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Recent particulate organic carbon and total suspended matter fluxes from the Ob and Yenisei Rivers into the Kara Sea (Siberia)

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Abstract

The Ob and Yenisei Rivers account for more than one-third of the total fresh water supply to the Arctic Ocean. In the past, their sediment load and particulate organic carbon (POC) discharge into the Kara Sea has been measured at stations in the hinterland far south of the estuaries. Suspended matter has been sampled in the estuaries and southern Kara Sea within the framework of the joint Russian–German "SIRRO" program (Siberian River Run-Off), allowing a reliable new estimate of fluxes from the rivers into the Kara Sea. Our estimates of annual supplies of sediment (3.76×10^6 t), particulate organic carbon (0.27×10^6 t) and particulate nitrogen (PN) (0.027×10^6 t) from the Ob River to the Kara Sea are lower than earlier estimates from the northernmost gauging station in the hinterland due to deposition of particulate matter in the Ob Bay. On the other hand, our estimates of the Yenisei's annual sediment (5.03×10^6 t), particulate organic carbon (0.57×10^6 t) and particulate nitrogen (0.084×10^6 t) supplies to the Kara Sea are probably too high, as they suggest a pure bypass system in the investigated area. We differentiate between an area of recent deposition in the south of the Kara Sea and an area of recent organic matter degradation further north.

Keywords: Kara Sea; Ob River; Yenisei River; carbon budget; carbon cycle; Arctic Ocean; POC; TSM

1. Introduction

The Arctic Ocean makes up only 1.5% of the global ocean, but receives about 10% of the global river discharge (Aagaard, 1994). Furthermore, with its large continental shelves, the Arctic Ocean is one of the key regions of global organic carbon burial. More than one-third of the total freshwater discharge to the Arctic Ocean is into the Kara Sea, mainly via the Ob and Yenisei Rivers (Aagaard and Carmack, 1989). The Kara Sea is a shallow shelf sea, partially enclosed to the west by Novaya Zemlya, to the south by the Russian mainland and on the east and southeast to the Zevernaya Zemlya Archipelago and Taimyr Peninsula (Fig. 1). To the north, the Kara Sea is open to the Arctic Basin. Small coastal openings connect the Kara Sea to the Laptev Sea (through Vilkitsky Strait) and to the Barents Sea (through Kara Strait). It encompasses an area of

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Fig. 1. Geographical position of the study area.

about 883,000 km^2 with a water volume of 98,000 km^3 (Pavlov and Pfirman, 1995). The central and the eastern parts of the Kara Sea are dominated by the Ob and Yenisei Delta (= Yamal Plateau) with a characteristic depth of 25–30 m. To the west, the Novaya Zemlya Trough reaches depths of more than 300 m and separates the Yamal Plateau from Novaya Zemlya. The Kara Sea is connected to the St. Anna Trough further North by a sill of about 200 m water depth (Johnson et al., 1997). The Yenisei River is Siberia's largest river and among the 10 largest rivers in the world (Gordeev, 2000; Milliman, 1991), with a drainage area of 2.58×10^6 km^2 and a length of 3844 km (Milliman and Meade, 1983; Telang et al., 1991).

In its upper and middle reaches, the Yenisei River crosses igneous basement rocks and fills eight large man-made reservoirs (e.g. the Krasnoyarsk and the Sayano-Shushenskaya). In its lower reaches, the Yenisei River crosses the West Siberian Plain in regions of Quaternary sediments rich in permafrost. The taiga is gradually replaced by forest tundra along the banks.

The Ob River is Siberia's third largest river in terms of annual discharge (429 km^3 year^{-1}; Gordeev, 2000) and is the longest Arctic river (6370 km including the Ob Bay) with the largest catchment area (2.99×10^6 km^2) (Milliman, 1991; Telang et al., 1991). Its upper course has its source in the Altai Mountains, and both the middle and the lower courses flow through easily eroded rocks, forming branches and flood plain lakes. The Ob River fills eight man-made reservoirs in its hinterland. The taiga is gradually replaced by forest tundra and then by tundra along the stream. With its mean gradient of 4.2×10^{-5}, the Ob River shows the typical characteristics of a plain-crossing river (Telang et al., 1991). The delta is nearly 100 km long and composed of about 50 islands.

Due to high river runoff, Kara Sea waters have salinities from <10 in the south to about 35 in the north. The residence time of fresh water in the Arctic shelf seas has been estimated to be 1–3 years (Schlosser et al., 1995). Fresh water discharge to the Kara Sea is highly seasonal with the main portion occurring during spring and summer. About 30% of the total annual water budget and 42% of the total annual sediment budget are discharged in June (Lammers and Shiklomanov, 2000), part of which occurs while the Southern Kara Sea is ice-covered. The Kara Sea is almost entirely ice-covered from October to May (e.g. Pavlov and Pfirman, 1995) with only a small narrow polynya north of the fast-ice zone remaining ice-free due to prevailing offshore winds (Harms et al., 2000; Pavlov and Pfirman, 1995). The completely ice-free period lasts for only three months, from mid-July to mid-October. The strong seasonal variations in river runoff, wind field and ice formation enforce strong seasonal variabilities in the surface hydrography of the southern Kara Sea, whereas deep water supplied from the central Arctic Ocean forms a stable salt wedge with salinities >30. Large amounts of the river suspension have been deposited as thick packages of sediments found mostly in the outer estuaries and the southernmost Kara Sea (Dittmers et al., 2003; Stein and Fahl, 2004; Stein et al., 2003a) and it has been assumed that the major flux of organic carbon deposited in the Kara Sea is of riverine origin (Stein and Fahl, 2004 and references therein). The most northerly water and sediment discharge data have until now originated from measurements at upstream monitoring stations in Salekhard (Ob River) and Igarka (Yenisei River; Fig. 1) located well south of the river mouths. Estimated sediment and organic carbon fluxes based on these discharges do not represent the true fluxes into the Kara Sea as they do not consider processes downstream of the monitoring stations (Lisitsyn, 1995). Only during the last years were studies carried out on concentrations and fluxes of suspended matter and organic carbon within the estuaries and estuary mouths, namely during the 1993 *RV Dmitriy Mendeleev* (e.g. Kuptsov et al., 1995; Lisitsyn et al., 1995) and the 1994 *RV Akademik Fedorov* cruises (e.g. Lobbes et al., 2000). However, fluxes from the estuaries to the Kara Sea were only calculated by Lobbes et al. (2000). A detailed overview of sediment discharge measurements and fluxes published so far for the Kara Sea can be found in Holmes et al. (2002).

The Arctic realm is one of the regions most sensitive to changes in environmental conditions such as global warming. Examination and quantification of recent fluxes from Arctic rivers into the adjacent oceans provide a baseline for detection and evaluation of future changes. Furthermore, recent flux calculations allow estimates of recent sedimentation budgets, which, in turn, can be compared to the Holocene record. The aim of this study performed within the multidisciplinary Russian–German research project "Siberian River Run-Off (SIRRO)" (Stein et al., 2003b) is to provide recent estimates of total suspended matter (TSM), particulate organic carbon (POC) and particulate nitrogen (PN) fluxes into the Kara Sea that are based on direct measurements instead of being based on discharge measurements from the northernmost gauging stations in the hinterland.

