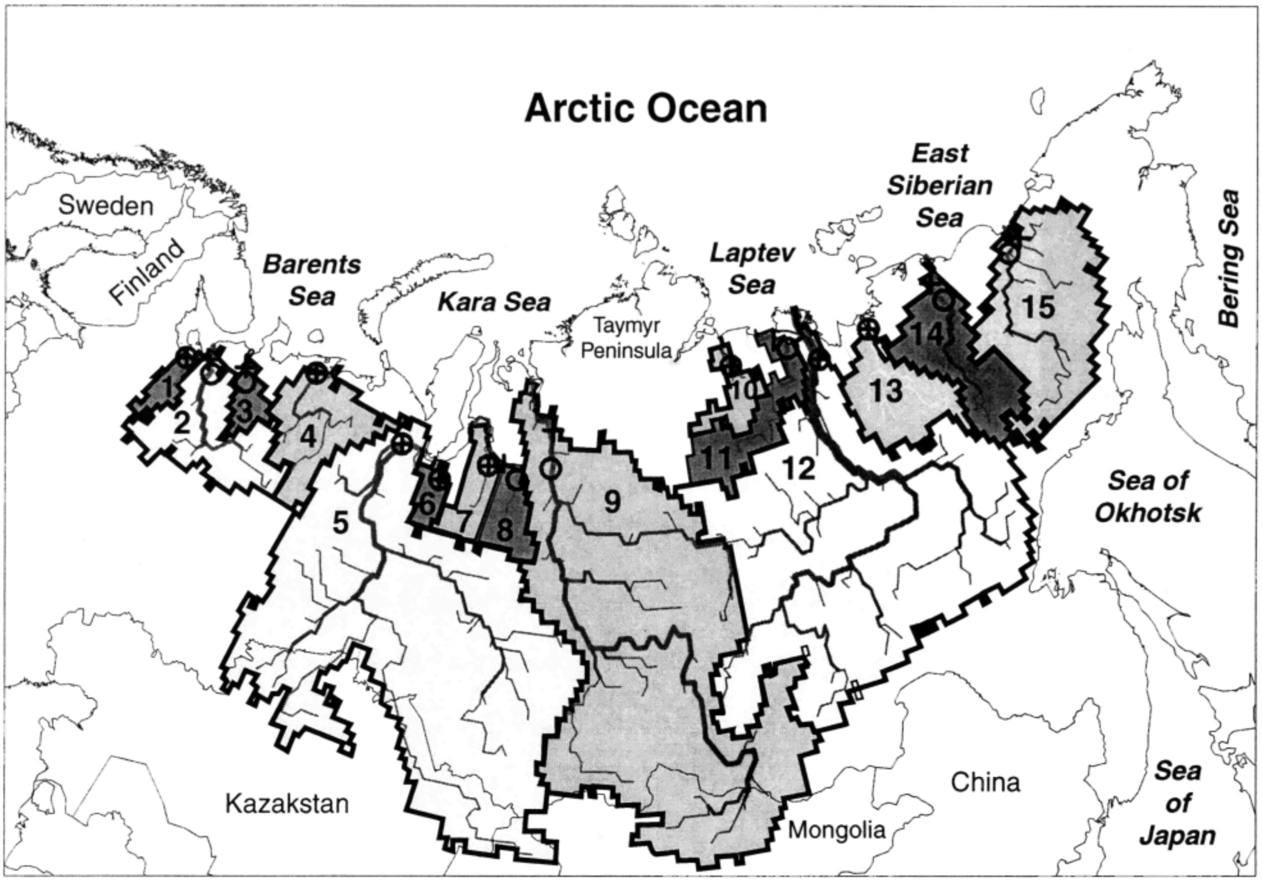

Figure 1. Map of Eurasia showing rivers in the United Federal Service for Observation and Control of Environmental Pollution (OGSNK/GSN) data set and their approximate watershed boundaries. Discharge stations are shown by open circles, and nutrient stations are given by crosses. Consult Table 1 for station names and coordinates. As is apparent, rivers in the OGSNK/GSN data set encompass most of the Eurasian watershed draining into the Arctic Ocean, with notable exceptions in the Russian Far East and on the Taymyr Peninsula. River codes are as follows: 1, Onega; 2, Severnaya Dvina; 3, Mezen'; 4, Pechora; 5, Ob'; 6, Nadym; 7, Pur; 8, Taz; 9, Yenisey; 10, Anabar; 11, Olenek; 12, Lena; 13, Yana; 14, Indigirka; and 15, Kolyma.

nutrient flux to the Arctic Ocean from Russian rivers, we have compiled and digitized the data archives of the FSU and the current Russian Federation for 15 Russian rivers entering the Arctic Ocean. The data come from samples that were collected and analyzed as part of the Unified Federal Service for Observation and Control of Environmental Pollution (OGSNK prior to 1992 and GSN from 1992 onward). We will refer to these data as the OGSNK/GSN data set.

The 15 river basins represented in the OGSNK/GSN data set nearly span the >5000 km width of Russia (Figure 1) and include three of the world's 13 largest rivers by discharge [*Shiklomanov*, 1993]. Watershed areas range from ~50–3000 × 10^3 km^2 (Table 1). The nutrient data set consists of time series of ammonium, nitrate, and phosphate concentrations for the 15 Russian rivers, with samples generally being collected at the downstreammost station that was free of tidal influence. The periods of record for nutrient concentrations in individual rivers typically are 10–20 years within the mid-1970s to the mid-1990s period, with rivers in the Siberian far east having the shortest records. Data were compiled on a monthly basis, but not all months in all years were represented, and means for individual months might represent one to several samples. More than 100 months of data are available for several of the rivers, particularly those around the Ob' Estuary, whereas rivers in eastern Siberia typically have about 50 months with data entries. Sample concentrations reported as below detection limit (BDL) were treated as zero, which may lead to a slight underestimation of nutrient flux.

Mean monthly river discharge (Figure 2), obtained from the R-ArcticNet database (www.R-arcticnet.sr.unh.edu) (R. B. Lammers et al., An assessment of the contemporary gauged river discharge and runoff in the Pan-Arctic region, submitted to *Journal of Geophysical Research*, 2000) (hereinafter referred to as Lammers et al., submitted manuscript, 2000), is used to compute monthly nutrient fluxes. In many but not all cases, R-ArcticNet discharge data are available for the nutrient sampling stations (Table 1). When discharge data are not available at the nutrient station, data from the closest discharge station are used. Annual river discharge at the R-ArcticNet stations, for the rivers represented in the OGSNK/GSN nutrient data set, ranges from 13.3 to 577.3 km^3/yr (Table 1).

3. Data

3.1. Mean Monthly Nutrient Concentrations and Fluxes

Mean monthly nitrate and ammonium concentrations varied temporally within individual rivers as well as spatially across

Table 1. Locations of OGSNK/GSN Nutrient Sampling Stations and R-ArcticNet Discharge Stations and Their Respective Periods of Record

River	OGSNK/GSN Nutrient Station	Nutrient Period of Record	R-ArcticNet Discharge Station	Discharge Period of Record	Drainage Area,[a] 10^3 km^2	Mean Annual Q at Discharge Station, km^3/yr
Yenisey[b]	Dudinka (69.2°N, 86.1°E)	1985–1995	Igarka (67.4°N, 86.5°E)	1936–1995	2440	577.3
Lena	Kyusyur (70.7°N, 127.4°E)	1984–1995	Kyusyur (70.7°N, 127.4°E)	1936–1994	2430	532.5
Ob'	Salekhard (66.6°N, 66.6°E)	1986–1995	Salekhard (66.6°N, 66.6°E)	1936–1994	2950	404.1
Pechora	Oksino (67.6°N, 52.2°E)	1979–1995	Oksino (67.6°N, 52.2°E)	1916–1993	312	135.1
Severnaya Dvina	Arkhangel'sk (64.3°N, 40.3°E)	1976–1995	Ust' Pinega (64.1°N, 41.9°E)	1881–1993	348	105.6
Kolyma	Cherskiy (68.4°N, 161.2°E)	1984–1994	Kolymskoye (68.7°N, 158.7°E)	1936–1988	526	70.8
Indigirka	Chokurdakh (70.4°N, 147.6°E)	1984–1995	Vorontsovo (69.6°N, 147.5°E)	1936–1994	305	50.4
Taz	Tazovskiy (67.3°N, 78.4°E)	1975–1995	Sidorovsk (66.6°N, 82.3°E)	1962–1994	100	33.1
Yana	Yubileynaya (70.8°N, 136.0°E)	1984–1995	Yubileynaya (70.8°N, 136.0°E)	1972–1994	224	32.2
Olenek	Taymylyr (71.6°N, 123.3°E)	1984–1995	(71.8°N, 123.6°E)	1965–1985	198	31.5
Pur	Samburg (67.0°N, 78.2°E)	1975–1992	Samburg (67.0°N, 78.2°E)	1961–1985	95	28.3
Mezen'	Dorogorskoye (64.4°N, 44.3°E)	1978–1994	Malonisogorskaya (65.0°N, 45.6°E)	1920–1988	56	20.4
Onega	Porog (63.8°N, 38.5°E)	1977–1995	Porog (63.8°N, 38.5°E)	1943–1993	56	15.7
Nadym	Nadym (65.6°N, 72.7°E)	1978–1995	Nadym (65.6°N, 72.7°E)	1955–1990	48	14.6
Anabar	Saskylakh (72.0°N, 114.1°E)	1975–1995	Saskylakh (72.0°N, 114.1°E)	1954–1988	79	13.3

