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A contemporary sediment and organic carbon budget for the Kara Sea shelf (Siberia)

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Abstract

It has recently been realized that the Arctic undergoes drastic changes, probably resulting from global change induced processes. This acts on the cycling of matter and on biogenic elements in the Arctic Ocean having feedback mechanisms with the global climate, for example by interacting with atmospheric trace gas concentration. A contemporary budget for biogenic elements as well as suspended matter for the Arctic Ocean as a baseline for comparison with effects of further global change is, thus, needed. Available budgets are based on the late Holocene sedimentary record and are therefore quiet different from the present which has already been affected by the intense anthropogenic activity of the last centuries.

We calculated a contemporary suspended matter and organic carbon budget for the Kara Sea utilizing the numerous available data from the recent literature as well as our own data from Russian-German SIRRO (Siberian River Run-off) expeditions. For calculation of the budgets we used a multi-box model to simplify the Kara Sea shelf and estuary system: input was assumed to comprise riverine and eolian input as well as coastal erosion, output was assumed to consist of sedimentation and export to the Arctic Ocean. Exchange with the adjacent seas was considered in our budget, and primary production as well as recycling of organic material was taken into account. According to our calculations, about 18.5×10^6 t yr^{-1} of sediments and 0.37×10^6 t yr^{-1} of organic carbon are buried in the estuaries, whereas 20.9×10^6 t yr^{-1} sediment and 0.31×10^6 t yr^{-1} organic carbon are buried on the shelf. Most sources and sinks of our organic carbon budget of the Kara Sea are in the same order of magnitude, making it a region very sensitive to further changes.
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1. Introduction

Since the Industrial Revolution, large amounts of carbon dioxide have been released into the atmosphere by the burning of fossil fuels and by massive

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changes in land use (7.7×10^6 t yr^{-1}, Mackenzie, 1998), intensifying the natural greenhouse effect and leading to global warming (Albritton and Meira Filho, 2001). The Arctic Ocean is a region susceptible to global change. Variations in ice formation may be directly related to increase of summer melt rather than to changes in wind direction and circulation (Laxon et al., 2003). The Arctic basin receives large amounts of freshwater from the rivers draining Northern Eurasia and North America, of which the Yenisei, Lena, Ob, Mackenzie, Yukon and Pechora rivers are the major ones (Holmes et al., 2002; Meade, 1996; Milliman and Meade, 1983). Ice formation and freshwater supply interact and influence physical properties such as radiation and heat budget. At the same time, their variations induce changes in the cycling of biogenic elements which, in turn, influence atmospheric trace gas concentrations. There are indications that recent anthropogenic activity has already had an impact on water discharge and, thus, on the carbon budget of the Arctic. Dam building in the 1950s and 1960s has, probably, reduced water discharge and changed its seasonality (Bobrovitskaya et al., 1997, 2003). The overall trend summarizing all available Arctic discharge data may, however, be an increase due to melting of permafrost soils (Peterson et al., 2002). Budgets are required as basic studies to estimate the impact of future changes because such changes strongly affect element cycling on the shelves and may change their role in the global cycles (Holmes et al., 2000).

In this study we summarize the available literature data in combination with our measurements in the Kara Sea in order to obtain a contemporary particulate carbon budget for the Kara Sea.

The role of continental shelves in the marine carbon cycle is still not well known and the subject of extensive discussions. Modern shelves make up <8% of the total ocean surface area, but account for about 10% to 33% of the global primary production (Wollast, 1991). Many studies on the role of shelves in the global carbon cycle have been carried out during the last decades, (e.g. Bender et al., 1989; Canfield et al., 1993a,b; De Haas et al., 2002; Frankignoulle and Borges, 2001; Milliman, 1991; Smith and Hollibaugh, 1993; Wollast, 1998), but results vary widely due to the different settings of the shelves. Berner (1982, 1989) pointed out that about 83% of the organic matter buried in marine sediments are buried in deltaic-shelf environments. Eisma et al. (1985) found that only 7% to 10% of the riverine sediment reaches the deep sea. Most of the river-delivered sediment is trapped on the inner shelves according to Milliman (1991). Wollast (1991) calculated total sedimentation in the pelagic, semipelagic and shelf provinces, pointing out that more sediment accumulates on the shelf than in the other realms. De Haas et al. (2002), in contrast, suggest that >95% of the primary production is recycled and remineralized in the water column and in the upper few centimetres of the sediment on the shelves. They further show that most of the accumulated organic matter is resuspended, transported over the shelf edge and laid down in canyons and on the shelf slope, from where it is eventually transported to the pelagic realm and buried in deep sea fans. They conclude that most of the present day shelf areas do not play an important role in the burial of organic matter. Smith and Hollibaugh (1993) postulate that in the coastal zones respiration exceeds primary production by 1.4%, a point which is confirmed by measurements of terrestrial, rather refractory, riverine particulate and dissolved organic matter mineralized on coastal shelves. Only locally, in areas of upwelling or bottom anoxia, are relatively large amounts of organic carbon being stored (e.g. shelves off Somalia, Yemen and Oman, see De Haas et al., 2002 and references therein).

The Arctic Ocean accounts for only 1.5% of the global ocean (Aagaard, 1994), but contains about 20% (i.e. 5×10^6 km^2) of the world's continental shelves (Macdonald et al., 1998). This means that nearly 30% of the Arctic Ocean's area is floored by continental shelves, compared to <8% in the global ocean (Wollast, 1991). With these large continental shelves (Fig. 1), the Arctic Ocean plays an important role in the global organic carbon cycle.

Shelves and continental margins, as the interface between land and open ocean, are the most important areas within the ocean in terms of the throughput of terrestrial material (e.g. Milliman, 1991; Romankevich, 1994; Smith and Hollibaugh, 1993) and primary production (e.g. Wollast, 1991). The Arctic shelves are not as well understood as other shelf areas due to sparse data. Only during recent decades have the Arctic shelves been paid more attention to, mostly due to a general interest in Arctic contaminant transport.