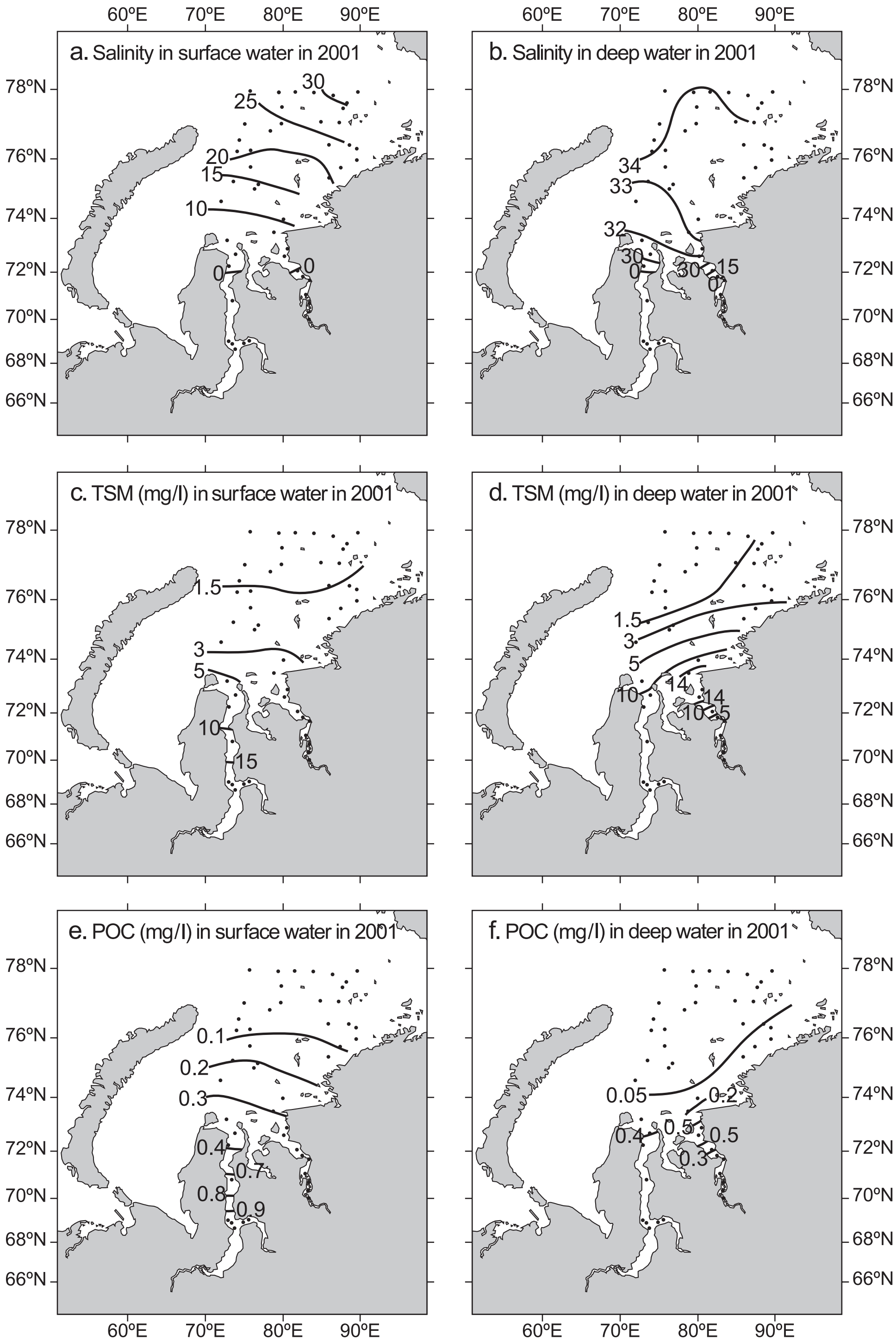

Fig. 2. Salinity, TSM and POC concentration in the Ob and Yenisei Rivers and the adjacent Kara Sea in 2001. Left panel: surface water, right panel: deep water. Salinity is given in (a) and (b); TSM (mg/l) in (c) and (d); and POC (mg/l) in (e) and (f). Dots mark the sampling points.

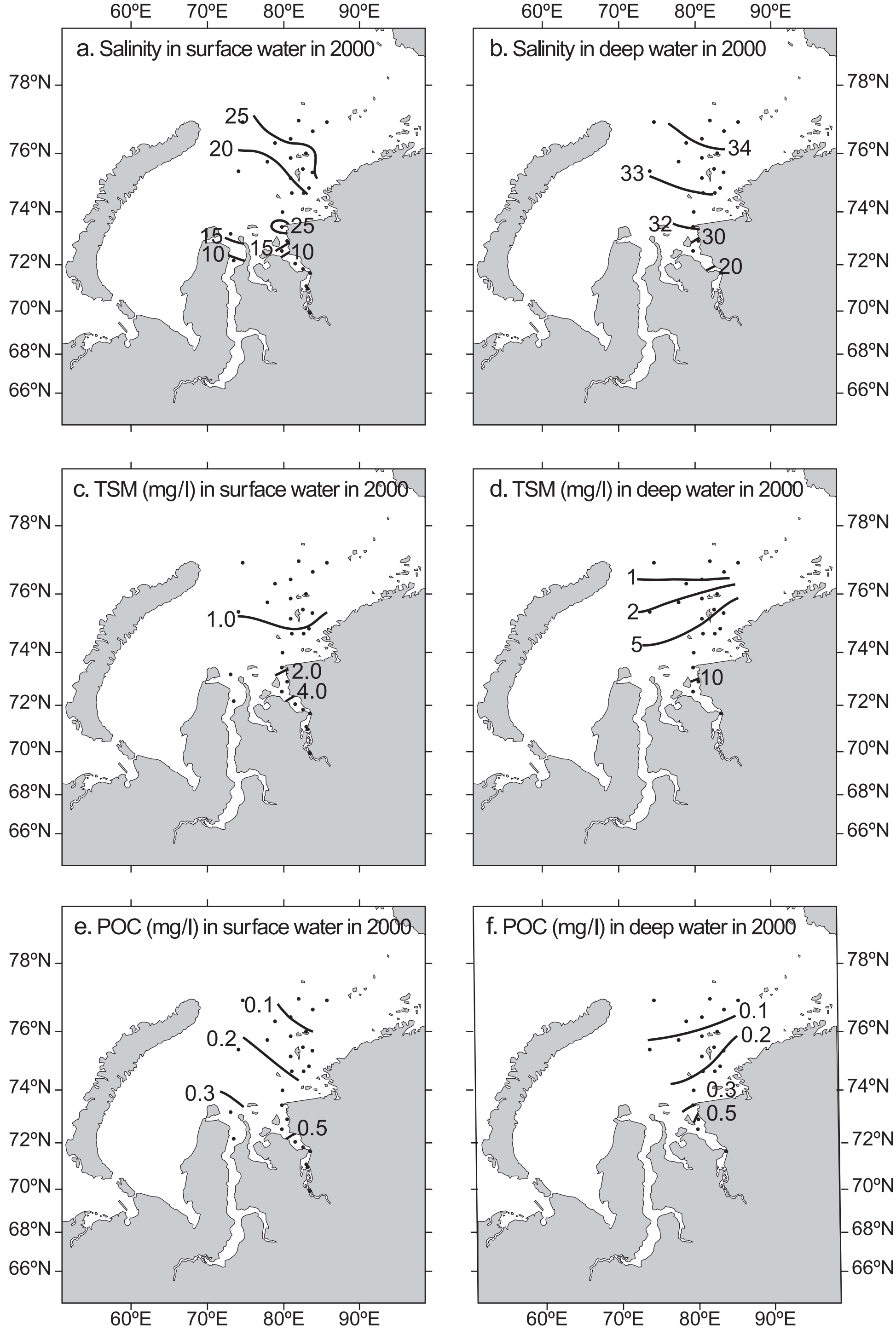

Fig. 3. Salinity, TSM and POC concentration in the Ob and Yenisei Rivers and the adjacent Kara Sea in 2000. Left panel: surface water, right panel: deep water. Salinity is given in (a) and (b); TSM (mg/l) in (c) and (d); and POC (mg/l) in (e) and (f). Dots mark the sampling points.

2. Materials and methods

2.1. Sampling

Samples were collected on cruises of the *RV Akademik Boris Petrov* in 1999, 2000 and 2001 as part of the German–Russian SIRRO project (Stein and Stepanets, 2000, 2001, 2002). Kara Sea and estuarine suspended matter samples were taken between August 24th and September 8th, 1999, between September 3rd and 20th, 2000, and between August 14th and September 11th, 2001. Suspended matter was sampled using Niskin bottles (intermediate and deep water), buckets (surface water) or large volume samplers (200 l bathomat; deep water). Subsequently, 0.25 to several litres of water were then filtered through Whatman GF/F glass fiber filters as well as through Whatman polycarbonate membrane filters (pore size: 0.4 μm) and dried at 40 °C. At most stations, suspended matter was sampled in surface, intermediate and bottom waters. Dots in Figs. 2 and 3 indicate the sample stations in 2001 (48 stations, Gebhardt et al., 2002) and 2000 (28 stations, Unger et al., 2001), respectively.

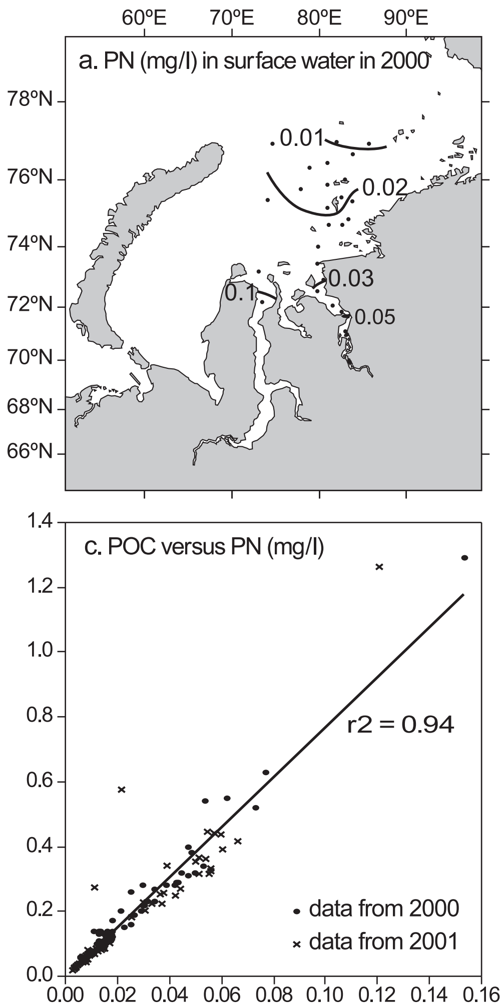

Fig. 4. PN concentration in the Ob and Yenisei Rivers and the adjacent Kara Sea in 2000 and 2001. PN concentrations are given in (a) and (b), correlation between POC and PN in (c). Dots in (a) and (b) mark the sampling points.