Annual discharge estimates are calculated by summing monthly discharge data, as given in the R-ArcticNet database. The rivers are ranked by discharge. The access address for R-ArcticNet is www.R-arcticnet.sr.unh.edu (R. B. Lammers, submitted manuscript, 2000).
[a]Drainage areas represent watershed areas above R-ArcticNet discharge stations, as reported in the R-ArcticNet database.
[b]Numerous English spellings exist for many Russian place names. For consistency, we have followed the spellings given by the Geographic Names Information System (GNIS) of the United States government. One name (Yubileynaya) could not be verified by the GNIS.

the Russian Arctic (Figure 3). Highest concentrations for both ammonium and nitrate often occurred in spring, whereas lowest concentrations were frequently observed during summer. Surprisingly high ammonium concentrations were measured in the rivers entering the Ob' Estuary (Ob', Nadym, Pur, and Taz rivers), although nitrate values for these rivers were more moderate. Maximum mean monthly ammonium concentration reached almost 3 mg N/L in the Pur River, whereas nitrate seldom exceeded 0.5 mg N/L in any of the rivers. Nitrite concentrations were very low, and the nitrate values reported in the OGSNK/GSN data set represent nitrate alone, not nitrate plus nitrite.

Nitrate and ammonium fluxes were generally highest in May or June (Figure 4), corresponding to the period of highest discharge (Figure 2). For example, approximately 60% of the annual ammonium flux in the Yenisey River occurs in a single month (June). Phosphate concentrations often showed less clear seasonal trends than did nitrate and ammonium but, as with ammonium, tended to be highest in rivers entering the Ob' Estuary (Figure 5). Phosphate flux in all of the rivers in our data set was strongly regulated by discharge, since discharge varied much more annually than did phosphate concentration (Figure 6).

3.2. Annual Flux Estimates, Flux Ratios, and Specific Fluxes

Annual nutrient fluxes were calculated by summing flux estimates determined for individual months. In general, fluxes were only calculated for months when both discharge and nutrient data were available. Since rivers in eastern Siberia often are missing nutrient data for winter months (Figures 3 and 5), this protocol will tend to underestimate their annual nutrient fluxes, but the magnitude of error is probably small given their very low discharge during winter (Figure 2). In a few cases, nutrient data were missing for a spring or summer month when discharge was substantial. In these cases, nutrient concentrations were estimated by interpolation between adjacent months, since exclusion of these high-discharge months from our annual estimates would lead to significant underestimation of annual nutrient flux.

A striking feature of the annual flux estimates is the high ammonium flux in the Ob' and Yenisey rivers. Although the Amazon is more than 10 times bigger (by discharge), ammonium flux in the Ob' river is more than twice as great (Table 2). In fact, if the data are correct, it seems likely that the Ob' River transports more ammonium than any other river on Earth. In contrast to ammonium, nitrate fluxes in the Ob', Yenisey, and other Russian rivers are much smaller than other large rivers such as the Amazon and Mississippi (Table 2).

When standardized by catchment area, ammonium and phosphate flux rates appear to be correlated and are greatest in central Siberian rivers (Figures 7a and 7c), whereas specific nitrate flux is generally higher in the western Russian rivers (Figure 7b). Although it has been estimated that on average 85% of dissolved inorganic nitrogen (DIN) transport in rivers is as nitrate [*Meybeck*, 1982], the OGSNK/GSN data set suggests that there is a strong spatial component to the ammonium to nitrate flux ratio in Russian Arctic rivers (Figure 8a). All of the rivers in the OGSNK/GSN data set transport more ammonium than nitrate, and those draining the Siberian lowland region transport more than 10 times as much ammonium as nitrate annually. In contrast, there is no clear spatial pattern of DIN to phosphate flux (Figure 8b).

4. Discussion

Our objective in this paper is to determine whether we can accurately determine the contemporary dissolved inorganic nitrogen and phosphate flux from Russian rivers to the Arctic Ocean and thus whether we will be able to detect changes in the future. To this end, we have assembled an extensive data set from the archives of the FSU and current Russian Federation, which, if reliable, will be sufficient for this purpose. Thus our next task is to evaluate the reliability of these data. We will

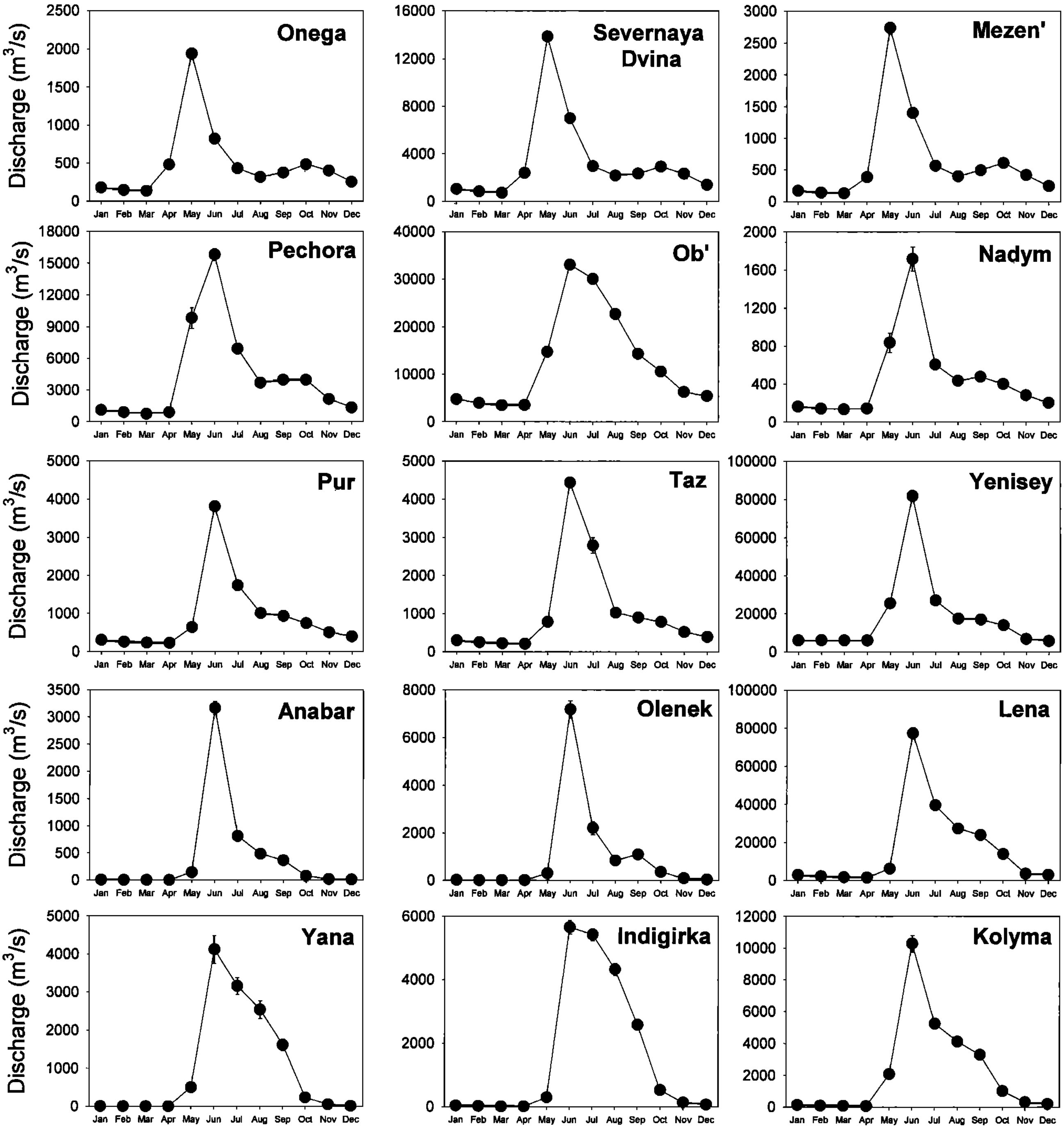

Figure 2. Mean monthly discharge for the 15 rivers in the OGSNK/GSN nutrient data set. Discharge data are from the R-ArcticNET database (www.R-arcticnet.sr.unh.edu) (Lammers et al., submitted manuscript, 2000). Error bars (many smaller than symbol size) represent standard errors. In Figures 2–6, rivers are arrayed from westernmost (top left) to easternmost (bottom right).

do this by critically examining trends in the data, by comparing the OGSNK/GSN data set to other nutrient data that are available for Russian rivers, and by comparison to model predictions.

