Modern Sedimentation Processes in the Kara Sea (Siberia)

Moderne Sedimentationsprozesse in der Karasee (Sibirien)

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Hamburg, den 20. April 2004

Preface

One of the important characteristics of the Arctic Ocean, surrounded by the world´s largest shelf seas and seasonally to permanently covered by sea ice, is its large river discharge which is equivalent to 10% of the global runoff. The freshwater balance of the Arctic Ocean is an important factor controlling sea-ice extent and intermediate/bottom water formation in the Northern Hemisphere, as well as Arctic Ocean surface-water conditions. The formation and melting of sea ice result in distinct changes in the surface albedo, the energy balance, the temperature and salinity structure of the upper water masses, and the biological processes, and thus play a major role in the global climate system. Having in mind this importance of river discharge, a bilateral Russian-German multidisciplinary research project to investigate the "Siberian River Run-Off" (SIRRO), specifically of the Westsiberian rivers Ob and Yenisei, was established in 1997 (see Stein et al., 2003, and further references therein for details). The SIRRO Project was coordinated by the Alfred Wegener Institute for Polar and Marine Research (AWI) Bremerhaven (Prof. Dr. D.K. Fütterer) and the Vernadsky Institute of Geochemistry and Analytical Chemistry (GEOKHI) Moscow (Acad. Prof. Dr. E. M. Galimov). The other German and Russian institutes involved in the project are the Institute of Biogeochemistry and Marine Chemistry (IfBM) Hamburg, the Research Center for Marine Geosciences (GEOMAR) Kiel, the Institute of Oceanography (IfM) Hamburg; the P.P. Shirshov Institute of Oceanology (IORAS) Moscow, the Arctic and Antarctic Research Institute (AARI) St. Petersburg, the Murmansk Marine Biological Institute (MMBI) Murmansk, and the Institute of Geology of Ore Deposits, Petrography, Mineralogy and Geochemistry (IGEM) Moscow. Funding of the main phase (2000-2003) mainly comes through the German Ministry of Education and Science (BMBF) and the Russian Foundation of Basic Research.

The overall goal of SIRRO is best described as to better understand the oceanographical, biological, biogeochemical, geochemical, and geological processes which influence and control the influx and distribution of riverine water and its dissolved and suspended particulate matter into the Kara Sea, and which are of relevance within the context of global environmental and climatic changes at present and in the past. Discussions of this thematically extremely wide and unspecific but multidisciplinary goal resulted in a number of more selective and especially better focused subprojects:

(A) The significance of biological processes for the transformation of matter in the Kara Sea
(B) Influence on modern and Late Quaternary water mass characteristics in the Kara Sea
(C) Composition and transformation of dissolved organic matter (DOM) and nutrients in the Kara Sea
(D) Effect of freshwater and sediment input on the biogeochemistry of carbon and silica

sedimentation in the Kara Sea

(E) Terrigenous sediment and particulate organic carbon flux: Sources, pathways sinks, and variability

(F) High resolution modelling of particulate and dissolved matter transport and sedimentation

(G) Evaluation of the Kara Sea anthropogenic pollution resulted from the Siberian rivers run-off.

This PhD Thesis by Catalina Gebhardt dealing with the Kara Sea organic carbon and nitrogen cycle has been carried out within Subproject D (leaded by B. Gaye-Haake, IfBM Hamburg). A close cooperation existed with scientists involved in Subproject E (leaded by R. Stein, AWI Bremerhaven). Several joint publications resulted from this cooperation (e.g., Fahl et al., 2003; Gaye-Haake et al., 2003; Gebhardt et al., 2004).

R. Stein
Alfred Wegener Institute, Bremerhaven (August 2004)

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Summary

During the last decades, global warming has been one of the major focuses of the Earth Sciences. It is undisputable that the Arctic Ocean plays a key role in the world's ocean system being one of the main sites of deep water formation, and that heat transfer from the lower to the higher latitudes is a key process in global climate systems. Additionally, with its large continental shelves, the Arctic Ocean is one of the key regions of global organic carbon burial. Climate changes rapidly influence the sensitive Arctic system. We improve our understanding of the world's climate mechanism by improving our understanding of the changes and mechanisms in the Arctic realm.

The Kara Sea, one of the Siberian shelf seas, receives about one third of the total freshwater discharge into the Arctic Ocean, mainly via the Ob and Yenisei rivers (Aagaard and Carmack, 1989). The Kara Sea and both rivers are highly seasonally influenced: the completely ice-free period lasts for only three months, from mid-July to mid-October (e. g. Pavlov and Pfirman, 1995). The main period of water and sediment discharge by the rivers occurs during spring and summer, with about 30% of the total annual water budget and about 42% of the total annual sediment budget discharged in June (Lammers and Shiklomanov, 2000).