2.2. Analytical procedures

Total carbon and nitrogen were measured using a Carlo Erba Nitrogen Analyzer 1500. The precision of this method is 0.05% for carbon and 0.005% for nitrogen. C/N ratios have been calculated on molar basis. Carbonate percentages of suspended matter samples were initially determined using a Wösthoff Charmograph 6. The typical standard deviation of results is 1%. All measurements were below 0.2% of carbonate with most below 0.1%. Because this is close to the error range of total carbon measurements, we have further assumed that total carbon of all samples equals total organic carbon.

Salinity measurements were performed immediately after water sampling using a LF 330/SET Conductivity Hand-Held Meter with Standard Conductivity Cell TetraCon 325. The precision of these measurements is ± 0.1.

TSM fluxes calculated from glass fiber filter agree well with TSM fluxes calculated from polycarbonate membrane filters; for this study, glass fiber filter data were used because this type of filter was also used to perform organic matter measurements. Particulate organic carbon and particulate nitrogen were measured as a percentage of total suspended matter and subsequently calculated as absolute values in milligrams per liter.

3. Results

3.1. Salinity

The Kara Sea surface waters are underlain by highly saline deep waters with a pycnocline separating the two water masses (as reported in Burenkov and Vasil'kov, 1995). Water with salinities >30 enters the estuaries as salt intrusions, forming a stable salt wedge in the Yenisei River which penetrates as far south as a narrows at 71.6°N. The salt intrusion into the Ob River is less pronounced, reaching as far south as 72°N, and is more mixed with the overlying surface water.

Salinities in the northern Kara Sea were quite similar in 2001 and 2000 (Figs. 2 and 3). Nevertheless, the salt water intrusion into the Yenisei River was much more saline and penetrated a little further south in 2000. A lens of highly saline surface water (about 25) was observed just north of the Yenisei estuary in 2000, during a sampling period about 1–2 weeks later than in 2001. The data suggest that in 2001 the fresh water influence of the rivers was still much higher in the estuary.

3.2. Total suspended matter

TSM was constant throughout the entire Yenisei River in both years, whereas TSM in the Ob River decreased from the Ob-Taz River confluence to the estuary in 2001 (Figs. 2 and 3). In the 2000 data, surface water TSM concentrations were slightly lower in the northern part of the study area, but higher in the Yenisei River. Ob River values show extremely high TSM, whereas POC is only slightly enhanced compared to 2001. Because the 2000 Ob River TSM data were obtained shortly after a storm, the data were biased by resuspension and therefore excluded in this study.

3.3. Particulate organic carbon and particulate nitrogen

Like the TSM data described above, Yenisei River POC values are constant in both years. However, a

Table 1
Salinity, TSM, POC and PN measured in 2001

	Salinity	TSM (mg/l)	POC (mg/l)	PN (mg/l)
Rivers	0–10[a]	Ob: 5.6–18 Yen.: 3.2	Ob: 0.35–0.9 Yen.: 0.36	Ob: 0.04–0.12 Yen.: 0.053
Gradients in the rivers[b]	N to S	Ob: S to N Yen.: no gradient	Ob: S to N Yen.: no gradient	Ob: S to N Yen.: no gradient
Surface waters[c]	0–30	1.1–5.6	0.05–0.36	0.01–0.053
Gradients in surface waters[b,c]	NE to SW	S to N	S to N	S to N
Deep waters[c]	32–34.8	0.9–14	0.02–0.4	<0.01–0.05
Gradients in deep waters[b,c]	N to S	SE to NW	SE–NW	SE to NE

[a] Values in riverine surface waters; deep water salt intrusions with salinities up to 30 were measured in the estuaries, but not indicated here.
[b] Gradients from highest towards lowest values.
[c] Surface waters of the open Kara Sea.

strong gradient is observable in the Ob River data from the Ob-Taz River confluence to the estuary (Fig. 4, Table 1). Surface POC values in the Yenisei River and in coastal waters along the Taimyr Peninsula are slightly higher in 2000 than in 2001. Deep water POC, too, is somewhat higher than in 2001.

PN in the Ob River shows a strong gradient, whereas values in the Yenisei River are rather homogenous. PN values are slightly lower in the estuaries and the areas just north of the estuaries, but slightly higher in the central part of the Kara Sea in 2000 than in 2001. POC and PN contents are significantly correlated ($r^2 = 0.94$), as found in other studies (e.g. Stein and Fahl, 2004).

4. Discussion

4.1. Interannual and intraseasonal variability

The Ob and Yenisei rivers' water and sediment discharges vary interannually due to differences in the factors controlling the water and sediment discharge such as air temperature, wind fields (Harms and Karcher, 1999), snow cover and melting rates in the hinterland. This leads to interannual differences in the date of ice break-up in the Yenisei and Ob rivers (ice distribution maps at http://www.seaice.de; Kaleschke et al., 2001), as well as in the length of the ice-free period. The central and western to northwestern part of the study area are mostly influenced by Ob River water, whereas the eastern part is mostly influenced by Yenisei River water. Due to different timing and discharge patterns, oceanographic conditions are variable in the Kara Sea. Furthermore, the summer cycle is quite short in Arctic regions ending with the new ice cover in October. The sampling periods in 1999, 2000 and 2001 span different segments (August 24th to September 8th in 1999, September 3rd to 20th in 2000 and August 14th to September 11th in 2001) of this highly variable summer cycle.

In 1999, the studied area was limited to the estuaries and southern Kara Sea (up to 74°30′N). The summer cycle was in an early stage and a large plankton bloom was sampled, documented by high chlorophyll *a* values (Nöthig et al., 2003) and high fluxes into a short-time sediment trap off the Ob estuary (Gaye-Haake et al., 2003). In 2000, when the study area was extended to 77°N, a rather late stage in the summer cycle was sampled during a period of reduced river run-off resulting in higher salinities in the estuaries. In 2001, the sampling area was further extended to 78°N, and the Ob River was intensively sampled at an intermediate stage in the summer cycle. River run-off was still quite high, as revealed by lower salinities in the estuarine surface waters in 2001 than in 2000 (Figs. 2 and 3). Due to the complex hydrographic situation in the Kara Sea, the datasets from the different years could not be merged. For the calculation of TSM, POC and PN budgets for the Ob and the Yenisei rivers, we have decided to use the 2001 dataset as it covers a larger part of the Kara Sea, as well as the rivers.

4.2. TSM and POC in the Ob and the Yenisei Rivers

Surface TSM (POC) concentrations decrease from 18 (0.9) to 5.6 mg/l (0.4 mg/l) along the course of the Ob River from our southernmost station to the estuary, whereas the POC (PN) contents of suspended matter remain constant at about 9.3% (1.5%). These data are consistent with previous studies (e.g. Lukashin et al., 1999; Shevchenko et al., 1996; Unger et al., 2001), that indicate TSM deposition without significant degradation of organic matter in the water column during downstream transport. Constant C/N ratios and insignificant changes in labile organic constituents further confirm these findings (D. Unger, unpubl. data). From the Ob-Taz River confluence to the estuary, TSM is reduced by 50% and POC concentration by 55%. Resuspension in deep water samples is indicated by enhanced TSM concentrations and reduced POC contents. Organic carbon contents of river bed sediments are between 1% and 2% (Fahl et al., 2003; D. Unger, unpubl. data) and, therefore, when resuspended, reduce the organic carbon contents of TSM. The Ob estuary and the northern part of the Ob Bay are significantly influenced by tidal energy (Harms and Karcher, 1999). This counteracts the strong stratification by salt water intrusion and causes the mixing of surface waters, deep waters and surface sediments, resulting in resuspension. During our observations in September, the Ob Bay appears to be a depositional area with resuspension and erosion taking place only in the tidally influenced, northernmost areas.