4.1. Are the Data Reasonable?

The OGSNK/GSN data set contains some unusual features and thus warrants close scrutiny. First, although the generally accepted paradigm is that rivers transport more nitrate than ammonium, all of the rivers in the OGSNK/GSN data set do not (Table 2). In fact, several Russian Arctic rivers apparently transport more than 10 times as much ammonium as nitrate, compared to rivers such as the Mississippi and Amazon that transport much more nitrate than ammonium. Exceptions to the general rule are typically heavily polluted rivers, but the rivers in our data set have relatively low human population densities, fertilizer use, and atmospheric N deposition rates. Thus the ammonium to nitrate flux ratio calculated using the OGSNK/GSN data set (Figure 7a) is anomalous.

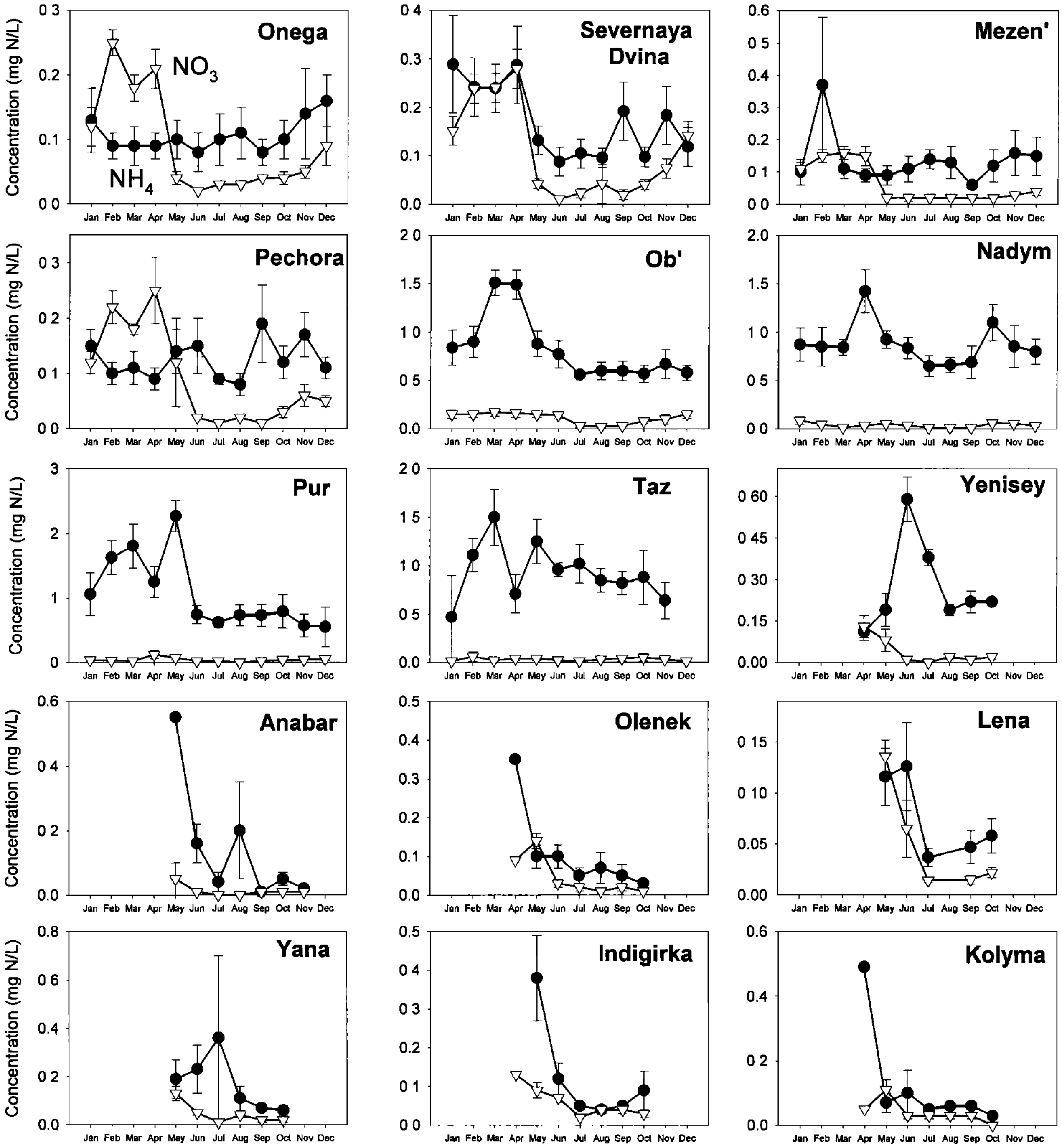

Figure 3. Mean monthly ammonium (circles) and nitrate (triangles) concentrations for the 15 rivers in the OGSNK/GSN data set.

Second, not only are the ammonium to nitrate flux ratios suspicious, but the reported ammonium concentrations are also high (Figure 3). Whereas the estimated global average river DIN concentration is about 0.12 mg/L (only 15% of which is ammonium) [*Meybeck*, 1982], many of the rivers in our data set have ammonium concentrations that greatly exceed this mean DIN value. Average ammonium concentrations in the Ob', Nadym, Pur, and Taz rivers often exceed 1 mg N/L, in contrast to even heavily polluted rivers elsewhere such as the Thames and Rhine rivers where mean ammonium concentrations are less than 1 mg N/L (Meybeck and Ragu, book draft 1995).

Third, although the Soviet water quality monitoring program was extensive and centrally organized, it has been noted that instrumentation, materials, and supplies were often of questionable reliability and that quality assurance and control (QA/QC) procedures were poorly executed [*Tsirkunov*, 1998]. For example, a study of the distribution of organochlorine insecticides in Russian rivers indicated widespread discrepancies between OGSNK/GSN laboratories and data collected by independent specialists [*Zhulidov et al.*, 1998]. The explanation for the differences was not clear, but it was noted that lack of supplies, equipment issues, and inexperienced personnel may