The German-Russian SIRRO project (Siberian River Run-Off) focuses on the historical (Holocene) and recent influences of the Ob and Yenisei rivers on the Kara Sea in both historical and recent context. During cruises on *Akademik Boris Petrov* in 1997, 1999, 2000, and 2001 (Matthiessen and Stepanets, 1998; Matthiessen et al., 1999; Stein and Stepanets, 2000; Stein and Stepanets, 2001; Stein and Stepanets, 2002), surface sediment samples were taken from multicorers, and water was filtered in order to sample the suspended load of the rivers and the Kara Sea (Gebhardt et al., 2002; Unger et al., 2001). With this data, recent fluxes of total suspended matter (TSM), particulate organic carbon (POC) and particulate nitrogen (PN) were calculated, and total organic carbon (TOC) of the surface sediment was quantified.

Flux calculations of suspended matter showed that the Yenisei river acts as a bypass system and delivers about 5.03×10^6 t sediment, 0.57×10^6 t POC and 0.084×10^6 t PN annually to the Kara Sea. In contrast, the Ob River retains about three quarters of the suspended load within the Ob Bay and discharges about 3.76×10^6 t sediment, 0.27×10^6 t POC and 0.027×10^6 t PN into the Kara Sea per year (chapter 3). Amino acids indicate that the suspended load of the Ob River is more degraded than in the Yenisei River due to the higher residence time of water and organic matter in the river and connected flood plains. The high fluxes of particulate organic carbon into the Kara Sea confirm earlier findings that a large portion of the organic matter in the Kara Sea's surface sediments are of terrestrial origin (e. g. Fernandes and Sicre, 2000; Krishnamurthy et al., 2001; Stein and Fahl, 2004a).

A sediment and organic carbon budget for the Kara Sea in recent times was calculated on the basis of our flux calculations. Sedimentation in the river estuaries is clearly dominated by

the river discharge of TSM and POC. Nevertheless, sedimentation on the shelf is dominated by the input due to coastal erosion, and fluvial input is minor. About 18.33x10^6 t sediment are buried on the shelf annually, compared to the 18.5x10^6 t that accumulate in the estuaries and 20.41x10^6 t that are transported further to the Arctic Ocean. About 0.657x10^6 t organic carbon are buried on the Kara Sea shelf and in the estuaries annually, and 0.872x10^6 t are transported further to the Arctic Ocean. More than 60% of the organic matter buried on the shelf is of terrestrial origin. Recycling of marine organic carbon from primary production is high; only <1% is permanently stored in the shelf sediment. The Kara Sea acts as a sink for organic carbon, but seems to be an area of lower-than-average carbon burial (chapter 4).

Processes affecting the suspended and dissolved substances on their way from the Yenisei River into the Kara Sea, in particular in the mixing zone between riverine and marine water, were studied in detail in summer 2000. Some substances are only affected by dilution with marine water (e. g. POC, PN), whereas others (e. g. Mn, Fe, TSM) undergo processes such as precipitation and flocculation due to the changing hydrography and salinity. POC behaves conservatively even though degradation can be observed within the mixing zone. TSM flocculates at the landward edge of the mixing zone. Dissolved manganese and iron precipitate at low salinities, and manganese is released from the anoxic sediment into the near-bottom layers of the water column. Changes in hydrography cause resuspension in the near-bottom layers, mixing the suspended matter with resuspended sediment of different composition. A reliable differentiation between processes induced by changes in salinity and by changes in hydrography was not possible with the current database (chapter 5).

Zusammenfassung

Globale Erwärmung ist seit Jahrzehnten eines der Schlagwörter in den Geowissenschaften. Es ist unumstritten, daß der arktische Ozean durch die Tiefenwasserbildung in der Framstraße eine Schlüsselrolle im weltweiten Ozeansystem spielt. Wärmetransport von niedrigen zu hohen Breitengraden ist eine der wichtigsten Komponenten im globalen Klimahaushalt. Außerdem ist der arktische Ozean durch seine großen Schelfgebiete eines der Hauptgebiete für die Sedimentation von organischem Kohlenstoff. Die Arktis wird durch Klimaveränderungen stark beeinflußt; erhöhen wir also unser Verständnis für die Prozesse und Mechanismen, die in der Arktis ablaufen, verbessern wir gleichzeitig unser Verständnis für die globalen Klimamechanismen.