Within the Yenisei River, surface water TSM and POC are remarkably constant with TSM around 3.2 mg/l and POC around 0.36 mg/l. Deep water TSM concentration is slightly higher than surface TSM, whereas deep water POC concentration is slightly lower, suggesting resuspension at the river bed. Resuspension is high in the estuary. During August, the studied section of the Yenisei River seems to be a bypass system for POC, where it is neither formed, deposited nor degraded significantly. TSM concentrations are slightly more variable because resuspension is rather common in the Yenisei River; nevertheless, even for TSM, the Yenisei River acts as a bypass system.

4.3. Transport, degradation and sedimentation of TSM and POC

The riverine surface water can be traced by its low salinities into the southern Kara Sea up to 76°N where salinities reach about 20 (Fig. 2a). The Ob River discharges mainly towards the north, whereas the Yenisei River outflow is towards the northeast, along the coast (Harms et al., 2000). The reduction of TSM and POC concentrations by about 50% south of 75°N could, to a large extent, be explained by conservative mixing of marine surface water (e.g. water from north of 76°N with a salinity of 30 and a TSM concentration of 1 mg/l) with Ob River water (salinity of 10 and TSM concentration of 5.6 mg/l at the river mouth) suggesting that little sedimentation takes place.

Salinity and POC concentrations are negatively correlated ($r^2 = 0.69$; Fig. 5a) indicating that the dilution of riverine POC-rich with a marine POC-poor water is the major process determining POC concentrations in surface waters similar to the conservative mixing observed for dissolved organic carbon (DOC) (Köhler et al., 2003). However, the correlation is less significant than that for DOC and salinity. This may be due to sedimentation and the primary production of POC. Data from 1999 do not fit into this pattern due to a plankton bloom in the southern Kara Sea. TSM correlation with salinity is less pronounced ($r^2 = 0.53$) due to resuspension processes (Fig. 5b).

This simple view, however, underestimates the significance of primary productivity. Short-term sediment traps deployed off the Ob and Yenisei estuaries in September 1999 have sampled a sinking flux of 50–1300 mg m^{-2} day^{-1} of organic carbon (Gaye-Haake et al., 2003), and sedimentological stations deployed in the estuaries and the adjacent portions of the Kara Sea during September 1993 revealed POC fluxes of 0.71–368 mg m^{-2} day^{-1} (Lisitsyn et al., 1995). Vertical organic carbon fluxes sampled by a

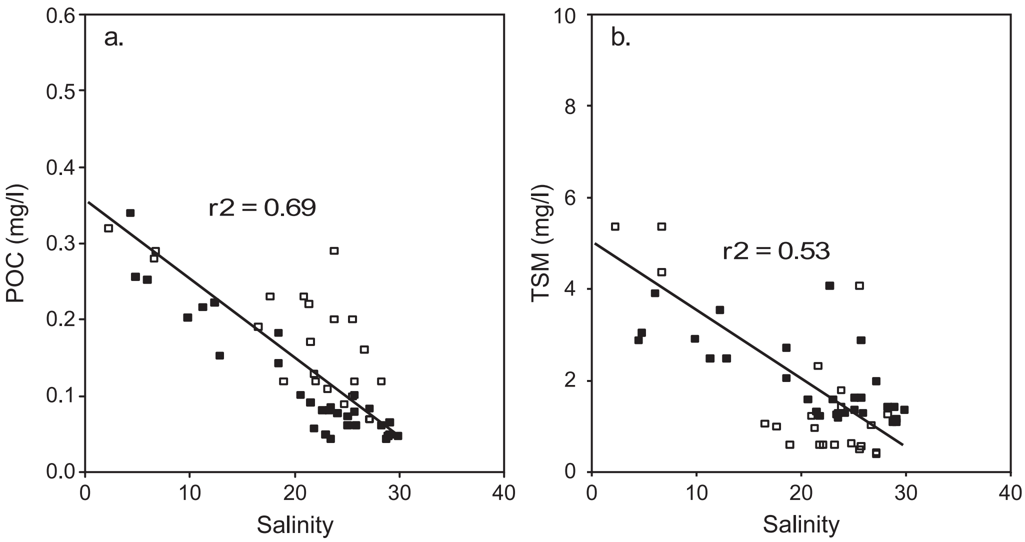

Fig. 5. Correlation of POC and TSM with salinity. Data from the Ob are left out due to high resuspension. (a) POC versus salinity, (b) TSM versus salinity. Open squares: data from 2000, closed squares: data from 2001.

trap in September 2000 were of the same order of magnitude (B. Gaye-Haake, unpubl. data). Although the bloom observed off the Ob River mouth in 1999 was more intense than in the following years, this shows the constraints of suspended matter sampling. It has been shown that the various methods for sampling particulate matter in the water column collect different types of particles. While sediment traps can sample the rather scarce but large fast-sinking aggregates, water bottles and in situ filtration devices sample the fine suspended matter with much longer residence times in the water column (Fowler and Knauer, 1986; Michaels and Silver, 1988; Walsh and Gardner, 1992). Our TSM sampling, possibly, underestimates vertically sinking organic matter from plankton blooms. However, because the amount and nature of measured suspended matter in the water column between the Ob estuary and 75°N does not change considerably, we believe that deposition in this area is in the same order of magnitude as primary production. Generally, this area is characterized by little deposition, mainly taking place in depressions such as incisions and paleovalleys (Dittmers et al., 2003). Between 75°N and 76°N, the surface salinities increase to 20 and deep water salinities to 34. TSM is reduced in this area by about 35%, whereas POC concentration is reduced by more than 75%. Thus, in this region, not only does conservative mixing take place, but also the degradation of organic matter. The riverine Yenisei water flows towards the northeast along the coast and finally enters the Laptev Sea through the Vilkitsky Strait (Harms et al., 2000). Surface water salinities increase from 5 to 20 towards 75°N, deep water salinities remain constant at 33, reflecting stable stratification. On its way to 75°N, the riverine Yenisei water loses about 50% of its TSM, but around 65% of its POC. As in the region north of the Ob River, mixing of marine and fluvial water takes place in connection with POC degradation. Differentiating areas of pure mixing from areas of mixing coupled with degradation would be too speculative due to the wider sampling grid and the presence of the nearby Taimyr Peninsula and the Pyasina River (Fig. 1) which could additionally influence the concentration and composition of both TSM and POC.

North of 76°N, TSM remains relatively constant at 1.1–1.4 mg/l, except in the vicinity of the Taimyr Peninsula and the Zevernaya Zemlya Archipelago. POC concentration shows a similar pattern with values between 0.05 and 0.08 mg/l. Altogether, the surface water is characterized by a decrease in TSM and POC concentrations towards the north and northeast, and the area north of 76°N has a rather constant concentration of all parameters (with the exception of areas close to the Taimyr Peninsula and the Zevernaya Zemlya Archipelago) that probably reflects the fact that background Kara Sea concentrations are not influenced much by riverine input.

Deep water in the southern and central Kara Sea shows a different pattern: salinities decrease from 34.8 to 31 towards the south, and TSM and POC concentrations decrease from northeast to southwest. This reflects the mean annual circulation of the deep water masses that follow a northeasterly current (Harms and Karcher, 1999). Pycnocline TSM shows the same trend as the surface water TSM, but all values are slightly higher than both surface and deep water TSM. POC concentrations decrease towards the north and are rather constant north of 76°N, which is similar to the surface water. The pycnocline is, thus, enriched in lithogenic material, but not in organic material, indicating that fine material probably is trapped and further degraded at the pycnocline.

Based on our results we can distinguish between (i) an area of deposition of fluvial matter in the Ob Bay and the estuaries, (ii) an area of little deposition of fluvial material in the southern Kara Sea and (iii) an area of enhanced organic matter degradation in the northern Kara Sea (Fig. 6). Stein and Fahl (2004, their fig. 7.6.22) provide new data about the Holocene sediment thicknesses. The Holocene accumulation centers are quite well reflected by our data from 2001; however, deposition of sediment between 76°N and 77°N north of the Ob estuary is not clearly visible. Several recent experimental studies (e.g. Serra et al., 1997; Winterwerp, 2002) as well as studies in the Scheldt estuary (The Netherlands) and the Rhône estuary (France) (e.g. Burban et al., 1989; Burban et al., 1990; Thill et al., 2001) showed that flocculation and aggregation leading to sedimentation of particulate matter in estuaries mainly depends on particle concentration and turbulence. The reduction of flow speed resulting in stronger turbulence as the Ob River widens into the Ob Bay and the Yenisei River into the southern Kara Sea would thus explain sedimentation taking place in these two areas. Flocculation and