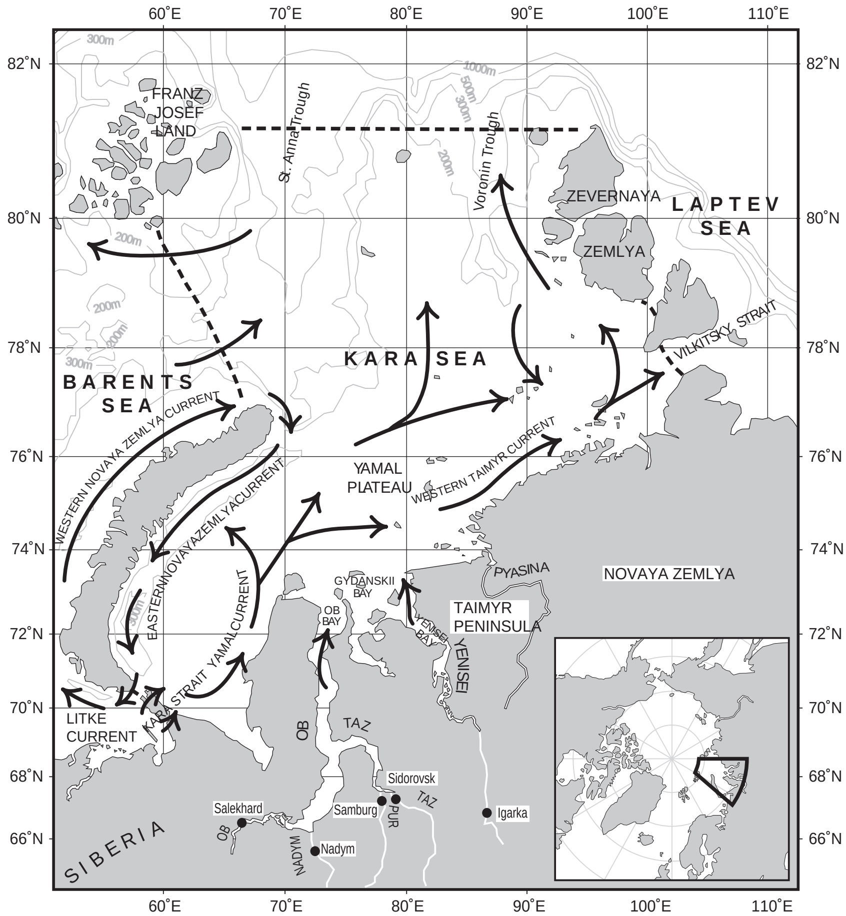

Fig. 1. General overview of the Arctic Ocean. Arrows show the general pattern of surface water currents (currents after Pavlov and Pfirman, 1995).

Estimates of the budgets of the Arctic shelves are rather scarce as these regions are often ice-covered, making it more difficult to collect data. Recently, an estimate of the modern Beaufort Sea sediment and organic carbon budget was carried out by Macdonald et al. (1998) and, elsewhere, studies about organic carbon burial on the Siberian Arctic shelves, and in the Fram Strait and Central Arctic Ocean were carried out (Stein and Macdonald, 2004, and references therein). In this study, we calculate a contemporary sediment and organic carbon budget for the Kara Sea. We further extrapolate a late Holocene sediment budget with data from before the construction of dams in the hinterland of the Ob and Yenisei rivers in order to better compare our recent findings with a late Holocene budget calculated by Stein and Fahl (2004a).

2. Overview of the Kara Sea shelf

The Kara Sea is the second largest shelf area of the Arctic Ocean (Dai and Martin, 1995), and is partially enclosed to the west and northwest by Novaya Zemlya and Franz Josef Land, to the south by the Siberian mainland, and to the east and southeast by the Zevernaya Zemlya Archipelago and the Taimyr Peninsula (Fig. 1). To the north, the Kara Sea shelf is open to the Arctic Ocean across the shelf break between Franz Josef Land and Novaya Zemlya (Jakobsson, 2002). The Kara Sea is connected to the Laptev Sea and southern Barents Sea through small coastal openings (the Vilkitsky and Kara Straits) and to the northern Barents Sea by the opening between Novaya Zemlya and Franz Josef Land (Fig. 1). The area of the Kara

Sea is 926,000 km^2 and, with a mean depth of 130 m, has a water volume of 121,000 km^3 (Jakobsson, 2002). About one third of the total freshwater discharge into the Arctic Ocean occurs through the Kara Sea, mainly from the Ob and Yenisei rivers, with a total annual discharge of about 1060 km^3 including their tributaries (Gebhardt et al., 2004; Lammers and Shiklomanov, 2000). The annual discharges would cover the Kara Sea area with 1.15 m of fresh water, and would refill the entire Kara Sea within about 114 yr. The mean residence time of fresh water in Arctic shelf areas has been estimated at about 1 to 3 yr by Schlosser et al. (1995) and Hanzlick and Aagaard (1980) propose some 2.5 yr. The Kara Sea is almost entirely ice-covered from mid-October to mid-May (e.g. Pavlov and Pfirman, 1995) except for a small narrow polynya north of the fast-ice zone (Harms et al., 2000; Pavlov and Pfirman, 1995). The Kara Sea is almost completely ice-free only from mid-July to mid-October. The riverine input of fresh water, and therefore the surface hydrography, is strongly seasonally influenced (Fig. 2), whereas deep water is much more stable (e.g. Harms et al., 2000).

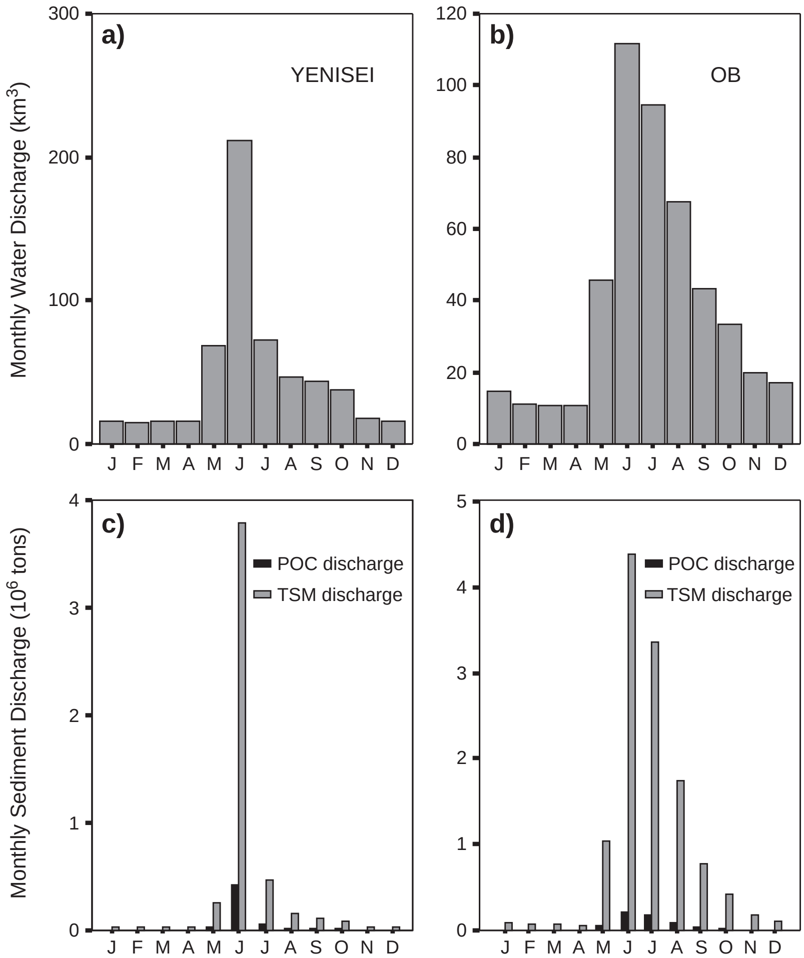

Fig. 2. Water and sediment discharge of the Yenisei and Ob rivers. Long-term mean water discharge is given in (a) (Yenisei) and (b) (Ob incl. Nadym, Pur and Taz), sediment and POC discharge is given in (c) (Yenisei) and (d) (Ob incl. Nadym, Pur and Taz). Periods of water discharge data used for calculation of mean monthly water discharge are given in Table 1. (a, b) Calculated with data from Lammers and Shiklomanov (2000). Data from after the dam constructions in the hinterland of the Ob and Yenisei rivers were used for calculations (for further detail refer to Gebhardt et al., 2004), (c, d) from Gebhardt et al. (2004).