Die Karasee ist eines der sibirischen Schelfmeere. Sie erhält etwa einen Drittel des totalen Frischwasserzufuhr in den arktischen Ozean, hauptsächlich durch ihre Zuflüsse Ob und Yenisei (Aagaard und Carmack, 1989). Die Karasee und die Flüsse Ob und Yenisei sind saisonal stark beeinflußt; nur etwa drei Monate - von Mitte Juli bis Mitte Oktober - ist das Gebiet total eisfrei (z. B. Pavlov und Pfirman, 1995). Der Hauptabfluß von Wasser und Sediment findet im

Frühjahr und Sommer statt; so werden im Juni ca. 30% des jährlichen Wasser- und 42% des jährlichen Sedimentabflusses gemessen (Lammers und Shiklomanov, 2000).

Das deutsch-russische Gemeinschaftsprojekt „SIRRO" (Siberian River Run-Off) konzentriert sich auf den Einfluß der beiden Flüsse Ob und Yenisei auf die Karasee, sowohl aus historischer als auch aus aktueller Perspektive. Während Fahrten mit dem Forschungsschiff *Akademik Boris Petrov* in den Jahren 1997, 1999, 2000 und 2001 (Matthiessen und Stepanets, 1998; Matthiessen et al., 1999; Stein und Stepanets, 2000; Stein und Stepanets, 2001; Stein und Stepanets, 2001) wurden Proben vom Oberflächensediment genommen. Gleichzeitig wurde Wasser filtriert, um die Suspensionsfracht der Flüsse und der Karasee zu beproben (Gebhardt et al., 2002; Unger et al., 2001). Mit diesen Daten konnten Stoffflüsse von der gesamten Suspensionsfracht (TSM), vom partikulären organischen Kohlenstoff (POC) und vom partikulären Stickstoff (PN) berechnet sowie der Gehalt an organischem Kohlenstoff im Oberflächensediment (TOC) quantifiziert werden.

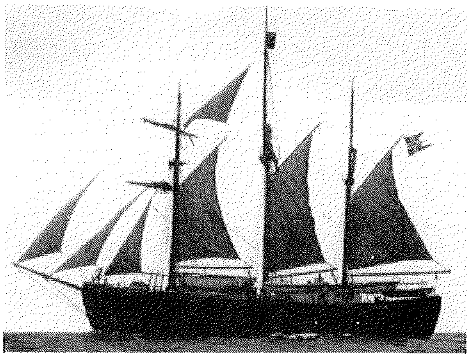
Stoffflußberechnungen zeigen auf, dass der Yenisei in seinem Unterlauf heute ein Bypaß-System darstellt. Rund 5,03x10^6 t TSM, 0,57x10^6 t POC und 0,084x10^6 t PN werden jährlich durch den Yenisei in die Karasee eingetragen. Im Gegensatz dazu werden im Unterlauf des Ob etwa drei Viertel der Suspensionsfracht abgelagert und nur etwa 3,76x10^6 t TSM, 0,27x10^6 t POC und 0,027x10^6 t PN erreichen die Karasee (siehe Kapitel 3). Anhand von Aminosäuren-Daten ist zu erkennen, daß das organische Material des Ob stärker abgebaut ist als dasjenige des Yenisei. Dies kann auf höhere Residenzzeiten des organischen Materials und des Flußwassers im Ob und in den mit dem Ob verbundenen Flutebenen zurückgeführt werden. Die hohen Flußraten von organischem Material von den Flüssen in die Karasee bestätigen die früheren Arbeiten (z. B. Fernandes und Sicre, 2000; Krishnamurty et al., 2001; Stein und Fahl, 2004a), die einen großen Anteil des organischen Materials der Schelfsedimente auf terrestrischen Ursprung zurückführen.

Auf der Basis dieser Flußberechnungen wurde ein Sedimentbudget sowie ein Budget des organischen Kohlenstoffs für die heutige Karasee erstellt. Die Sedimentation in den Ästuaren ist durch den Flußeintrag von Sediment und organischem Material dominiert, währenddessen auf dem Schelf der Eintrag durch Küstenerosion dominiert und der Flußeintrag eine untergeordnete Rolle spielt. Etwa 18,33x10^6 t Sediment werden jährlich auf dem Schelf akkumuliert (in den Ästuaren sind es 18,5x10^6 t), und etwa 20,41x10^6 t werden jährlich in den arktischen Ozean weiterverfrachtet. Rund 0,657x10^6 t POC akkumulieren jährlich in den Ästuaren und auf dem Schelf, und etwa 0,872x10^6 t werden in den arktischen Ozean weitertransportiert. Mehr als 60% des organischen Kohlenstoffs in den Schelfsedimenten stammen aus terrestrischen Quellen. Mehr als 99% der marinen Primärproduktion werden gleich rezykliert, und weniger als 1% davon geht permanent ins Sediment über. Die Karasee ist heute eine Senke für organisches Material, auch wenn sie weniger als der durchschnittliche Schelfbereich akkumuliert (siehe

Kapitel 4).