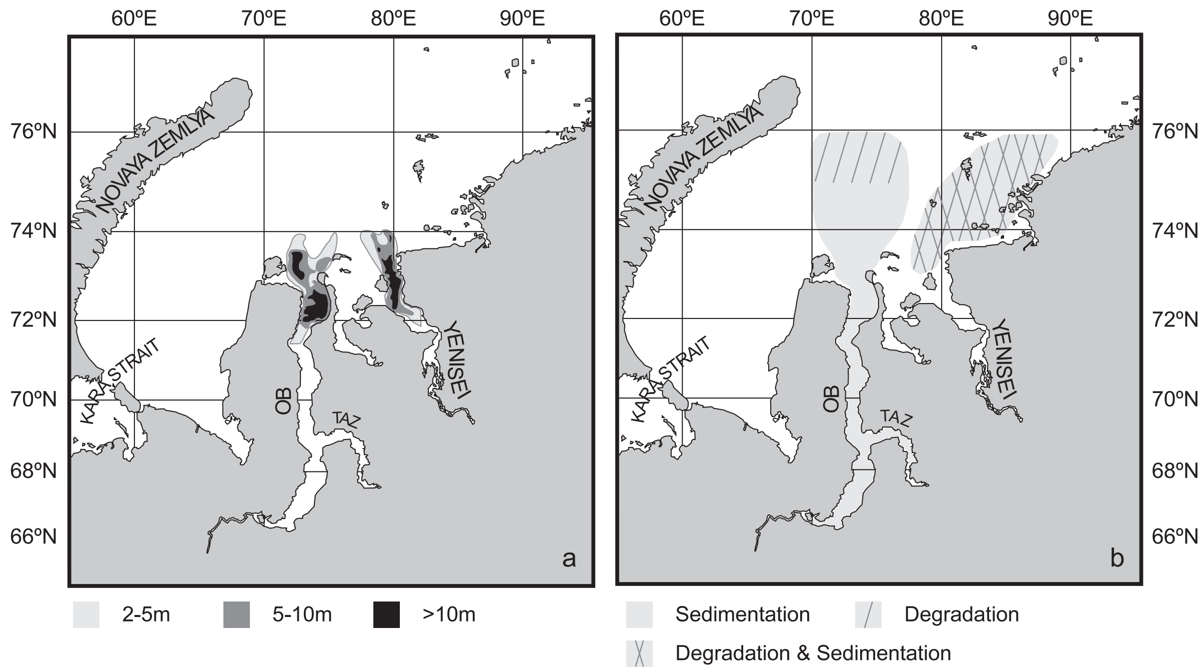

Fig. 6. Areas of sedimentation and degradation in the Ob and Yenisei Rivers and the adjacent Kara Sea. Holocene sediment thickness is given in (a) (after Dittmers et al., in press), areas of recent sedimentation and degradation in (b).

coagulation of dissolved and suspended matter in the area of fresh and salt water mixing, called the "marginal filter" of Lisitsyn (1995), adds to sedimentation in the estuaries.

4.4. TSM, POC and PN budget for the Ob and Yenisei Rivers

A budget for TSM, POC and PN discharge by the Ob and Yenisei Rivers into the Kara Sea was calculated based on the new field measurements and existing discharge data. For calculation, water and sediment discharge data from Lammers and Shiklomanov (2000) and Bobrovitskaya et al. (1997), as well as suspension data from 2001 sampled from August 15th to 22nd, 2001 (Yenisei River) and from September 7th to 11th, 2001 (Ob River) were used. The data from Lammers and Shiklomanov (2000) and Bobrovitskaya et al. (1997) consist of monthly means of water and sediment discharge measured at the gauging stations in Salekhard (Ob River) and in Igarka (Yenisei River). As the Ob River meets three tributaries downstream of Salekhard (Pur, Taz and Nadym rivers), the water discharge data of these three small rivers were added to the Ob River discharge. Large dams were built from the 1950s to the 1970s in the upper reaches of both the Ob and Yenisei Rivers. Therefore, only water and sediment discharge data from after the dam closures were used to calculate the fractions (Table 2). On the basis of these data, modern annual TSM, POC and PN budgets for the Ob and Yenisei Rivers were calculated (Tables 3 and 4).

4.4.1. Calculation of the budgets

For calculation of the TSM, POC and PN budgets, a few assumptions are made: (i) that the annual variation is the same for TSM, POC and PN; (ii) that the annual variation is the same for the gauging stations in the hinterland of the rivers and in the estuaries; and (iii) that the annual variation is the same for the Ob River and its tributaries. Budgets were calculated for the Yenisei River mouth because the TSM, POC and PN values are constant within the Yenisei River; within the Ob River, a strong gradient was observed for TSM, POC and PN, and therefore

Table 2
Periods of water and sediment discharge data used for calculation of mean monthly water and sediment discharge applied in the TSM, POC and PN budgets

River	First year	Last year	Number of years	Gaps[a]	Gauging station (Fig. 1)
Ob[b]	1958	1994	37	no	Salekhard
Ob[c]	1960	1987	28	yes	Salekhard
Yenisei[b]	1978	1995	18	no	Igarka
Yenisei[c]	1970	1986	17	yes	Igarka
Pur[b]	1939	1990	52	yes	Samburg
Taz[b]	1962	1994	33	yes	Sidorovsk
Nadym[b]	1955	1990	36	yes	Nadym

[a] Gaps: missing data in some years (mostly during winter months).
[b] Water discharge (Lammers and Shiklomanov, 2000).
[c] Sediment discharge (from Bobrovitskaya et al., 1997).

budgets were calculated for both the Ob-Taz River confluence and the river mouth.

With the sediment and water discharge data from the gauging stations, the TSM concentrations for each month were calculated using this expression:

$$C_{\mathrm{TSM}i} = \frac{Q_i}{S_i}. \tag{1}$$

In this expression: $C_{\mathrm{TSM}i}$ = sediment concentration (corresponds to TSM) for month i, Q_i = water discharge for month i at the gauging station and S_i = sediment discharge for month i at the gauging station.

The calculated sediment concentrations at the gauging stations were compared to the measured TSM concentrations in the Ob and Yenisei estuaries and the Ob-Taz River confluence for the corresponding months (August for the Yenisei River and September for the Ob River), and the proportion, p, of TSM reaching the estuaries or the Ob-Taz River confluence, is calculated:

$$p = \frac{C_{\mathrm{TSM}i}}{m_{\mathrm{TSM}i}}. \tag{2}$$

Here, $m_{\mathrm{TSM}i}$ = measured TSM concentrations in the estuaries and at the Ob-Taz River confluence in month i (August for the Yenisei River and September for the Ob River).

With the proportions calculated for August (Yenisei River) and September (Ob River), the sediment discharges for each month at the estuaries and the Ob-Taz River confluence are given by:

$$s_i = p \cdot S_i, \tag{3}$$

where s_i = calculated sediment discharge in the estuaries and the Ob-Taz River confluence for month i. POC budgets are calculated on the basis of the TSM budgets:

$$q_i = \frac{m_{\mathrm{POC}i}}{m_{\mathrm{TSM}i}}, \tag{4}$$

in which q_i = ratio of measured POC to measured TSM month i (August for the Yenisei River and September for the Ob River) and $m_{\mathrm{POC}i}$ = measured POC concentrations at the estuaries and the Ob-Taz River confluence in month i (August for the Yenisei River and September for the Ob River).

The ratio between TSM and POC was applied to the calculated monthly sediment discharges in order to yield an estimate of POC discharge in the estuaries and at the Ob-Taz River confluence in month i (POC_i):

$$\mathrm{POC}_i = q \cdot s_i. \tag{5}$$

The PN budget was calculated exactly the same way as the POC budget except that in Eq. (4) the

Table 3
Calculation of a TSM and POC budget for the Yenisei River

Month	Water discharge[a] (km^3 month^{-1})	Sediment discharge[b] (10^6 t month^{-1})	TSM budget at the river mouth[c] (10^6 t month^{-1})	POC budget at the river mouth[d] (10^3 t month^{-1})
January	16.16	0.03	0.03	3.32
February	14.76	0.03	0.03	3.29
March	16.03	0.03	0.03	3.32
April	15.65	0.03	0.03	3.79
May	68.39	0.25	0.25	28.51
June	211.88	3.74	3.79	426.89
July	72.62	0.46	0.46	52.45
August	46.83	0.15	0.15	16.86
September	43.94	0.11	0.11	12.19
October	37.57	0.09	0.09	10.05
November	17.84	0.03	0.03	3.79
December	15.65	0.03	0.03	3.16
Total	577.32	4.98	5.03	567.62

[a] Long term mean monthly water discharge of the Yenisei River at the gauging station in Igarka (Lammers and Shiklomanov, 2000).
[b] Long term mean monthly sediment discharge of the Yenisei River at the gauging station in Igarka (Bobrovitskaya et al., 1997).
[c] Calculated for a TSM concentration of 3.2 mg/l during August.
[d] Calculated for a POC concentration of 0.36 mg/l during August.