Table 1
Periods of water discharge data used for calculation of mean monthly water discharge (data from Lammers and Shiklomanov, 2000)

River	First year	Last year	Number of years	Gaps[a]	Gauging station (Fig. 1)
Ob	1958	1994	37	No	Salekhard
Yenisei	1978	1995	18	No	Igarka
Pur	1939	1990	52	Yes	Samburg
Taz	1962	1994	33	Yes	Sidorovsk
Nadym	1955	1990	36	Yes	Nadym

[a] Gaps: missing data in some years (mostly during winter months).

The water and sediment discharge of the Ob and Yenisei rivers are strongly seasonally influenced (Fig. 2). River ice break-up starts in mid-May, and water and sediment peak discharges occur immediately after the ice-break up in the Yenisei River. Peak water and sediment discharges in the Ob River are much more dispersed due to different morphological conditions in the hinterland; during peak flow, a large amount of water and sediment is stored in the Ob River's flood plain lakes and is only released with a time delay (Smith and Alsdorf, 1998), so that the main water and sediment discharge occurs in spring and summer (Fig. 2; Table 1). The rivers start to freeze in mid-October, and only a small amount of water and sediment is discharged during the winter months.

3. Inputs of sediment and organic carbon to the Kara Sea shelf

3.1. Sediment and particulate organic carbon input from the Ob and Yenisei rivers

During recent decades, many studies were carried out on sediment and organic carbon fluxes from the Ob and Yenisei rivers into the Kara Sea (e.g. Bobrovitskaya et al., 1996, 1997; Gordeev et al., 1996; Lisitsyn, 1972; Lisitsyna, 1974; Nesterova, 1960; Romankevich et al., 2000b; Telang et al., 1991). All these studies use data from the northernmost gauging stations in the hinterland (Igarka for the Yenisei River and Salekhard for the Ob River; Fig. 1), neglecting all sedimentation and erosion processes taking place downstream of the gauging stations.

A detailed overview of Ob and Yenisei sediment discharge calculations and their reliability can be found in Holmes et al. (2000). Only recently were budgets published based on data from the Ob and Yenisei river mouths (Gebhardt et al., 2004; Köhler et al., 2003; Lobbes et al., 2000). The Yenisei River north of Igarka has been shown to be a bypass system with similar total suspended matter (TSM) and particulate organic carbon (POC) fluxes measured at the gauging station and at the river mouth (Gebhardt et al., 2004). Gebhardt et al. (2004) present the most recent flux calculation, using data from after the constructions of dams in the hinterland, and calculated annual TSM and POC discharges of 5.1×10^6 t and 0.57×10^6 t, respectively, for the Yenisei River. Data from the gauging station in Salekhard situated at the opening of the Ob Bay are used for the Ob River in this study (Fig. 1). Published estimates of annual Ob River sediment discharge range from 13.0×10^6 t to 16.6×10^6 t (Holmes et al., 2002, and references therein). We consider a mean annual sediment discharge of 15.5×10^6 t as proposed by Holmes et al. (2002) to be a reasonable estimate. POC measurements for the Ob River are scarce. Nesterova (1960) suggests an annual POC flux of 0.27×10^6 t for Salekhard, whereas Gebhardt et al. (2004) calculated an annual POC flux of 0.61×10^6 t for the Ob-Taz confluence situated downstream of the gauging station (Fig. 1). Sedimentation is likely to remove some of the suspended load between the gauging station and the Ob-Taz confluence, but the POC contribution of three downstream tributaries (Pur, Taz and Nadym rivers) is taken into account in our flux calculation. We therefore consider the POC flux proposed by Nesterova (1960) as a slight underestimate and prefer to use the values from the Ob-Taz confluence of Gebhardt et al. (2004).

3.2. Dissolved organic carbon input from the Ob and Yenisei rivers

Dissolved organic carbon (DOC) plays a major role in the global carbon cycle. Recent estimates suggest that 700×10^9 t carbon are stored in dissolved organic form in the ocean, compared to only 570×10^9 t in the terrestrial biota (Hedges et al., 1997). On its way from the rivers to the ocean, DOC is affected by biological, physical, and chemical transformations, such as bacterial decomposition, flocculation and photolysis (e.g. Sholkovitz, 1976; Spitzy and Leenheer, 1991; Thurman, 1985). In estuaries and shallow shelves, where waters of different biological, physical and chemical characteristics mix, these processes are particularly pronounced. Nevertheless, the fate of DOC in estuaries is still poorly understood. A conservative behaviour of DOC is proposed in some field studies (e.g. Cauwet and Sidorov, 1996; Kattner et al., 1999; Mantoura and Woodward, 1983; Moore et al., 1979), whereas other studies (e.g. Ertel et al., 1986; Sholkovitz, 1976) show the removal of fractions of riverine dissolved organic matter in the mixing zone. Köhler et al. (2003) point out that in the Ob and Yenisei river estuaries and adjacent Kara Sea, DOC behaviour is nearly conservative, this means that DOC concentrations are only affected by dilution with marine waters of lower DOC concentrations. About 3% of the DOC might be entrapped in the mixing zone. We think that the input of DOC by the river bypasses the Kara Sea shelf and is transported towards the Laptev Sea and the Arctic Ocean. DOC is, therefore, neglected in our budget. We also consider the groundwater DOC inflow into the Kara Sea to behave conservatively.

3.3. Input from smaller rivers

Besides the Ob and Yenisei rivers, a few smaller rivers drain into the Kara Sea. The Pyasina River on Taimyr Peninsula and the Savin and Abrasimov rivers on Novaya Zemlya are the largest of these (Fig. 1). Data from the Pyasina River are scarce. Gordeev et al. (1996) propose an annual sediment discharge of 3.4×10^6 t, and Pavlov and Pfirman (1995) estimate an annual water discharge of 50 km^3. The Pyasina River is only active in summer; its discharge ceases in October and resumes the following June. Considering the Pyasina River to otherwise resemble the Ob and the Yenisei rivers, we believe that Gordeev et al. (1996) overestimate the Pyasina sediment discharge; the Pyasina discharges about 4.5 times less water than the Ob River, whereas the estimated sediment discharge is about the same. Pfirman et al. (1995) present an annual water discharge of 32.5 km^3 from Novaya Zemlya into both the Barents Sea and the Kara Sea, but do not provide any sediment discharge data. We think that the main part of the sediment and organic carbon discharged by the Novaya Zemlya rivers towards the Kara Sea accumulates directly in the Novaya Zemlya Trough, and cannot be transported further to the Arctic Ocean due to a shallow sill (about 200 m) (Johnson et al., 1997) separating the Novaya Zemlya Trough from the St. Anna Trough. Considering all the facts, and that the water discharges of the Pyasina, Savin and Abrasimov rivers are much less than the sum of the Ob and Yenisei rivers, their input is neglected in this study.