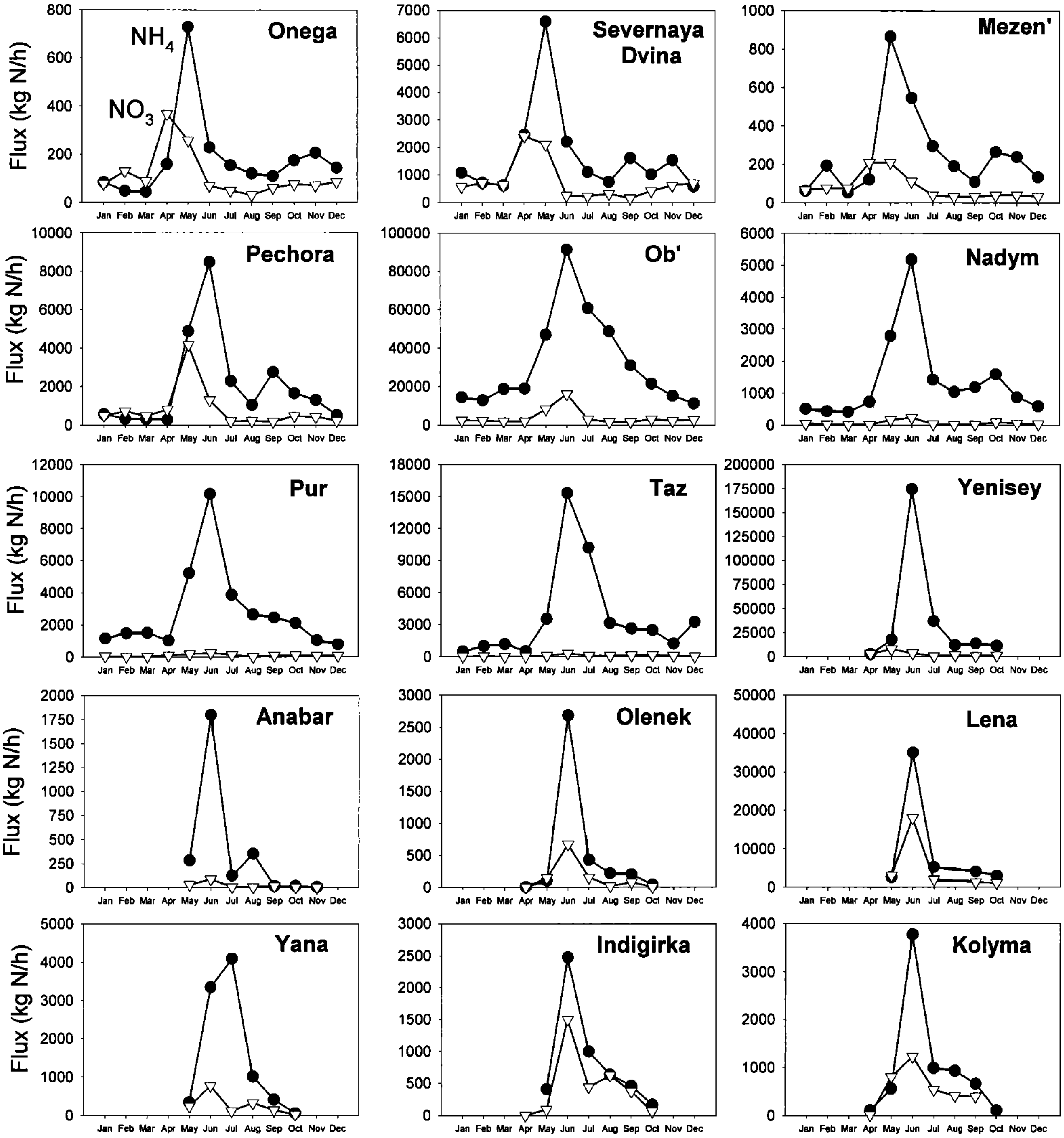

Figure 4. Mean monthly ammonium (circles) and nitrate (triangles) fluxes for the 15 rivers in the OGSNK/GSN data set.

have contributed. Similarly, an analysis of OGSNK/GSN data for the lower Don River found that a high percentage of nutrient data were unreliable, and the authors speculated that analytical problems may have been widespread in the federal monitoring system [*Boeva et al.*, 1999]. Although official QA/QC procedures for the OGSNK/GSN monitoring system may have been adequate, it appears that in practice minimal QA/QC actually occurred (A. V. Zhulidov et al., The State Service of Observation and Control of Environmental Pollution (OGSNK) in the former Soviet Union: A concise critical analysis, submitted to *Canadian Journal of Fisheries and Aquatic Sciences*, 2000) (hereinafter referred to as Zhulidov et al., submitted manuscript, 2000). Moreover, while all regional laboratories theoretically used identical analytical methods, it now seems that in reality a variety of methods were used with little intercalibration (Zhulidov et al., submitted manuscript, 2000). At this point it is difficult or impossible to reconstruct details of past QA/QC procedures, but it is clear that significant problems existed. This lack of QA/QC information creates obvious problems for evaluating data reliability, since well-documented QA/QC procedures should be considered vital to any water quality monitoring program.

Although we have just outlined several reasons to be suspicious of the reliability of the OGSNK/GSN data set, there are

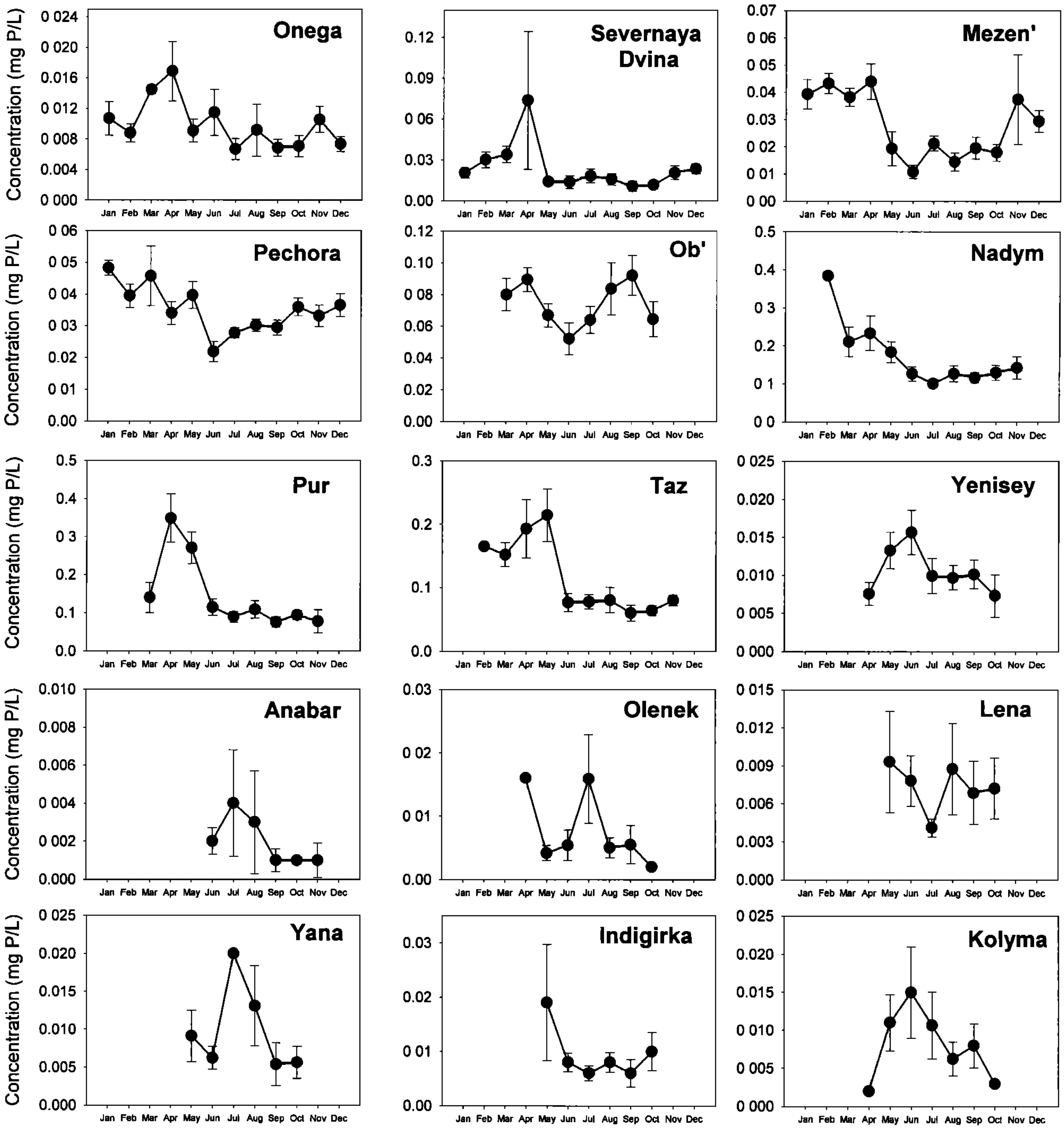

Figure 5. Mean monthly phosphate concentration for the 15 rivers in the OGSNK/GSN data set.

intriguing patterns in the data (both seasonally and spatially) that might not be expected from erroneous data. For example, specific fluxes of ammonium and phosphate peak in the vicinity of the Ob' Estuary and decrease to the east and west, whereas specific nitrate flux generally increases to the west (Figure 7). These trends combine to give a distinct pattern of ammonium to nitrate flux that is highest in the watersheds of the western Siberian lowlands (Figure 8). The rivers which are most suspect with respect to ammonium concentrations (Ob', Nadym, Pur, and Taz) are all in the western Siberian lowlands, which have low-lying, marshy soils that might through natural processes lead to the patterns that we have observed [*Neischtadt*, 1971; *Smirnov*, 1994; *Zhulidov et al.*, 1997]. In addition to these and other spatial patterns, there are also clear seasonal trends in the data. For example, nutrient concentrations are frequently highest during the spring runoff period and are lowest during summer low-flow conditions. It is difficult to imagine how poor quality data could exhibit such clear seasonal and spatial patterns.