Table 4
Calculation of a TSM and POC budget for the Ob River

Month	Water discharge[a] (km^3 month^{-1})	Water discharge[b] (km^3 month^{-1})	Sediment discharge[c] (10^6 t month^{-1})	TSM budget at the river mouth[d] (10^6 t month^{-1})	TSM budget at the Ob-Taz confluence[e] (10^6 t month^{-1})	POC budget at the river mouth[f] (10^3 t month^{-1})	POC budget at the Ob-Taz confluence[g] (10^3 t month^{-1})
January	13.48	15.51	0.12	0.03	0.08	1.84	4.14
February	10.25	11.79	0.09	0.02	0.06	1.41	3.17
March	10.05	11.61	0.09	0.02	0.06	1.38	3.10
April	9.86	11.35	0.08	0.02	0.06	1.28	2.87
May	38.24	44.29	1.42	0.32	1.03	22.89	51.49
June	87.77	113.59	5.34	1.34	4.32	95.91	215.80
July	82.37	96.13	4.56	1.03	3.32	73.72	165.86
August	60.69	67.31	2.48	0.53	1.72	38.21	85.97
September	36.82	42.79	1.06	0.24	0.77	17.11	38.51
October	27.92	33.07	0.56	0.13	0.42	9.28	20.89
November	16.70	20.09	0.22	0.05	0.17	3.74	8.41
December	15.44	18.08	0.15	0.03	0.11	2.46	5.54
Total	409.59	485.61	16.17	3.76	12.12	269.23	605.75

[a] Long term mean monthly water discharge of the Ob River at the gauging station in Salekhard (Lammers and Shiklomanov, 2000).
[b] Long term mean monthly water discharge of the Ob River at the gauging station in Salekhard incl. discharge of the Nadym (in Nadym), Pur (in Samburg) and Taz rivers (in Sidorovsk) (Lammers and Shiklomanov, 2000).
[c] Long term mean monthly sediment discharge of the Ob River at the gauging station in Salekhard (Bobrovitskaya et al., 1997).
[d] Calculated for a TSM concentration of 5.6 mg/l during September.
[e] Calculated for a TSM concentration of 18 mg/l during September.
[f] Calculated for a POC concentration of 0.4 mg/l during September.
[g] Calculated for a POC concentration of 0.9 mg/l during September.

measured POC values were substituted by the measured PN values.

4.4.2. TSM, POC and PN budgets for the Yenisei River in 2001

The Yenisei River is mostly frozen during winter. Ice melting and break-up starts around the middle of May, and is followed by the main water discharge peak at the end of May to the beginning of June, due to ice melt in the hinterland. The highest monthly water discharge occurs in June. The peak sediment discharge similarly occurs in June, and is even more pronounced (Figs. 7 and 8). Freezing of the Yenisei River starts again in October. These peaks are measured at the gauging station in Igarka, but water and sediment discharge data from Igarka do not exactly reflect the seasonality at the Yenisei River mouth where the peak is expected to be observed several weeks later (Meade et al., 2000; I. Harms, IfM Hamburg, Germany, pers. comm.).

During August 2001, TSM and POC were almost homogeneous in the Yenisei River (Figs. 2 and 3) with an average TSM concentration of 3.2 mg/l ($\pm$ 0.47 mg/l) and an average POC concentration of 0.36 mg/l ($\pm$ 0.07 mg/l; measurement points for TSM and POC: 8 stations).

4.4.3. TSM, POC and PN budgets for the Yenisei River were calculated (Table 3) as described above

According to these calculations, the Yenisei River delivers 5.03×10^6 t sediment, 0.57×10^6 t POC and 0.084×10^6 t PN annually to the Kara Sea (see Table 5).

4.4.4. TSM and POC budgets for the Ob River in 2001

Water and sediment discharge patterns of the Ob River differ from those of the Yenisei River. The water discharge peak is measured at the end of May to the beginning of June, and June is the month with the highest average water discharge (Figs. 7 and 8). Nevertheless, the peaks are not as sharp as in the Yenisei River. As with the Yenisei River data, the water discharge data originate from an upstream gauging station in Salekhard and do not exactly reflect the water discharge pattern at the river mouth; peak

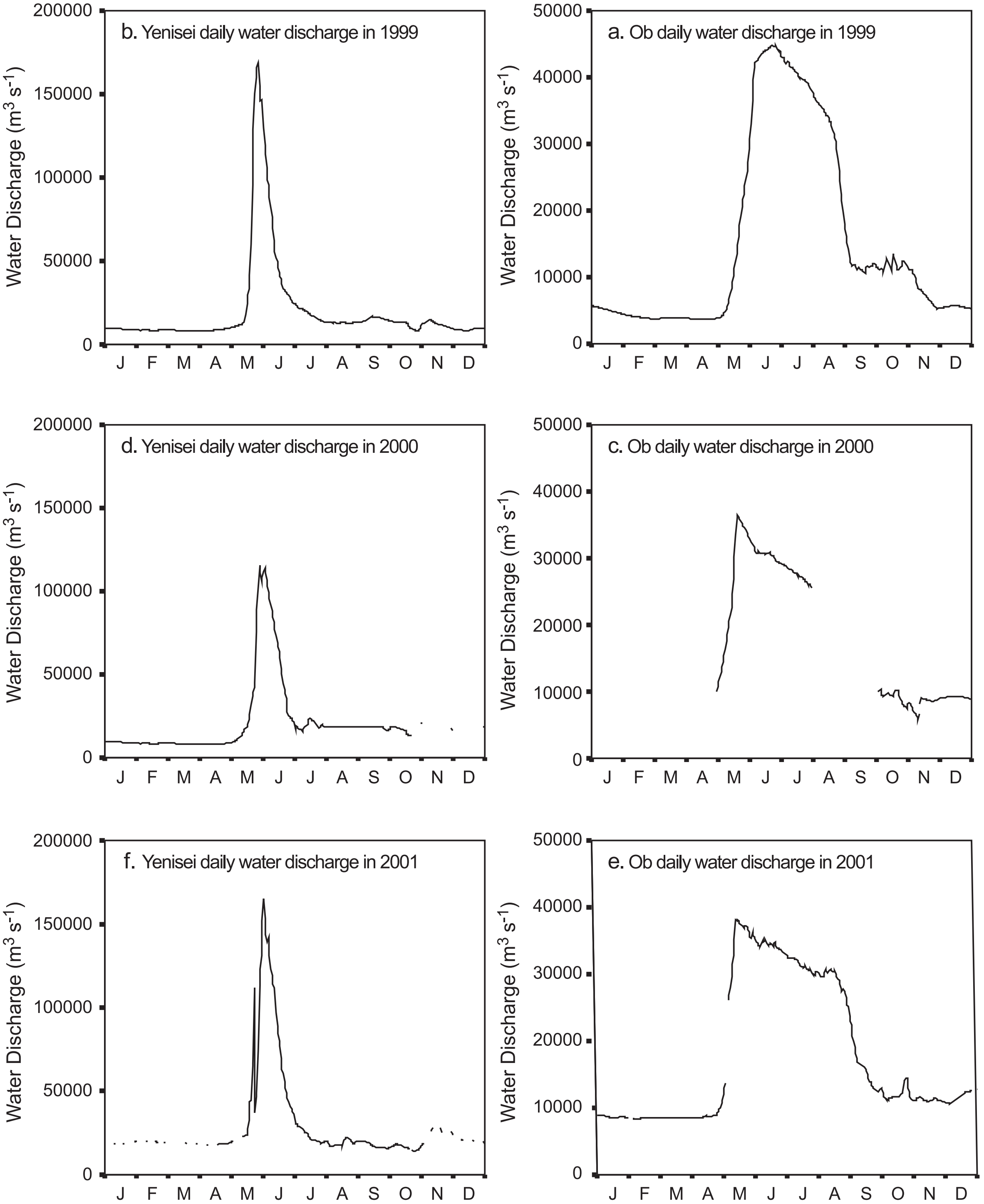

Fig. 7. Daily water discharge for the Ob and Yenisei Rivers in 1999, 2000 and 2001. Left panel: Yenisei, right panel: Ob. Gaps due to time spans without measurements.