3.4. Coastal erosion in the Kara Sea

Coastal erosion data from the Kara Sea are sparse. A first study was done by Romankevich and Vetrov (2001) which report an annual coastal erosion of 109×10^6 t sediment and 1×10^6 t organic carbon. These values seem to be far too high (V. Rachold, AWI Potsdam, Germany, pers. comm.). These values would in fact mean that coastal erosion in the Kara Sea is almost twice as high as in the Laptev Sea (Rachold et al., 2000). New estimates from Vasiliev et al. (2005) are much lower: 32.5×10^6 t sediment and 0.35×10^6 t POC. In this study, we use the new estimates of Vasiliev et al. (2005) as they seem to reflect the coastal erosion better than the older estimates. We think that the material eroded from the coast accumulates close to its origin and is later transported away by ice and by storm events. Finally, this material reaches channels where it is redistributed by bottom currents. Some of this material is probably transported as far as the shelf edge and, conceivably, beyond.

3.5. Primary production on the Kara Sea shelf and in the river estuaries

In situ production of organic matter by photosynthesis plays an important role in the carbon cycle, linking the gaseous and solid parts of the cycle by fixation of carbon dioxide. The Arctic shelves are thought to play a major role in Arctic primary production due to their large area, seasonal melting of ice and nutrient input by rivers and upwelling (Legendre et al., 1992). Studies about the productivity and structure of photosynthetic communities, mainly of the Barents and Kara Sea, were carried out in the 1990s (Vinogradov et al., 2000, and references therein). Vinogradov et al. (2000) report an early estimate of 13.5×10^6 t of annual primary production in the Kara Sea by Danyushevskaya et al. (1990), and themselves suggest an annual primary production of 20×10^6 t C based on remote sensing data (ocean colour measurements) combined with in situ measurements. Days without ocean colour data, due to cloudy cover, were interpolated and it was assumed that the chlorophyll concentration was zero during times of ice cover, ignoring the contribution of ice algae. Wheeler et al. (1996) measured the contributions of ice algae to primary production on a transect from the Chukchi Sea to the Arctic Ocean, and onwards to the Nansen Basin and the Greenland Sea, showing that primary production in the water column decreases from the shelves towards the Arctic Ocean while algal production within the ice increases, and a recent study by Legendre et al. (1992) likewise showed the importance and contribution of ice algae. A year-long deployment, in the southern Kara Sea off the Yenisei estuary, has shown an ice associated bloom that occurs prior to ice break-up in April to June. Quantitatively, it contributes less than 5% of annual organic carbon fluxes (Gaye-Haake et al., 2003).

General estimates of primary production vary greatly. The estimate, by Subba Rao and Platt (1984), of 27g C m^{-2} yr^{-1} for Arctic shelves yields an estimated 25×10^6 t yr^{-1} for the Kara Sea, whereas that of Anderson et al. (1990) (45 ± 20 g C m^{-2} yr^{-1}) gives 41.7×10^6 t $yr^{-1} \pm 18.5 \times 10^6$ t yr^{-1}. These values are both similar to Vinogradov et al.'s (2000) estimate that we therefore use in our budget calculation.

Unfortunately, primary production data for the Ob and Yenisei rivers are rare and have poor temporal resolution (e.g. Vedernikov et al., 1995). Amino acid data (Unger et al., 2005) show that the particulate organic matter discharged by the rivers is rather refractory, suggesting that primary productivity plays a minor role in the rivers, at least during the months of main discharge. This may be due to limited light penetration in turbid waters. Furthermore, the organic matter accumulated in the estuaries is mainly of terrestrial origin (Fahl et al., 2003; Fernandes and Sicre, 2000; Krishnamurthy et al., 2001; Stein and Fahl, 2004a). Vinogradov et al. (1995) report that the estuarine primary production is not consumed in the estuaries, but transported towards the shelf. All in all, we assume that primary production in the estuaries is of negligible contribution to the Kara Sea organic carbon budget.

3.6. Input from the Barents Sea

Water exchange between the Barents Sea and the Kara Sea takes place south and north of Novaya Zemlya. In the south, water flows in from the Barents Sea through the Straits of Karskiye Vorota and Yugorsky Shar (herein after referred to as the Kara Strait), and the resultant current flows along the Yamal Peninsula as the Yamal Current (Fig. 1) (Pavlov and Pfirman, 1995). At the northern tip of the Yamal Peninsula, the Yamal Current divides into three branches, one flowing eastward along the coast, forming part of the Taimyr Current, one flows towards the central Kara Sea and onwards into the Arctic Ocean, and one turns back towards Novaya Zemlya and flows southeastward along its coast, forming part of the Eastern Novaya Zemlya Current (Burenkov and Vasil'kov, 1995). The Eastern Novaya Zemlya Current returns to the Barents Sea as the Litke Current (Fig. 1) (Pavlov and Pfirman, 1995). An annual flow of 1640 km^3 through the Kara Stait into the Kara Sea is found by Pavlov and Pfirman (1995). Medvedev and Potekhina (1986) report TSM concentrations of about 1.5 mg l^{-1} at the Kara Strait during summer. Seasonal variations of TSM concentrations in the Barents Sea are much weaker than in the Kara Sea, but nevertheless significant. We consider the mean concentration to be about 3 times less than summertime measurements (i.e. we consider the summer concentration to last for about 4 months, and we consider the winter month concentrations not to be significant for budget calculation). This yields an annual flux of 0.8×10^6 t TSM through the Kara Strait from the Barents to the Kara Sea.

The exchange between the Barents and Kara Seas north of Novaya Zemlya is rather complicated. Water masses enter the Kara Sea from the Arctic Ocean and flow directly into the Barents Sea around Franz Joseph Land, others enter the Kara Sea from the Barents Sea north of Novaya Zemlya and flow directly towards the Arctic Ocean and water masses from the Western Novaya Zemlya Current turn around the northern tip of Novaya Zemlya and flow onwards as part of the Eastern Novaya Zemlya Current, re-entering the Barents Sea through the Kara Strait. An annual flow of 5000 to 10,000 km^3 from the Barents Sea to the Kara Sea, through the opening north of Novaya Zemlya, is found by Pavlov and Pfirman (1995). Medvedev and Potekhina (1986) report TSM concentrations of about 3.5 mg l^{-1} in the northeastern part of the Barents Sea. We consider this value to be about 3 times higher than the mean annual concentration, as we did for the import through the Kara Strait. We calculate the flux through the opening between Franz Josef Land and Novaya Zemlya with a mean net water inflow of 7500 km^3, what leads to an annual input of 8.8×10^6 t TSM. An annual total net import of 9.6×10^6 t TSM from the Barents to the Kara Sea (0.8×10^6 t through the Kara Strait and 8.8×10^6 t through the opening between Franz Josef Land and Novaya Zemlya) is used in this study. With an average POC content of about 4% (as revealed from data from the Kara Sea shelf, away from the estuaries), we calculate a net inflow of 0.38×10^6 t POC yr^{-1}. The POC concentrations derived from the assumptions that it contributes 4% to total TSM are well in agreement with POC data from Romankevich et al. (2000a).

3.7. Eolian input

Pollen, spores, plant products, and weathering products of soils and rocks are the main sources for eolian transport into the Kara Sea. The present annual supply of eolian matter to the Kara Sea is estimated as 0.1×10^6 t of sediment, comprising 0.044×10^6 t of organic carbon (Romankevich et al., 2000b; Shevchenko et al., 1996, 1999).