As we have noted, a particularly surprising aspect of the OGSNK/GSN data set is the high ammonium concentration reported for several of the Russian Arctic rivers. In order to accumulate ammonium in rivers, nitrification (the microbial conversion of ammonium to nitrate) must be blocked or saturated, or at least nitrification and ammonium uptake must proceed more slowly that ammonium production. This is rarely

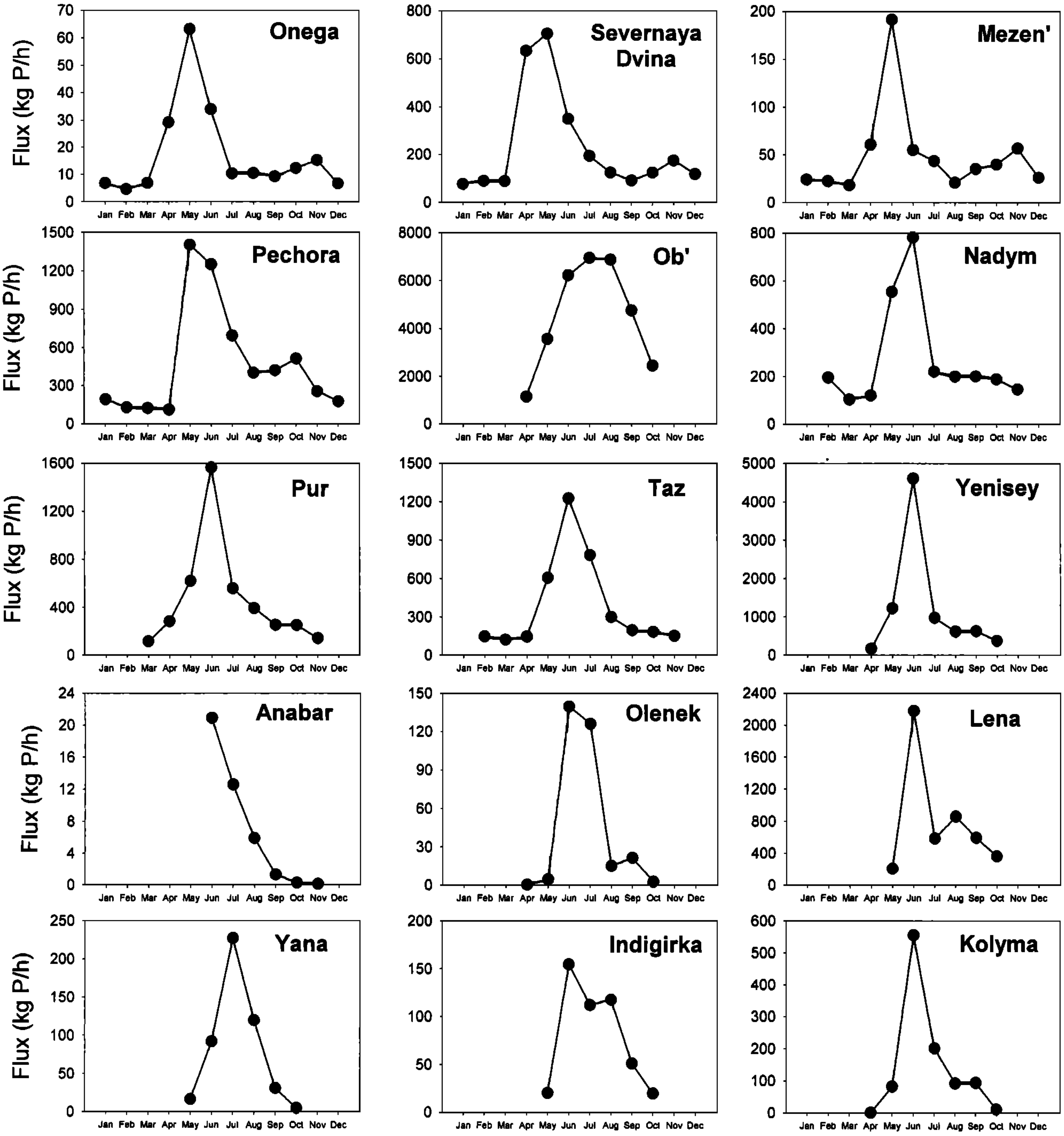

Figure 6. Mean monthly phosphate flux for the 15 rivers in the OGSNK/GSN data set.

observed in nature, particularly in relatively pristine ecosystems. However, some possibilities for blocking nitrification exist, including limitation by dissolved oxygen availability, limitation by cold temperatures, and inhibition by specific organic compounds [*Focht and Verstraete*, 1977; *Sprent*, 1987; *Dyreborg and Arvin*, 1995]. Interestingly, the Ob' River has high levels of ferrous iron, and its oxidation periodically causes hypoxia [*Telang et al.*, 1991]. Although data are limited, it seems likely that other rivers in the central Siberian lowlands (including the Pur, Taz, and Nadym) may also have elevated iron levels, given their similar catchment characteristics. Moreover, high dissolved organic matter concentrations in these rivers might also contribute to oxygen consumption and hypoxia. If, in fact, hypoxia were a common feature of these systems, nitrification would be blocked and ammonium could accumulate to the levels we have reported. More data will be needed to adequately test this hypothesis.

4.2. Comparison With Other Estimates

The best method for testing the reliability of the OGSNK/GSN data set is to compare it to independent nutrient concentration and flux estimates. Unfortunately, many of the publications that at first appear promising [*Tarasov et al.*, 1988; *Smirnov*, 1994; *Gordeev et al.*, 1996; *Tsirkunov et al.*, 1998] actually use values from the official state data (i.e., part of the OGSNK/GSN data set) to derive their estimates. Similarly,

Table 2. Annual Nutrient Flux Estimates Derived From the OGSNK/GSN Nutrient Data Set and the R-ArcticNet Discharge Data, Ordered by Decreasing Ammonium Flux

	Flux to Ocean, 1000 t/yr		
River	NH_4-N	NO_3-N	PO_4-P
Ob'	287.4	34.8	23.5
Yenisey	207.8	18.4	6.2
Lena	39.4	19.5	3.5
Taz	30.5	0.75	2.8
Pur	24.3	0.74	3.0
Pechora	17.8	7.1	4.2
Severnaya Dvina	14.9	6.7	2.0
Nadym	12.2	0.55	2.0
Yana	6.8	1.2	0.36
Kolyma	5.2	2.5	0.76
Indigirka	3.8	2.3	0.35
Olenek	2.7	0.78	0.23
Mezen'	2.2	0.71	0.44
Anabar	1.9	0.09	0.03
Onega	1.6	0.99	0.15
Amazon	131.8	1021.5	160.7
Mississippi	21.2	740.6	71.4
Yukon	9.1	21.7	2.1
Mackenzie	...	23.6	1.5

Note that for some rivers, monthly discharge data were not available at the OGSNK/GSN nutrient station, so the closest R-ArcticNet discharge station was used to compute fluxes. Flux estimates for the Amazon, Mississippi, Yukon, and Mackenzie rivers were made using data contained in the GEMS-GLORI database [*Meybeck and Ragu*, 1997]. Ellipsis indicates data are not available in GEMS-GLORI database.

large United Nations–sponsored databases, GEMS/Global Register of River Inputs (GLORI) (Meybeck and Ragu, book draft, 1995) and GEMS/Water (www.cciw.ca/gems/), also summarize parts of the official Russian data. Although the OGSNK/GSN data set we present is far more extensive than these other reports, the data sets ultimately come from the same source and therefore cannot justifiably be used for critical comparisons.

Fortunately, other sources of information exist. The most extensive independent data set comes from Russian scientists working outside of the OGSNK/GSN framework. Their results have been compiled for a 10-year period (1986–1995) for 10 Arctic rivers, all of which are included in the 15-river OGSNK/GSN data set that we have already presented. From this data set (which we shall refer to as data set II) we calculated annual DIN (nitrate plus ammonium) flux, using discharge from the R-ArcticNet database, and compared it to the OGSNK/GSN data and to model estimates derived from *Seitzinger and Kroeze* [1998] (Table 3).

DIN flux estimates vary greatly depending on the data set used (Table 3). For example, annual DIN flux estimates for the Ob' River range from less than 50×10^3 t N/yr using data set II to greater than 300×10^3 t/yr using the OGSNK/GSN data set, with the model estimate of *Seitzinger and Kroeze* [1998] being intermediate. Moreover, it is not simply a systematic offset between the two data sets; in the case of ammonium in the Ob' River, there appears to be almost no relationship between the two data sets (Figure 9). Obviously, at least one, if not both, of the data sets is grossly in error.