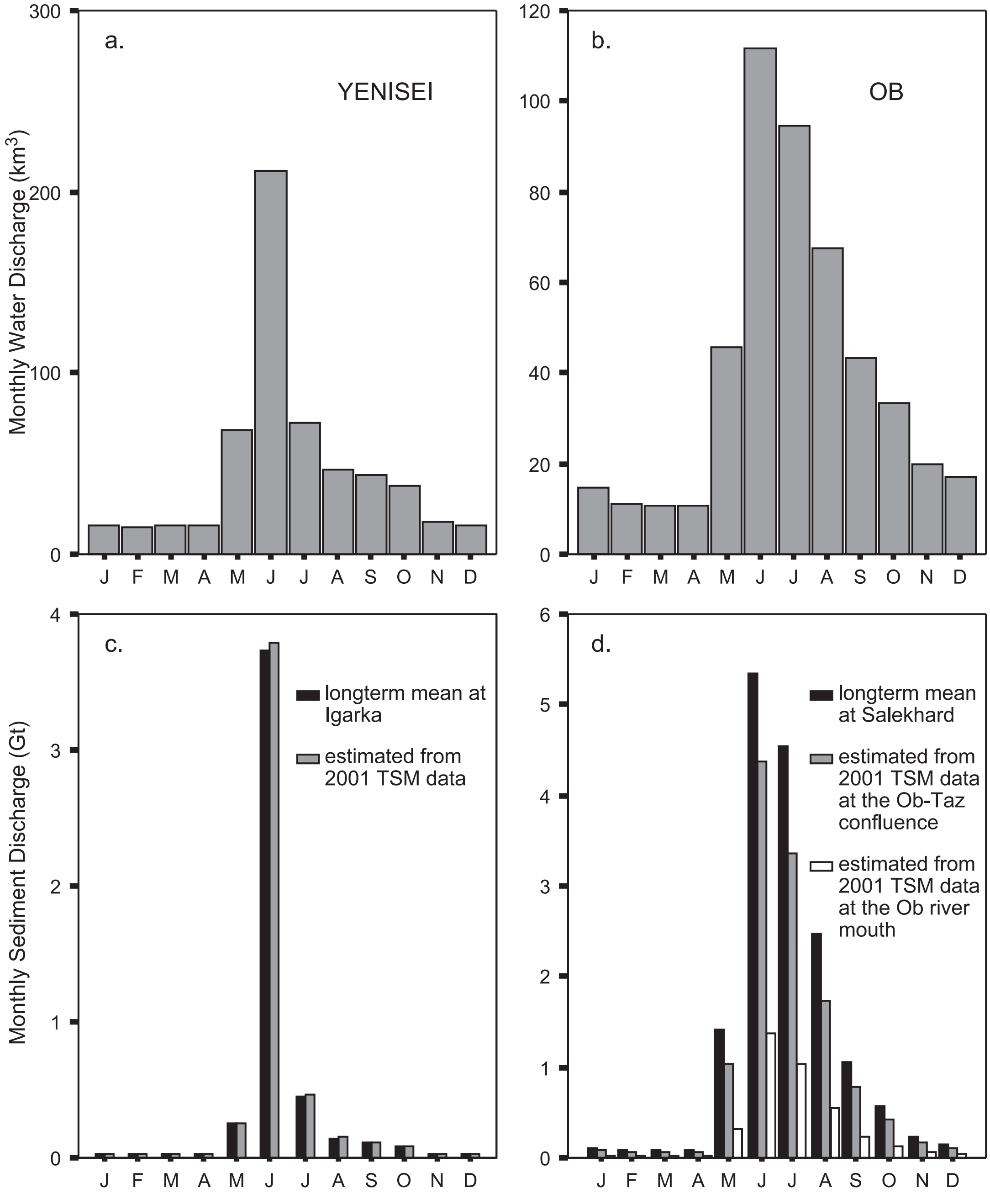

Fig. 8. Water and sediment discharge of the Yenisei and Ob Rivers. Long term mean water discharge are given in (a) (Yenisei) and (b) (Ob incl. Nadym, Pur and Taz), sediment discharge is given in (c) (Yenisei) and (d) (Ob incl. Nadym, Pur and Taz).

flows should be expected to arrive several weeks later at the river mouth on the basis of the gauging station data (Meade et al., 2000; Ingo Harms, pers. comm.).

The peak water discharge is more dispersed than in the Yenisei River due to the different morphological conditions in the hinterland: when ice break-up

Table 5
Annual TSM, POC and PN discharge of the Yenisei and Ob Rivers into the Kara Sea

River	TSM discharge (10^6 t year^{-1})	POC discharge (10^6 t year^{-1})	PN discharge (10^6 t year^{-1})	Source
Yenisei	5.03	0.57	0.084	current paper
	9.2[a]			Dittmers et al. (2003)
		0.31		Köhler et al. (2003)
		0.17[b]		Lobbes et al. (2000)
	4.2[b]			Bobrovitskaya et al. (1996)
	5.9[b]			Gordeev et al. (1996)
	14.5[c]			Telang et al. (1991)
	13[c]			Lisitsyn (1972)
Ob	3.76	0.27	0.027	current paper
	12.11[d]	0.61[d]	0.081[d]	current paper
	14.3[a]			Dittmers et al. (2003)
		0.27		Nesterova (1960)
	16.2[b]			Bobrovitskaya et al. (1996)
	18.4			Gordeev et al. (1996)
	13.4			Telang et al. (1991)
	15.0[b]			Lisitsyna et al. (1974)
	16			Lisitsyn (1972)

[a] Average Holocene value.
[b] Values for period after dam constructions.
[c] Values for period before dam constructions.
[d] At the Ob-Taz River confluence.

occurs, the Ob River floods, and sedimentation and erosion take place on its floodplains. Smith and Alsdorf (1998) found that, during the peak flows, more than 90% of the lakes in the adjacent flood plains were actively connected to the Ob River; but that by September, the flood plain had been reduced in area by over an order of a magnitude. The water discharge by thawing of ice and snow in the hinterland is evidently stored in the flood plain lakes and released with a time delay to the Ob River system. Kiselev (1970) found that, in addition, the phytoplankton in the Ob River primarily originates from the lakes and ponds temporarily connected to it. Sediment discharge measured at Salekhard (Bobrovitskaya et al., 1997) generally follows the water discharge pattern: during the main peak water flow in May to June, 70% of the annual sediment discharge is measured, whereas during August, September and October only 25% are measured, and during the winter months 5% are measured (Fig. 8).

For the Ob River, budget calculation was slightly different from that for the Yenisei River. Bobrovitskaya et al. (1997) and Lammers and Shiklomanov (2000) provide sediment and water discharge data for the Ob River at the gauging station in Salekhard. For the three smaller rivers entering the Ob River downstream of Salekhard (Nadym, Pur and Taz rivers; Fig. 1), only water discharge data are available (Lammers and Shiklomanov, 2000). It was assumed that the Nadym, Pur and Taz rivers have similar TSM, POC and PN contents as the Ob River at Salekhard. Furthermore, in contrast to the Yenisei River, the TSM and POC concentrations from the central Ob Bay to the estuary were inhomogeneous in September 2001. Therefore, two budgets were calculated: one for the Ob-Taz River confluence (TSM = 18 mg/l, POC = 0.9 mg/l, PN = 0.12 mg/l) and one for the Ob estuary (TSM = 5.6 mg/l, POC = 0.4 mg/l, PN = 0.04 mg/l; Table 4).

The Ob River delivers 3.76×10^6 t sediment, 0.27×10^6 t POC and 0.027×10^6 t PN to the Kara Sea annually. The Ob-Taz River confluence budget calculation yield 12.21×10^6 t of estimated sediment, 0.61×10^6 t POC and 0.081×10^6 t PN annually (Table 5). Data obtained during an expedition to Salekhard in June 2000 fit well into the estimates and are in the range of the values at the Ob-Taz River confluence (Table 6).

4.4.5. Applicability of the 2001 budgets

The sediment discharge budget calculated for the Yenisei River on the basis of TSM data from August 2001 agrees quite well with the long-term mean sediment discharge measured at the gauging station in Igarka. In fact, this means that the Yenisei River is a bypass system from Igarka downstream to the estuary; sedimentation takes place only as the river widens into the estuary. Nevertheless, comparing our budget to the long term sediment discharge measurements at Igarka,

Table 6
TSM, POC and PN values at Salekhard and at the Ob-Taz River confluence during June

TSM		POC		PN	
Observed[a] (mg/l)	Calculated[b] (mg/l)	Observed[a] (mg/l)	Calculated[b] (mg/l)	Observed[a] (mg/l)	Calculated[b] (mg/l)
35.9	38.0	1.3	1.9	0.16	0.25

[a] Measured at Salekhard in June 2000.
[b] Calculated on basis of (a) the budget calculation (Table 5) and (b) water discharge data from Lammers and Shiklomanov (2000).

we see that slightly more sediment than the long term Igarka sediment discharge is released into the Kara Sea in 2000. This may be due to increasing river discharge during the last decades (Peterson et al., 2002). However, our flux is well within the annual flux measurements from Igarka from after the dam constructions (Bobrovitskaya et al., 1996; Gordeev et al., 1996). When comparing TSM in 2000 to TSM in 2001 it is observable that in 2000 a strong loss of TSM took place when flowing into the Yenisei estuary, whereas values are constant within the estuary as well as in the area north of it. Nevertheless, bottom sediment investigations suggest that deposition takes place only in the outer estuary (Dittmers et al., 2003). This discrepancy could be explained with recent hydrographic changes due to the damming of the Yenisei River: in 1966, the Krasnoyarsk dam was finished, and during the seventies, dams were built in Bratsk and Ust Ilim on the Angara River which is one of the most important tributaries of the Yenisei River. Meade et al. (2000) reported an average sediment discharge of 6.3×10^6 t year^{-1} at Divnogorsk (just downstream of the Krasnoyarsk dam) before the dam closure and 0.2×10^6 t year^{-1} afterward. A strong decrease in annual sediment discharge was also observed at Igarka (see Meade et al., 2000, their Fig. 4). Hence, it is likely that though the Yenisei River was accumulating sediment before dam construction, the Yenisei River changed into a bypass system after the construction of the dams. Another possible explanation is that the 2001 August sampling period was not representative of the discharge system of the entire summer: i.e. only during times of high water discharge does the Yenisei River act as a bypass system, with deposition in the Yenisei estuary taking place during times of weaker water discharge. If this is the case, the budget calculated on the basis of data from August 2001 is a maximum estimate of sediment and POC discharge for the Yenisei River.