4. Losses of sediment and organic carbon to the adjacent seas and the Arctic Ocean

4.1. Export to the Laptev Sea

The Western Taimyr Current flows along the Taimyr Peninsula coast with the Coriolis-deflected Yenisei River plume and, southwest of Zevernaya Zemlya, splits into two parts. One part flows towards the north, along the coast of the western Zevernaya Zemlya archipelago and into the Arctic Ocean, whereas the other part flows through Vilkitsky Strait into the Laptev Sea (Fig. 1). The annual water flow from the Kara Sea into the Laptev Sea through Vilkitsky Strait is estimated to be 4900 to 11,000 km^3 (Pavlov and Pfirman, 1995). According to Harms et al. (2000), export takes place mainly during autumn and winter (October to March).

We calculate the average TSM and POC concentrations in the Yenisei River estuary for the autumn and winter months. With the TSM and POC distribution maps from Gebhardt et al. (2004) we interpolate a twofold (TSM) or threefold (POC) dilution between the estuaries and Vilkitsky Strait. Taking this into account, we estimate the autumn–winter concentrations for the Vilkitsky Strait as 0.4 mg l^{-1} TSM and 0.025 mg l^{-1} POC. Furthermore, we use a mean annual water outflow of 7950 km^3 to estimate the annual export through Vilkitsky Strait. This results in estimated annual exports of 3.2×10^6 t TSM and 0.19×10^6 t POC through Vilkitsky Strait.

4.2. Export to the Arctic Ocean

Export of sediment and organic matter from the Kara Sea to the Arctic Ocean takes place (i) by transport of suspended and dissolved matter within the water masses and (ii) down the continental slope by means of debris flows and saline brines. Furthermore, sediment and POC is transported towards the Arctic Oceans incorporated in ice. The contribution of ice transport will be discussed later.

(i) Net water flow from the Kara Sea directly into the Arctic Ocean is found by Pavlov and Pfirman (1995) to be 19,000 to 22,000 km^3 annually. This export takes place mainly during the spring and summer months (April to September). We calculate the average TSM and POC concentrations from the Ob River estuary for the spring and summer months. Dilution between the estuaries and the Arctic Ocean is interpolated between data from Gebhardt et al. (2004); we assume a fourfold dilution of TSM and a fivefold dilution of POC (0.5 mg l^{-1} TSM and 0.02 mg l^{-1} POC) that, with an average water outflow of 20,500 km^3, results in an estimated annual export of 10.3×10^3 t TSM and 0.41×10^6 t POC.

(ii) Stein and Fahl (2004a) estimate a late Holocene downslope sediment transport of 24.8×10^6 t based on mass balance calculations: according to their data, downslope transport is about 17% of the total input. We calculate a much lower sediment input to the Kara Sea shelf, thereby suggesting that their absolute value overestimates the present downslope transport of sediment. Nevertheless, we use their ratio of 17% downslope transport, what results in a much lower absolute value in our budget. Macdonald et al. (1998), in comparison, calculated a ratio of 13% for the small Beaufort Sea including sediment transported by turbidity flows as well as incorporated in ice. The total annual sediment input into the Kara Sea can be calculated as 44.3×10^6 t (2.1×10^6 t by the rivers, 0.1×10^6 t by eolian input, 32.5×10^6 t by coastal erosion and 9.6×10^6 t through the Kara Strait), giving an estimated annual downslope sediment transport of 7.5×10^6 t. With an estimated 1% of organic carbon (TOC values of 1% to 2% occur in the St. Anna and the Voronin Trough, whereas values on the Central Kara Sea Plateau separating the troughs are lower, Stein and Fahl, 2004a), we calculate an annual transport of 0.08×10^6 t organic carbon from the Kara Sea to the Arctic Ocean by turbidity flows.

4.3. Export of suspended matter incorporated in ice (ice-rafted sediments)

Dirty ice floes and ice covered with algae were already observed during the Fram expedition from 1893 to 1896 (Bøggild, 1906; Nansen, 1906). Such ice floes may transport incorporated sediment (ice-rafted sediment, IRS) a great distance from their origin, for example by the Transpolar Ice Drift. Recently, studies were carried out of ice sediment incorporation processes and concentrations of IRS in the ice drift (e.g. Harms et al., 2000, and references therein; Pfirman et al., 1995; e.g. Smedsrud, 2000). With the exception of a small narrow polynya along the coast persisting throughout much of the winter, the Kara Sea is almost entirely ice-covered during the winter months (Pavlov and Pfirman, 1995; Pfirman et al., 1997). The polynya is the source of much of the first year ice formed on the Kara Sea shelf (Pavlov and Pfirman, 1995). The Ob and Yenisei river water discharges are quite small during winter, and during some periods the rivers are even entirely frozen. Sediment can be incorporated into the newly formed ice (a) by bottom adfreezing in the rivers and river mouths (anchor ice formation) and (b) by incorporation of resuspended bottom sediment due to convection reaching down to the seafloor in the polynya area. It is still not clear whether the river discharge flows mainly beneath or above the residing ice during the ice break-off and the associated main peak discharge. If it flows above the ice, it will accumulate suspended matter (e.g. Dean and Searcy, 1991; Reimnitz and Barnes, 1976); if so, this would act as a third process incorporating sediment into forming ice. During the break-off and associated ice melting, most of the fast ice melts at its origin and the incorporated sediment is released almost in situ (Pavlov and Pfirman, 1995; Smedsrud, 2000). Only a rather small portion of the ice and thus of IRS is observed as far north as 80°N.

Pfirman et al. (1997) report a study carried out between 1930 and 1934 by Vize (1937) who released over 300 wooden buoys with return addresses to surface waters. Only a few buoys originating from the southern Kara Sea were recovered in the North Atlantic, whereas 83% of the drifters released in the northwestern Kara Sea were finally recovered. Even though ice, buoys and surface waters respond differently to wind-driven forcing and even though wooden buoys might be destroyed by ice ridges, this experiment gives evidence that ice formed in the southern Kara Sea–where suspended matter is most likely to be incorporated into the newly formed ice due to higher suspended matter concentration close to the river estuaries–is less likely to be exported to the North Atlantic than ice formed in the northern Kara Sea. Most of the ice formed in the Kara Sea will, nonetheless, not even reach the Arctic Ocean due to melting (Pfirman et al., 1997).

Eicken (2003, and references therein) calculate an annual export of TSM and POC of 2.4×10^6 t and 0.017×10^6 t by sea-ice. These values are used in our budget calculation.