Although the OGSNK/GSN data set generally yields a higher DIN flux estimate than does data set II, the pattern is not universal. For example, data set II gives a much higher DIN flux estimate for the Lena River than does the OGSNK/GSN data set. In this case the major discrepancy is not with the ammonium flux estimate (39.4 versus 40.4×10^3 t/yr, OGSNK/GSN data set versus data set II, respectively) but instead with the nitrate flux estimate (19.5 versus 137.8×10^3 t/yr, OGSNK/GSN data set versus data set II, respectively). Therefore there may not only be a problem with ammonium but also with nitrate in at least some rivers.

If Russian rivers behaved as would be expected based on a recently published model [*Seitzinger and Kroeze*, 1998; *Caraco and Cole*, 1999], they would be transporting less DIN than the OGSNK/GSN data suggest (Table 3). We should note that the model is not specific for Arctic rivers but, instead, was calibrated largely using data from temperate and tropical rivers. Overall, the OGSNK/GSN data give an estimate of annual DIN flux 2.3 times greater than the model estimate for the nine rivers in common. However, for some rivers such as the Pur and Taz Rivers, the estimates differ much more, by about an order of magnitude. In some cases the model estimates are closer to the values reported in data set II, but in other cases they are not (e.g., nitrate in the Lena River).

The Lena River in particular has received considerable international attention during the 1990s, largely because of interest in the role of freshwater input on sea-ice formation in the Laptev Sea (into which the Lena flows) and its impact on global climate [*Aagaard and Carmack*, 1989; *Cauwet and Sidorov*, 1996; *Saliot et al.*, 1996; *Kassens et al.*, 1998; *Lara et al.*, 1998; *Rachold and Hubberten*, 1998]. *Lara et al.* [1998] report results from a river expedition in July 1994, where nutrient concentrations at Kyusyur near the mouth of the Lena River were 0.0077 and 0.0014 mg/L for NO_3-N and NH_4-N, respectively. Comparable numbers (same month and year) from the OGSNK/GSN data set are 0.02 mg/L NO_3-N and 0.01 mg/L NH_4-N, whereas data set II lists 0.28 mg/L NO_3-N and 0.04 mg/L NH_4-N. Thus nitrate and ammonium concentration measurements for the Lena River in July 1994 vary by more than 2500%. At this point it is not possible to determine which values are more reliable, although those reported by *Lara et al.* [1998] are closer to what might be expected for a relatively pristine Arctic watershed.

5. Conclusions

Nutrient flux from land to ocean integrates changes in terrestrial ecosystems, in land use, and in other human activities. As global change due to greenhouse warming and human population growth accelerates, a record of water quality is one metric of that change. On the ocean side the coastal deltas, estuaries, and seas respond to changing nutrient fluxes with changes in the intensity and distribution of primary productivity, which in turn impact coastal fisheries. Thus monitoring of nutrient fluxes can provide essential information for watershed management, for coastal fisheries management, and for detection of regional aspects of global change in the Arctic.

In the title of the paper we ask whether it is currently possible to establish a reliable baseline against which to judge future changes in nutrient export to the Arctic Ocean from Russia. It is not.

The most extensive data set available, the OGSNK/GSN data set of the FSU and current Russian Federation, is of questionable reliability. It is possible that the data are accurate,

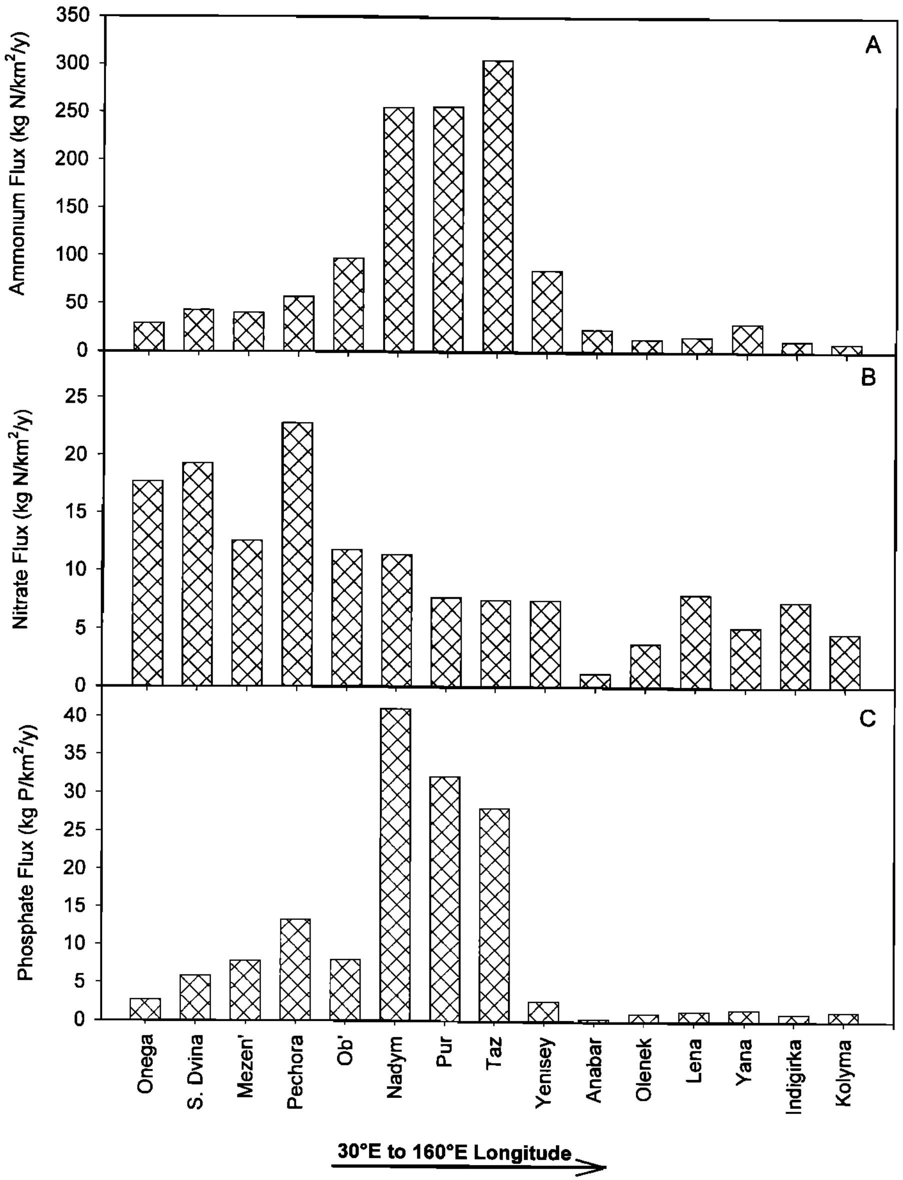

Figure 7. Specific fluxes (normalized to catchment area) of (a) ammonium, (b) nitrate, and (c) phosphate for the 15 rivers in the OGSNK/GSN data set. Rivers are arrayed from west to east.