TSM concentrations decrease continuously downstream in the Ob River. The sediment discharge budget therefore is not uniform for the entire Ob River: on its way from Salekhard to the Ob-Taz River confluence, the Ob River loses one quarter of its sediment load, another 52% is lost between the Ob-Taz River confluence and the Ob river mouth; that is to say, only one quarter of the sediment discharge measured at Salekhard reaches the Kara Sea. According to Meade et al. (2000), the flood plains flanking the Ob River function as sediment sinks (sedimentation>erosion), and the northern Ob River bed is filled by accumulating Holocene sediment as documented by Dittmers et al. (2003) for the northernmost part of the Ob River. The sediment, POC and PN discharge budgets for the Ob River, probably provide a reliable estimate of the TSM, POC and PN discharge by the Ob River into the Kara Sea.

4.5. Comparison of the budget with other studies

According to our budget, the Yenisei River delivers 5.03×10^6 t of sediment and 0.57×10^6 t of POC to the Kara Sea annually (Table 5). Except for the older sediment discharge data of 14.5×10^6 t year^{-1} of Telang et al. (1991) and the 13×10^6 t year^{-1} estimate of Lisitsyn (1972), our data are similar to the recent estimates of Bobrovitskaya et al. (1996) who measured a total of 4.2×10^6 t year^{-1} sediment discharge at Igarka and Gordeev et al. (1996) who reported a total suspended matter discharge of 5.9×10^6 t year^{-1} (Table 5). POC discharge data from the literature are lower than our estimate of 0.57×10^6 t year^{-1} POC. Köhler et al. (2003) have calculated a POC discharge of 0.31×10^6 t year^{-1} from their DOC data and the POC/DOC ratio proposed in Nesterova (1960) (Table 5). Lobbes et al. (2000) calculated a POC discharge of 0.17×10^6 t year^{-1} (see Table 5).

Dittmers et al. (2003) propose a total sediment volume at the Yenisei River mouth of 9.2×10^{10} t for the last 10,000 years, that can be converted to an annual deposition of 9.2×10^{6} t assuming constant accumulation rates during the last 10,000 years. Even if the Yenisei River deposited its entire sediment load directly into the estuary, it would not match the mean Holocene sedimentation rate. This can be explained in two ways: (a) sedimentation rates were not constant throughout the entire Holocene, but higher in the early and lower in the late Holocene as reported by Stein and Fahl (2004) and by Stein et al. (2003a,b) the dam closures in the hinterland significantly changed the sedimentation regime of the Yenisei River. Sediment discharge values measured at Igarka prior to the dam closure range from 13×10^{6} to 14.5×10^{6} t year^{-1} (Lisitsyn, 1972; Telang et al., 1991) and are slightly higher than the mean Holocene sedimentation rate; measurements from after the dam constructions range from 4.2×10^{6} to 5.9×10^{6} t annually (Bobrovitskaya et al., 1996; Gordeev et al., 1996), being lower than the average Holocene sedimentation rate. Assuming a constant mean Holocene sedimentation rate, the flux of TSM from the Yenisei River into the Kara Sea prior to dam closure can be calculated as at least 9.2×10^{6} t year^{-1} (Dittmers et al., 2003).

We have estimated that the Ob River delivers 3.76×10^{6} t of sediment and 0.27×10^{6} t of POC to the Kara Sea per year (Table 5). Most previous estimates have been based on data from Salekhard and are, of course, much higher than our estimated discharge to the Kara Sea. They are, however, comparable to our estimates for discharge at Salekhard. Bobrovitskaya et al. (1996) measured an annual sediment discharge of 16.2×10^{6} t at Salekhard which is about four times higher than the actual sediment discharge at the river mouth. Similarly, Gordeev et al. (1996) reported 18.4×10^{6} t year^{-1}. Telang et al. (1991) proposed a sediment discharge of 13.4×10^{6} t year^{-1}, Lisitsyna (1974) a sediment discharge of 15.0×10^{6} t year^{-1} and Lisitsyn (1972) reported 16×10^{6} t year^{-1}. The estimate by Romankevich et al. (2000) of 0.27×10^{6} t POC released annually to the Kara Sea is in perfect agreement with our measurements.

Dittmers et al. (2003) calculated a total sediment volume of 14.3×10^{10} t at the Ob River mouth for the last 10,000 years, a value that equals an annual sedimentation rate of 14.3×10^{6} t. This is somewhat higher than the 8.45×10^{6} t year^{-1} that are recently deposited between the Ob-Taz River confluence and the estuary. Furthermore, based upon the work of Dittmers et al. (2003), it is known that the area with thick sediment packages lies further to the north, within and north of the river mouth. In the area where sedimentation of fine suspended matter takes place due to our data, only coarse-grained sandy sediments are found at the river bed. Thus, this leads to the assumption that suspended matter is deposited between the Ob-Taz River confluence and then redistributed northward. Different mechanisms must be considered for this northward transport: (i) resuspension (which was observed during our sampling program), (ii) rapid transport due to the flush effect on the onset of the peak discharge and (iii) transport by incorporation of sediment into ice (Smedsrud, 2000).

5. Conclusion

About three quarters of the suspended matter measured in Salekhard are lost on its way to the Ob River mouth and are deposited in the Ob Bay between the Ob-Taz River confluence and the river mouth. The Ob River yields an annual amount of 3.76×10^{6} t TSM, 0.27×10^{6} t POC and 0.027×10^{6} t PN to the Kara Sea. The organic matter suspended in the Ob River is more degraded and refractory than in the Yenisei River, due to its long residence time in the Ob Bay where it can, probably, be retained in the adjacent floodplains and released with a time delay into the main stream. On the floodplains, sedimentation, erosion and exchange between the suspended matter and the permafrost soil take place.

The Yenisei River has changed its depositional regime in recent decades. Prior to the dam closures in its hinterland, it yielded about 9.2×10^{6} t sediment per year to the Kara Sea. The present situation is rather complicated to monitor due to the strong seasonality. The calculated 5.03×10^{6} t of sediment, 0.57×10^{6} t of POC and 0.084×10^{6} t of PN should be considered a high estimate for the Yenisei River functioning now as a pure bypass system. This has probably been the case since the dam closures due to a regime change. For comparisons between the present Yenisei River depositional regime and the Holocene record, we recommend use of the data collected prior to dam construction.

Considering all constraints, a reliable TSM and POC budget for the Ob River is presented here indicating that the Ob Bay is an active sediment accumulation zone. For the Yenisei River, the budget presented here is a maximum estimate for the year 2001. Water and suspended matter have a much higher residence time in the Ob River than in the Yenisei River, a conclusion which is supported by amino acids indicating a much higher degradational stage of suspended organic material in the Ob River than in the Yenisei River (D. Unger, unpubl. data). Despite the deposition in the Ob Bay, more than 0.8×10^6 t year^{-1} of POC are discharged to the Kara Sea confirming the findings of Krishnamurthy et al. (2001), Fernandes and Sicre (2000) and Stein and Fahl (2004) that large parts of the organic matter in Kara Sea surface sediments are of terrestrial origin.

The southern Kara Sea is strongly affected by river input. The river water plume can best be observed by the low surface water salinities from spring to autumn. The suspended matter is distributed by the plume and reaches as far north as about 76°N where it is diluted to marine background values. Conservative mixing of fluvial and marine end-member waters can explain the observed TSM and POC distribution in the Kara Sea. Degradation of POC is evident from a reduction of POC and PN contents in the area between 75°N and 76°N north of the Ob River and the area along the Taimyr Peninsula.

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