5. Sedimentation within the estuaries and on the Kara Sea shelf

5.1. Sediment and organic carbon accumulation in and off the estuaries

The Ob and Yenisei rivers transport large amounts of suspended material from the hinterland to the river mouths (Holmes et al., 2002, and references therein). The marginal filter proposed by Lisitsyn (1995) holds back the main part (i.e. 90% to 95%) of the suspended matter in the estuaries of the supplying rivers, and only a small amount escapes to the adjacent seas. In the Ob River, sediment settling and subsequent permanent storage do not take place in the same area. Accumulation takes place throughout the entire Ob Bay (Gebhardt et al., 2004), but the corresponding thick Holocene sediment package is found in the northernmost part of the Ob Bay (Dittmers et al., 2003). Sand is found at the river bottom and the fine suspended matter must have been transported northward after its accumulation in the river between the Ob-Taz confluence and the Ob River mouth. Samples taken just after a storm during the "Akademik Boris Petrov" cruise in 2000 (Stein and Stepanets, 2001) show a strong resuspension signal and, even during normal weather conditions, the lower part of the river water masses are enriched in suspended matter due to resuspension (Gebhardt et al., 2004). Transport due to anchor ice formation could also explain the sediment dislocation: Smedsrud (2000) points out that anchor ice is formed within the river bays, and in spring the incorporated sediment is not transported far, but released almost in situ. After several cycles of anchor ice formation and melting, the sediment could be dislocated from its initial accumulation area to its final burial area. Surface sediment cores from the Ob Bay show coarse grained sediment, mainly sand (Stein et al., 2004; Steinke, 2002). We therefore think that winnowing could be another process dislocating the fine-grained sediment: winnowing could be the result of a strong tidal influence in the northern part of the Ob River as reported e.g. by Harms and Karcher (1999). Furthermore, Meade et al. (2000) pointed out that the Ob River discharge undergoes a decadal cyclicity: it seems that once in a decade the Ob River flushes its bed. This process could also transport newly accumulated sediment to the river mouth where a strong change in turbidity, velocity and shear promotes its re-accumulation.

The sediment accumulating in the Yenisei River marginal filter is found in the northern part of the river. Present sediment discharge data suggest that the Yenisei River changed its regime from a formerly sediment accumulating to a bypass system after the construction of dams in the hinterland (Gebhardt et al., 2004). Sediment presently accumulates at a more northerly location than during the Holocene. Dittmers et al. (2003) calculated average annual Holocene sediment accumulations of 14.3×10^6 t and 9.2×10^6 t in the Ob and Yenisei river marginal filters, respectively. The Holocene record for the Ob River seems to resemble its present situation, whereas the Holocene Yenisei River seems to have transported about three times its present sediment load (Lisitsyn, 1972: 13×10^6 t yr^{-1}; Telang et al., 1991: 14.5×10^6 t yr^{-1}). This discrepancy is most probably a result of dam construction in the 1960s and 1970s: Meade et al. (2000) report a sediment discharge reduction of about 97% at the gauging station just downstream of the Krasnoyarsk dam after the river closure, and Bobrovitskaya et al. (2003) report that the sediment yield in the Yenisei River at Igarka after the construction of reservoirs is about two times lower.

According to Lisitsyn (1995), the marginal filters of global river estuaries catch about 90% to 95% of suspended matter, so that only about 5% to 10% escapes into the adjacent oceans. Lisitsyn (1995) further shows that the marginal filter in Arctic rivers acts differently from other rivers due to their different runoff regimes. During the summer, when most of the water and sediment is discharged, the marginal filter acts quite similar to those in other rivers. In winter, the material trapped in the marginal filter is often not accumulated, but incorporated into ice. It was shown that this ice melts almost in situ during spring (Smedsrud, 2000). We therefore assume that the sediment accumulating within the marginal filter zone is 90% of the total suspended matter supplied by the rivers. With the annual TSM (POC) discharge of the Ob and Yenisei rivers being about 15.5×10^6 t (0.61×10^6 t) and 5.1×10^6 t (0.57×10^6 t) and, considering the marginal filter to catch about 90% of the suspended load, the amounts of TSM and POC annually withdrawn at the estuaries can be, respectively, calculated as 14.0×10^6 t and 0.55×10^6 t for the Ob River and

4.6×10^6 t and 0.51×10^6 t for the Yenisei River. The total annual TSM and POC withdrawn at the marginal filter (northern parts of the Ob and Yenisei river mouths plus Gydanskii Bay, Fig. 1) can be summed up as 18.5×10^6 t and 1.06×10^6 t annually. Furthermore, the amount of TSM and POC escaping the marginal filters and thence accumulating in the Kara Sea can be calculated as 2.1×10^6 and 0.12×10^6 t yr^{-1}, respectively.

Sediments in the marginal filter area contain about 2% organic carbon (Stein and Fahl, 2004a); if the estimated 1.06×10^6 t POC would all be buried, the sediments would contain 5.7% organic carbon. We suggest that, in a first step, 1.06×10^6 t of organic carbon are accumulated, but then 0.69×10^6 t are recycled and remineralized by bioturbation and early diagenesis, so that only 0.37×10^6 t are finally buried. The process of organic matter degradation is further supported by inorganic proxies (Beeskow and Rachold, 2003).

5.2. Sediment and organic carbon accumulation on the Kara Sea shelf

In a first step, 44.3×10^6 t sediment (2.1×10^6 t river input, 0.1×10^6 t eolian input, 32.5×10^6 t due to coastal erosion and 9.6×10^6 t from the Barents Sea) and 0.89×10^6 t organic carbon (0.12×10^6 t river input, 0.044×10^6 t eolian input, 0.35×10^6 t due to coastal erosion and 0.38×10^6 t from the Barents Sea) are brought annually to the Kara Sea shelf. About 10.3×10^6 t sediment and 0.41×10^6 t POC are transported further to the Arctic Ocean by suspension, 7.5×10^6 t sediment and 0.08×10^6 t POC by high-saline brines, resuspension and debris flows, 2.4×10^6 t sediment and 0.017×10^6 t by IRS, and 3.2×10^6 t sediment and 0.19×10^6 t POC are transported further to the Laptev Sea by suspension. By means of mass balance, we can calculate the annual sediment accumulation on the Kara Sea shelf to be 20.9×10^6 t and a terrestrial organic carbon accumulation of 0.19×10^6 t. Assuming that the sediment in the Kara Sea contains an average of about 1.5% TOC (using data from Gurevich, 1995) we can calculate a total of 0.31×10^6 t TOC accumulated on the Kara Sea shelf, which means that about 0.12×10^6 t, or 39%, must be of marine origin. This is in good agreement with several studies on the terrestrial versus marine TOC content of the Kara Sea shelf (e.g. Fahl et al., 2003; Fernandes and Sicre, 2000; Krishnamurthy et al., 2001; Stein and Fahl, 2004a).

Stein and Fahl (2004a) estimate 123×10^6 t sediment and 1.38×10^6 t organic carbon (i.e. 1.15×10^6 t of terrigenous and 0.23×10^6 t of marine origin) accumulated in the Kara Sea and the estuaries during the late Holocene (0–6 cal. kyr BP) by means of mass balance. Stein and Fahl (2004a) use an old coastal erosion value (Romankevich and Vetrov, 2001) of 109×10^6 t yr^{-1} sediment and 1×10^6 t yr^{-1} organic carbon which recently was shown to be far too high (Vasiliev et al., 2005); therefore, we think that they overestimate the Kara Sea shelf sedimentation.

6. Preliminary budget for the shelf

6.1. A contemporary sediment budget for the Kara Sea shelf

For calculation of a contemporary sediment budget, we simplified the Kara Sea shelf system using a multi-box model as proposed by Macdonald et al. (1998) for the Beaufort Sea shelf (Fig. 3a). We estimate that 90% of the river input is accumulated within the estuaries. With mass balance calculations we estimate that 44.3×10^6 t sediment are brought to Kara Sea shelf annually, of which 20.2×10^6 t (46%) are transported further to the Arctic Ocean (2.4×10^6 t by ice, 10.3×10^6 t by suspension and 7.5×10^6 t by saline brines, resuspension and debris flows down the shelf edge). About 3.2×10^6 t are transported through the Vilkitsky Strait into the Laptev Sea. The amount of sediment annually buried on the Kara Sea shelf can be calculated as 20.9×10^6 t (47% of the total input into the Kara Sea).