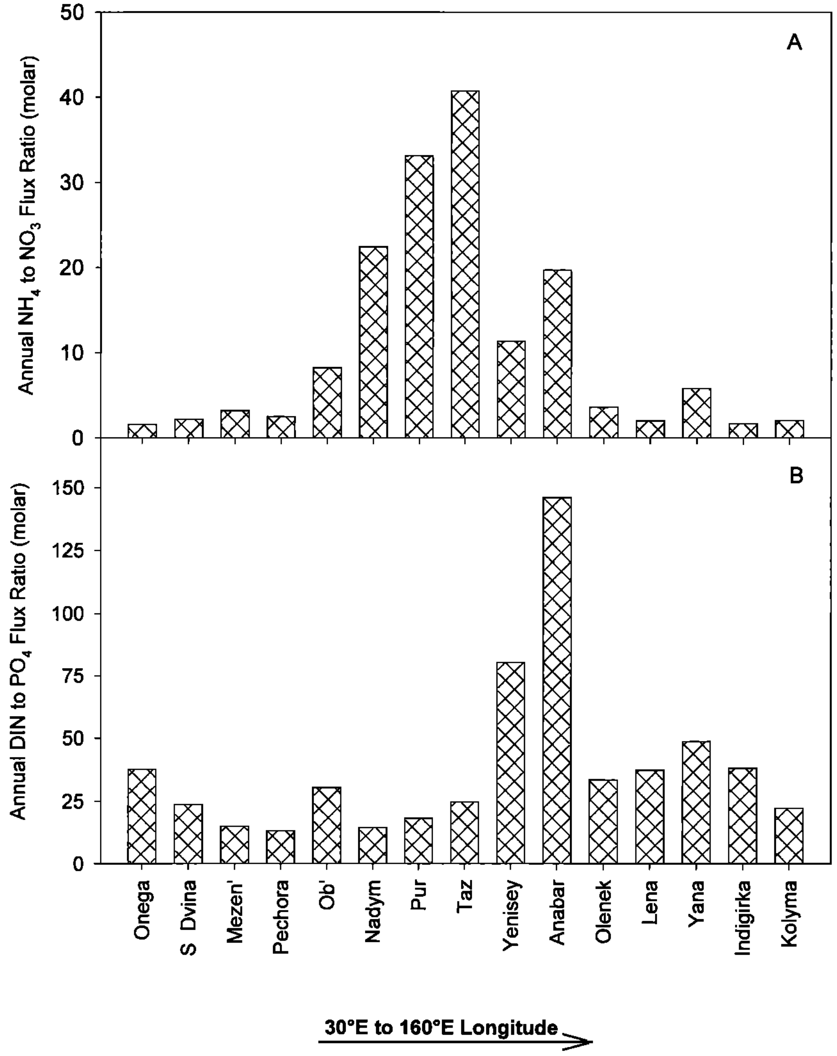

Figure 8. Mean annual nutrient flux ratios. (a) Ammonium to nitrate flux ratio. (b) Dissolved inorganic nitrogen (DIN) to phosphate flux ratio. Rivers are arrayed from west to east.

Table 3. Comparison of Annual DIN (Nitrate Plus Ammonium) Flux Estimates for Selected Russian Arctic Rivers

River	Nitrate Plus Ammonium Flux, 1000 t N/yr		
	OGSNK/GSN	Data Set II	Model[a]
Ob'	322.3	45.4	161.3
Yenisey	226.2	134.9	73.98
Lena	58.9	169.5	33.62
Taz	31.3		4.87[b]
Pur	25.1		4.87[b]
Pechora	25.0	15.4	10.24
Severnaya Dvina	21.6	7.5	
Yana	8.0	2.2	1.15
Kolyma	7.6	6.1	4.64
Indigirka	6.0	2.8	1.95
Olenek	3.4	1.3	1.72
Onega	2.6		2.70
Anabar	2.0	0.5	0.72
Total[c]	659.4	378.1	289.3

R-ArcticNet monthly discharge data (Lammers et al., submitted manuscript, 2000) were used to compute fluxes for the OGSNK/GSN and data set II, whereas the model estimates used annual discharge estimates.

[a]From *Seitzinger and Kroeze* [1998], based on model of *Caraco and Cole* [1999]. Estimates for most of the individual Russian rivers were not reported in the Seitzinger and Kroeze paper but were kindly provided to us by the authors.

[b]The model estimate (4.87×10^3 tons N/yr) is for the sum of the Pur and Taz rivers.

[c]The total is for rivers common to both data sets and the model.

but other data sets often give far different values, and we are not able to determine which of the available data sets are most reliable. If the OGSNK/GSN data set that we have presented can be proven reliable, then we have accurately quantified nutrient flux to the Arctic Ocean from these Russian rivers. Perhaps more exciting, we will have identified an unusual biogeochemical phenomenon (high ammonium export from sparsely inhabited catchments) that we currently do not understand. Although further research would be needed to understand the observed patterns, at least the existing data would allow us to detect future changes.

If, however, the nutrient concentration data are not reliable, then the flux estimates that we and others have provided are wrong. This will lead to incorrect conclusions concerning future changes and a faulty understanding of the current biogeochemical functioning of these catchments.

As is the case for hydrologic and sediment flux modeling, one of the major challenges for the construction and calibration of large-scale biogeochemistry models is data availability [*Milliman and Syvitski*, 1992; *Vörösmarty et al.*, 1996, 2000]. Thus every effort must be made to augment the available discharge, suspended sediment, and nutrient chemistry databases, both regionally in the Arctic as well as globally, either by collecting new data or making available previously collected data. In augmenting nutrient databases, however, data quality must be closely scrutinized. For Russian Arctic rivers it is unclear whether any of the currently available long-term data sets are reliable.

The clarification of this puzzle requires independently collected and analyzed nutrient samples. Only in this way will we be able to fully assess the quality of current data sets and state with any confidence the magnitude of contemporary nutrient flux to the Arctic Ocean. Until new samples are collected and a contemporary nutrient flux baseline is established, we will be squandering one of our better chances for early detection of global change in the Arctic, and our understanding of Arctic-wide biogeochemical cycling and land-ocean interactions in the Arctic will remain uncertain.

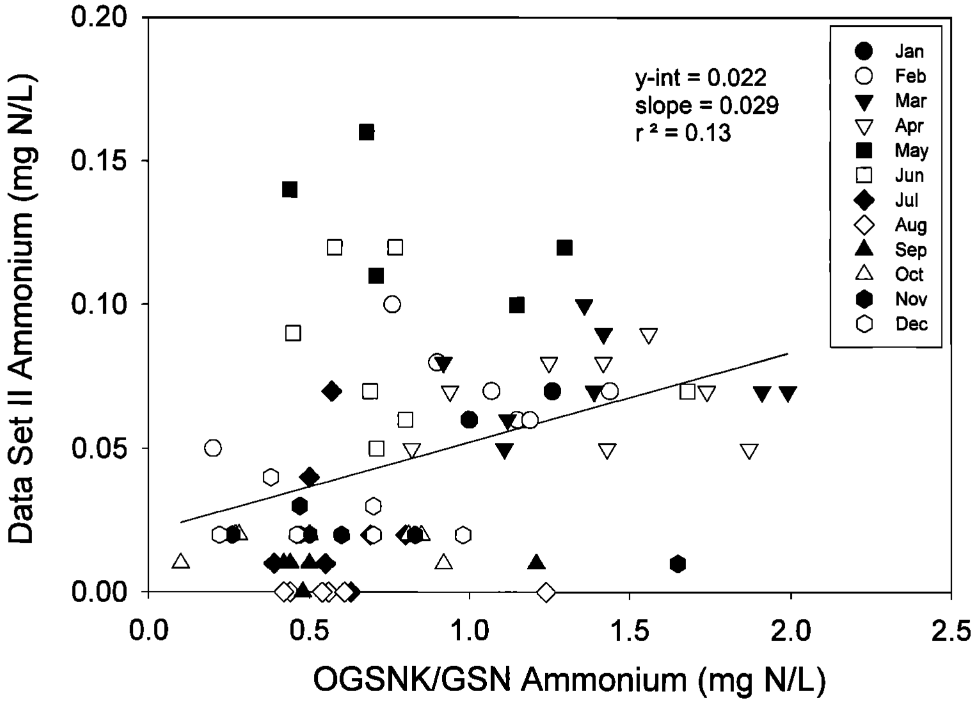

Figure 9. Comparison of ammonium concentration estimates for the Ob' River (1988–1994) using the OGSNK/GSN data set and data set II.

Acknowledgments. This research was funded by the National Science Foundation (NSF-OPP-9524740 and NSF-OPP-9818199). We gratefully acknowledge David Clow, Bob Meade, and two anonymous reviewers for comments on the manuscript. We also thank Rainer Amon, Ludmila Boeva, Ed Landa, Joerg Lobbes, Gerhard Kattner, Vladimir Khlobystov, Bob Meade, Richard Robarts, and Dmitry Varlyguin for insightful discussions and assistance during the preparation of this manuscript and Sybil Seitzinger for sharing her model results with us.

References

Aagaard, K., and E. C. Carmack, The role of sea ice and other fresh water in the arctic circulation, *J. Geophys. Res.*, *94*, 14,485–14,498, 1989.

Alekin, O. A., and L. V. Brazhnikova, *Flux of Dissolved Substances From the Territory of the USSR*, 144 pp., Nauka, Moscow, 1964.

Anderson, L. G., K. Olsson, and M. Chierici, A carbon budget for the Arctic Ocean, *Global Biogeochem. Cycles*, *12*, 455–465, 1998.

Anisimov, O. A., and F. E. Nelson, Permafrost distribution in the northern hemisphere under scenarios of climate change, *Global Planet. Change*, *14*, 59–72, 1996.

Boeva, L. V., Y. Y. Vinnikov, A. V. Zhulidov, G. S. Volovik, V. V. Khlobystov, and S. R. Brown, An assessment of the quality of OGSNK/GSN data relating to nutrient compounds, organochlorine pesticides and biochemical oxygen demand (BOD_5) in the water of the Lower Don, *SIL News*, *28*, 4–5, 1999.