6.2. Extrapolation of a late Holocene sediment budget for the Kara Sea shelf

Stein and Fahl (2004a) suggest that sedimentation conditions during the last 6000 yr approximated modern conditions. However, the river fluxes of TSM and POC have drastically changed since the late 20th century dam constructions in the hinterland of the rivers. We therefore recalculate a late Holocene budget based on (i) the new data for coastal erosion and

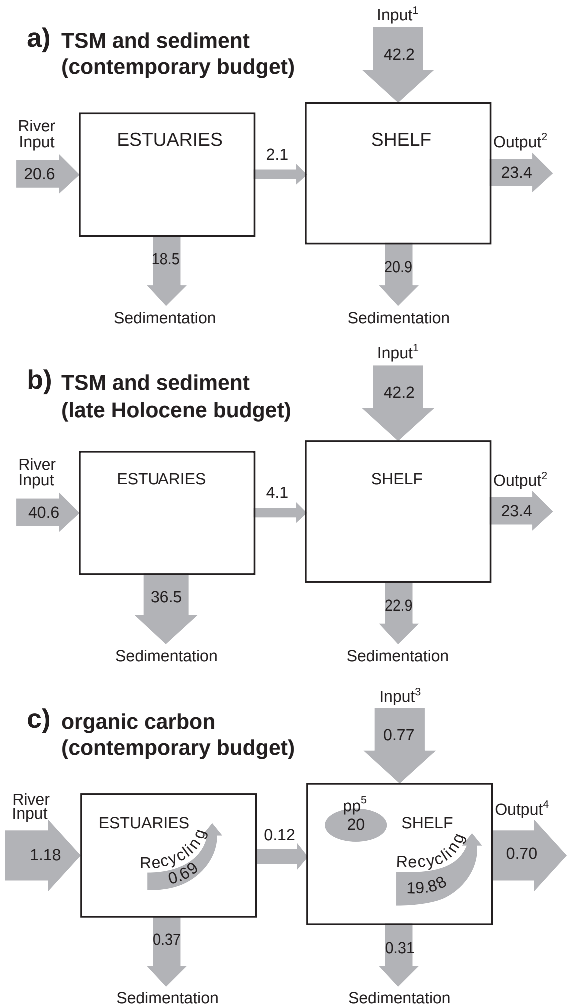

Fig. 3. Simplified multi-box model for the Kara Sea sedimentation and organic carbon burial (in 10^6 t yr^{-1}). (a) Sediment and TSM burial, (b) interpolation of a late Holocene budget, (c) organic carbon burial. [1]Input: 0.1×10^6 t yr^{-1} eolian input (Romankevich et al., 2000b; Shevchenko et al., 1996, 1999), 32.5×10^6 t yr^{-1} input due to coastal erosion (Vasiliev et al., 2005) and 9.6×10^6 t yr^{-1} from the Barents Sea; [2]Output: 2.4×10^6 t yr^{-1} by ice, 3.2×10^6 t yr^{-1} to the Laptev Sea, 10.3×10^6 t yr^{-1} to the Arctic Ocean by suspension and 7.5×10^6 t yr^{-1} as sediment downslope the shelf edge to the Arctic Ocean; [3]Input: 0.044×10^6 t yr^{-1} eolian input (Romankevich et al., 2000b; Shevchenko et al., 1996, 1999), 0.35×10^6 t yr^{-1} input due to coastal erosion (Vasiliev et al., 2005) and 0.38×10^6 t yr^{-1} from the Barents Sea; [4]Output: 0.017×10^6 t yr^{-1} by ice, 0.19×10^6 t yr^{-1} to the Laptev Sea, 0.41×10^6 t yr^{-1} to the Arctic Ocean by suspension and 0.08×10^6 t yr^{-1} as sediment downslope the shelf edge to the Arctic Ocean; [5]pp = primary production (Vinogradov et al., 2000).

(ii) an enhanced burial in the marginal filter zone, probably induced by recent changes as well as (iii) river input data originating from before the dam constructions of the 20th century as used in the late Holocene budget calculation by Stein and Fahl (2004a). We assume that 90% of this river input was caught in the marginal filter. We use our modern data for input into the Kara Sea other than river input; the same is done for output from the Kara Sea to the adjacent seas. With a total late Holocene river input that was almost double the recent input (40.6×10^6 t total of which 15.5×10^6 t are by the Ob River, 14.4×10^6 t by the Yenisei and 10.7×10^6 t by other rivers, Stein and Fahl, 2004a), and with all other assumptions similar as for the contemporary budget, we estimated an almost doubled TSM burial for the estuaries, a doubled export of TSM to the shelf and a slightly higher shelf sedimentation rate during the late Holocene (Fig. 3b).

6.3. A contemporary organic carbon budget for the Kara Sea shelf

Similar to the sediment budget calculation, we simplified the Kara Sea system using a multi-box model as proposed by Macdonald et al. (1998) for the Beaufort Sea (Fig. 3c). About 1.18×10^6 t POC are annually brought to the marginal filter, of which 90% (1.06×10^6 t) accumulate there. About 0.69×10^6 t organic carbon are recycled and only about 0.37×10^6 t are permanently stored. About 10% (0.12×10^6 t) POC escapes the marginal filter and is transported to the Kara Sea shelf. Using mass balance calculations we estimate an annual input of 0.89×10^6 t POC to the Kara Sea shelf (0.12×10^6 t by river input, 0.044×10^6 t by eolian input, 0.35×10^6 t through coastal erosion and 0.38×10^6 t from the Barents Sea). A loss of about 0.7×10^6 t POC (0.017×10^6 t by ice, 0.08×10^6 t to the Arctic Oceans by saline brines, resuspension and debris flows, 0.41×10^6 t to the Arctic Ocean by suspension and 0.19×10^6 t through the Vilkitsky Strait to the Laptev Sea) can be estimated. About 0.31×10^6 t organic carbon are permanently buried on the shelf. Of the annual primary production of 20×10^6 t, about 19.88×10^6 t are recycled and only 0.12×10^6 t (0.6%) are permanently stored on the Kara Sea shelf.

7. Discussion

7.1. Comparison with the late Holocene Kara Sea budget

Great differences in sedimentation are obvious at first glance when comparing the late Holocene budget of Stein and Fahl (2004a) to the budget estimated in this study (Table 2). These differences can easily be explained: (a) in our budget, much more sediment is buried in the estuaries. This means that, at present, the marginal filter is more effective than in average late Holocene times. Stein and Fahl (2004a) report a marginal filter effectiveness of about 70% during the late Holocene. Nevertheless, they point out that during the last 2000 yr conditions have changed and that accumulation rates suggest an increase in effectiveness of the marginal filter. (b) A large difference of about 76.5×10^6 t yr^{-1} is obvious in the coastal erosion data used for the budgets (Table 2). As discussed above, recent data by Vasiliev et al. (2005) show that the earlier coastal erosion data by Romankevich and Vetrov (2001) overestimate the annual coastal erosion in the Kara Sea by far. This explains why about 72.3×10^6 t yr^{-1} less sediment is accumulated on the Kara Sea shelf in our budget. Further research on the coastal erosion data is needed to improve the accuracy of estimated budgets of this area.

Nevertheless, our late Holocene interpolation is not valid for the present situation, but for the situation some 50 yr ago. The dam constructions in the hinterland have considerably changed the patterns of water and sediment discharge in the Ob and Yenisei rivers (Meade et al., 2000), so that the Yenisei now delivers only about one third of its pre-dam sediment discharge (Holmes et al., 2002, and references therein). This also affects the effectiveness of the marginal filter. Our investigations can thus only give an estimate based on the present status of research and identify the need for further investigations to clearly distinguish between a late Holocene and a contemporary sedimentation signal in the marginal filter sedimentation area.

Table 2
TSM and sediment in the Holocene Kara Sea sediment budgets of Stein and Fahl (2004a) and in this study

	Stein and Fahl (2004a) (in 10^6 t yr^{-1})	This study (in 10^6 t yr^{-1})	Difference (in 10^6 t yr^{-1})
River input	40.6	40.6	–
Sedimentation in the estuaries	27.8	36.5	− 8.7
Coastal erosion	109	32.5	76.5
Sedimentation on the shelf	95.2	22.9	72.3

7.2. Comparison with the Beaufort Sea

The Beaufort Sea is much smaller than the Kara Sea (Macdonald et al., 1998: 60,000 km^2 shelf area, 100 km width). Input into the Beaufort Sea is dominated by the river sediment and POC discharge of the Mackenzie River (127×10^6 t sediment and 2.1×10^6 t POC annually) and coastal erosion is of minor importance in the Beaufort Sea (5.6×10^6 t yr^{-1}, Macdonald et al., 1998, and references therein), whereas the Kara Sea is only river-dominated in the estuaries of the Ob and Yenisei rivers, but dominated by the coastal erosion input on the shelf area. The marginal filter in the Mackenzie River catches about 51% of the sediment, whereas we assume that the marginal filter in the Ob and Yenisei rivers catches about 90% of the material. About 90% of the organic carbon buried in the Beaufort Sea is of terrestrial origin, compared to about 60% in the Kara Sea. Almost all marine organic carbon is recycled in both seas (Kara Sea: >99%, Beaufort Sea: 98%).

Macdonald et al. (1998) compares the amount of organic carbon in the Beaufort Sea to the global estimate for a global shelf area of about 26×10^6 km^2 and the hypothetical amount of about 0.3×10^6 t organic carbon buried annually on the Beaufort Sea shelf. As 1.4×10^6 t organic carbon are annually buried on the Beaufort Sea shelf, it is an area of much higher-than-average carbon burial. Similar calculations for the Kara Sea result in a hypothetical annual burial of 3.85×10^6 t of organic carbon. As we estimate a total burial of 0.68×10^6 t (0.37×10^6 t in the estuaries and 0.31×10^6 t on the shelf), the Kara Sea shelf seems to be an area of lower-than-average carbon burial.

7.3. Comparison with the Laptev Sea

A first budget on the Laptev Sea sedimentation was calculated by Rachold et al. (2002) on the basis of three representative sediment cores. The authors show that throughout the whole Laptev Sea coastal erosion is the main source of sediment input, whereas riverine input is significantly lower, comparable to the Kara Sea situation. Sediment sources and sinks are well balanced in the Laptev Sea. Within the Arctic Ocean, the Laptev Sea shows the highest production rates of sea ice (Kassens et al., 1999). With exception of the western Laptev Sea where sediment export by sea ice is the main output factor, the main part of the material brought to the Laptev Sea is simply accumulated on the Laptev Sea shelf. During the last 5000 yr, about 60.8×10^6 t sediment was deposited annually on the Laptev Sea shelf according to Rachold et al. (2002).

A detailed budget on the Laptev Sea sedimentation was recently calculated by Stein and Fahl (2004b). Contrary to the Kara Sea rivers which have large estuaries, the Lena River draining into the Laptev Sea forms a delta. The Lena River delta acts as a filter only for coarse material (sand, gravel), but does not hold back as large amounts of fine-grained material as the Ob and Yenisei rivers (Stein and Fahl, 2004b). According to Stein and Fahl (2004b), 40.5×10^6 t of sediment and 0.67×10^6 t of organic carbon are annually accumulated on the Laptev Sea shelf; another 17×10^6 t of sediment and 0.17×10^6 t of organic carbon are annually buried on the adjacent continental slope. This sums up to 41% of the total sedimentary input being stored permanently on the shelf and 20% on the slope. About 11% are transported further by ice and 28% by currents. In terms of organic carbon, 22% are stored on the shelf, 5% on the slope and 36% are transported further to the Arctic Ocean (6% by ice and 30% by currents). In the Kara Sea, about 47% of the total sedimentary input is permanently stored on the shelf. Some 46% are transported further to the Arctic Ocean (5% by ice and 41% by currents and gravitational flow), and 7% are transported through the Vilkitsky Strait into the Laptev Sea. The Laptev Sea and the Kara Sea are, therefore, quite similar in their accumulation conditions. Transport of sedimentary material into the Arctic Ocean by ice is slightly enhanced in the Laptev Sea due to the higher production rates of sea ice. In both seas, less than 1% of the primary production is stored in the sediment, and terrestrial organic matter clearly dominates the organic sedimentary carbon buried (Stein and Fahl, 2004a,b).

8. Conclusion

Sedimentation in the Ob and Yenisei river estuaries is clearly dominated by the river discharge of TSM and POC. Nevertheless, sedimentation on the Kara Sea shelf is dominated by the input due to coastal erosion and river input is of minor contribution. Input from the adjacent seas should not be neglected; during years with wind conditions favoring enhanced inflow through the straits and openings, enhanced TSM and POC input from the adjacent sea is possible (being as high as the total riverine input, as computable with TSM values from Medvedev and Potekhina, 1986, and maximum water through-flow values from Pavlov and Pfirman, 1995).

Most of the organic carbon (i.e. $>60\%$) buried on the shelf is of terrestrial origin, and most of the primary production of marine carbon is recycled; less than 1% of the organic carbon from primary production is stored permanently in the sediment. About 0.68×10^6 t organic carbon (i.e. 35% of the organic carbon brought to the Kara Sea by rivers, coastal erosion and eolian input) is annually buried in the Kara Sea (0.56×10^6 t of terrestrial and 0.12×10^6 t of marine origin), and about 0.7×10^6 t organic carbon are transported further into the Arctic Ocean and into the Laptev Sea. The Kara Sea, therefore, acts as an organic carbon sink. All sources and sinks of the organic carbon in the Kara Sea budget are in the same range (excluding primary production on the shelf), which makes the Kara Sea shelf very sensitive to changes in the carbon cycle. It is hence likely that the dam constructions in the hinterland have greatly changed the organic carbon burial regime in the Kara Sea; perhaps more organic carbon was buried before the dams were built.

For improvement of our budget, further research is needed mainly in terms of quantification of (a) coastal erosion, (b) fluxes through the connections between the Kara Sea and the adjacent seas and (c) sedimentation on the Kara Sea shelf. Furthermore, investigation of primary production on the Kara Sea shelf, as well as in the rivers and estuaries is needed for better understanding and estimation of an organic carbon budget for the Kara Sea.

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