Broecker, W. S., Thermohaline circulation, the Achilles heel of our climate system: Will man-made CO_2 upset the current balance?, *Science*, *278*, 1582–1588, 1997.

Caraco, N. F., and J. J. Cole, Human impact on nitrate export: An analysis using major world rivers, *Ambio*, *28*, 167–170, 1999.

Cauwet, G., and I. Sidorov, The biogeochemistry of Lena River: Organic carbon and nutrients distribution, *Mar. Chem.*, *53*, 211–227, 1996.

Chapin, F. S., G. R. Shaver, A. E. Giblin, K. J. Nadelhoffer, and J. A. Laundre, Responses of arctic tundra to experimental and observed changes in climate, *Ecology*, *76*, 694–711, 1995.

Dyreborg, S., and E. Arvin, Inhibition of nitrification by creosote-contaminated water, *Water Res.*, *29*, 1603–1606, 1995.

Focht, D. D., and W. Verstraete, Biochemical ecology of nitrification and denitrification, *Adv. Microbial Ecol.*, *1*, 135–214, 1977.

Gordeev, V. V., and V. V. Tsirkunov, River fluxes of dissolved and suspended substances, in *A Water Quality Assessment of the Former Soviet Union*, edited by V. Kimstach, M. Meybeck, and E. Baroudy, pp. 311–350, Routledge, New York, 1998.

Gordeev, V. V., J. M. Martin, I. S. Sidorov, and M. V. Sidorova, A reassessment of the Eurasian river input of water, sediment, major elements, and nutrients to the Arctic Ocean, *Am. J. Sci.*, *296*, 664–691, 1996.

Hobbie, J. E., B. L. Kwiatkowski, E. B. Rastetter, D. A. Walker, and R. B. McKane, Carbon cycling in the Kuparuk basin: Plant production, carbon storage, and sensitivity to future changes, *J. Geophys. Res.*, *103*, 29,065–29,073, 1998.

Houghton, J. T., L. J. Meira Filho, B. A. Callander, N. Harris, A. Kattenberg, and K. Maskell, *Climate Change 1995: The Science of Climate Change*, 584 pp., Cambridge Univ. Press, New York, 1996.

Kassens, H., I. Dmitrenko, V. Rachold, J. Thiede, and L. Tomokhov, Russian and German scientists explore the Arctic's Laptev Sea and its climate, *Eos Trans. AGU*, *79*, 317, 322–323, 1998.

Lara, R. J., V. Rachold, G. Kattner, H. W. Hubberten, G. Guggenberger, A. Skoog, and D. N. Thomas, Dissolved organic matter and nutrients in the Lena River, Siberian Arctic: Characteristics and distribution, *Mar. Chem.*, *59*, 301–309, 1998.

Meybeck, M., Carbon, nitrogen, and phosphorus transport by world rivers, *Am. J. Sci.*, *282*, 401–450, 1982.

Milliman, J. D., and J. P. M. Syvitski, Geomorphic/tectonic control of sediment discharge to the ocean: The importance of small mountainous rivers, *J. Geol.*, *100*, 524–544, 1992.

Neischtadt, M. I., World natural phenomenon (bogginess of the West Siberia Plain), *Izv. USSR AS, Ser. Geogr.*, *1*, 21–34, 1971.

Rachold, V., and H. W. Hubberten, Carbon isotope composition of particulate organic material in east Siberian rivers, in *Land-Ocean Systems in the Siberian Arctic: Dynamics and History*, edited by H. Kassens et al., pp. 223–238, Springer-Verlag, New York, 1998.

Saliot, A., G. Cauwet, G. Cahet, D. Mazaudier, and R. Daumas, Microbial activities in the Lena River delta and Laptev Sea, *Mar. Chem.*, *53*, 247–254, 1996.

Seitzinger, S. P., and C. Kroeze, Global distribution of nitrous oxide production and N inputs in freshwater and coastal marine ecosystems, *Global Biogeochem. Cycles*, *12*, 93–113, 1998.

Serreze, M. C., J. E. Walsh, F. S. Chapin, T. Osterkamp, M. Dyurgerov, V. Romanovsky, W. C. Oechel, J. Morison, T. Zhang, and R. G. Barry, Observational evidence of recent change in the northern high-latitude environment, *Clim. Change*, in press, 2000.

Shiklomanov, I. A., World freshwater resources, in *Water in Crisis: A Guide to the World's Fresh Water Resources*, edited by P. H. Gleick, pp. 13–24, Oxford Univ. Press, New York, 1993.

Smirnov, M. P., Assessment of the discharge of nutrients into seas of the Arctic and Pacific oceans and of the anthropogenic component of this discharge (in Russian), *Hydrochem. Mater.*, *113*, 121–147, 1994.

Sprent, J. I., *The Ecology of the Nitrogen Cycle*, 151 pp., Cambridge Univ. Press, New York, 1987.

Tarasov, M. N., M. P. Smirnov, I. A. Kruchkov, and G. I. Laki, The river discharge of nutrients in the USSR and its temporal changes (1936–1980) (in Russian), *Hydrochem. Mater.*, *103*, 49–66, 1988.

Telang, S. A., R. Pocklington, A. S. Naidu, E. A. Romankevich, I. I. Gitelson, and M. I. Gladyshev, Carbon and mineral transport in major North American, Russian arctic, and Siberian rivers: The St. Lawrence, the Mackenzie, the Yukon, the arctic Alaskan rivers, the arctic basin rivers in the Soviet Union, and the Yenisei, in *Biogeochemistry of Major World Rivers*, edited by E. T. Degens, S. Kempe, and J. E. Richey, pp. 75–104, John Wiley, New York, 1991.

Tsirkunov, V. V., Water quality monitoring systems, in *A Water Quality Assessment of the Former Soviet Union*, edited by V. Kimstach, M. Meybeck, and E. Baroudy, pp. 95–112, Routledge, New York, 1998.

Tsirkunov, V. V., M. P. Polkanov, and V. G. Drabkova, Natural composition of surface water and groundwaters, in *A Water Quality Assessment of the Former Soviet Union*, edited by V. Kimstach, M. Meybeck, and E. Baroudy, pp. 25–68, Routledge, New York, 1998.

Vörösmarty, C. J., C. J. Willmott, B. J. Choudhury, A. L. Schloss, T. K. Stearns, S. M. Robeson, and T. J. Dorman, Analyzing the discharge regime of a large tropical river through remote sensing, ground-based climatic data, and modeling, *Water Resour. Res.*, *32*, 3137–3150, 1996.

Vörösmarty, C. J., B. Fekete, M. Meybeck, and R. B. Lammers, The global system of rivers: Its role in organizing continental land mass and defining land-to-ocean linkages, *Global Biogeochem. Cycles*, *14*, 599–621, 2000.

Zhulidov, A. V., J. V. Headley, D. F. Pavlov, R. D. Robarts, L. G. Korotova, V. V. Fadeev, O. V. Zhulidova, Y. Volovik, and V. Khlobystov, Distribution of organochlorine insecticides in rivers of the Russian Federation, *J. Environ. Qual.*, *27*, 1356–1366, 1998.

Zhulidov, A. V., J. V. Headley, R. D. Robarts, A. M. Nikanorov, and A. A. Ischenko, *Atlas of Russian Wetlands: Biogeography and Metal Concentrations*, 309 pp., Natl. Hydrol. Res. Inst., Saskatoon, Saskatchewan, Canada, 1997.

V. V. Gordeev and P. P. Shirshov Institute of Oceanology, Russian Academy of Sciences, Moscow 117218, Russia. (gordeev@geo.sio.rssi.ru)

R. M. Holmes and B. J. Peterson, The Ecosystems Center, Marine Biological Laboratory, Woods Hole, MA 02543. (rholmes@mbl.edu; peterson@mbl.edu)

R. B. Lammers and C. J. Vörösmarty, Complex Systems Research Center, University of New Hampshire, Durham, NH 03824. (richard.lammers@unh.edu; charles.vorosmarty@unh.edu)

M. Meybeck, Laboratorie de Géologie Appliquée, CNRS, Place Jussieu, 75257 Paris, France. (meybeck@biogeodis.jussieu.fr)

A. V. Zhulidov, Centre for Preparation and Implementation of International Projects on Technical Assistance, Rostov-on-Don 344104, Russia. (zhulidov@ncbcppi.rnd.runnet.ru)

(Received November 15, 1999; revised April 7, 2000; accepted April 7, 2000.)