Verschiedene Prozesse beeinflussen die gelösten und partikulären Substanzen auf ihrem Weg vom Fluss bis in die Karasee; vor allem in der Mischzone zwischen fluviatilem und marinem Wasser können diese Prozesse beobachtet werden. Eine detaillierte Studie dieser Prozesse wurde anhand von Daten aus dem Yenisei durchgeführt. Einige Substanzen werden lediglich durch Verdünnen mit marinem Wasser beeinflußt (z. B. POC und PN), während andere Substanzen durch Änderungen in der Hydrographie und in der Salinität ausflocken und ausfällen (z. B. TSM, Mangan und Eisen). POC verhält sich konservativ, obwohl in der Mischzone Abbau von organischem Material stattfindet. TSM flockt am Süsswasserende der Mischzone aus. Gelöstes Mangan und Eisen fällen bei niedriger Salinität aus; Mangan wird außerdem vom anoxischen Sediment in die darüberliegenden Wasserschichten freigelassen. Veränderungen in der Hydrographie bewirken Resuspension von Sediment. Dies wirkt sich insofern auf die Suspensionsfracht aus, als daß resuspendiertes Sediment mit anderem Substanz-Gehalt die Suspensionsfracht durchmischt und die primären Konzentrationen überprägt. Mit der gegenwärtigen Datengrundlage ist es nicht möglich, glaubhaft zwischen Salinitäts-induzierten und Hydrographie-induzierten Prozessen zu unterscheiden (siehe Kapitel 5).

Part A:
Introduction



The Fram

1 Introduction

This thesis "*Modern Sedimentation Processes in the Kara Sea (Siberia)*" deals with the sedimentation processes of both lithogenic and organic material in the Kara Sea. The quantification of fluxes to the Kara Sea as well as accumulation and degradation of the suspended load is discussed.

The Kara Sea is one of the Siberian shelf seas, located between the Barents Sea to the West and the Laptev Sea to the East, and connected to the open Arctic Ocean to the North (Figs. 1-1 and 1-2). It encompasses an area of about 883,000 km^2 with a water volume of 98,000 km^3 (Pavlov and Pfirman, 1995). 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 Yenisei River is Siberia's largest river and among the ten largest rivers in the world (Gordeev, 2000; Milliman, 1991), with a drainage area of 2.58x10^6 km^2 and a length of 3844 km (Milliman and Meade, 1983; Telang et al., 1991).

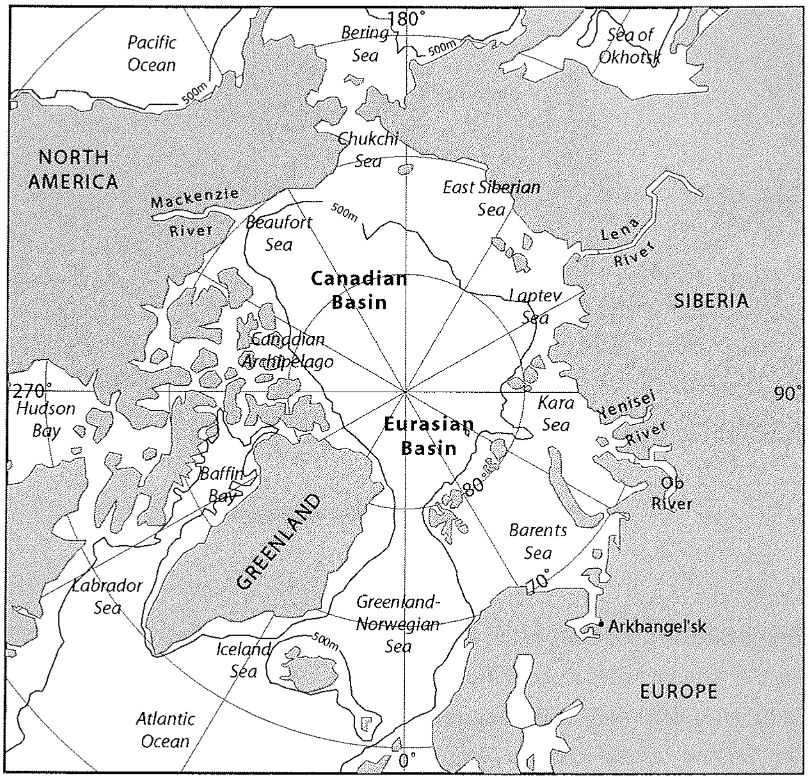


Fig. 1-1: Overview of the Arctic realm

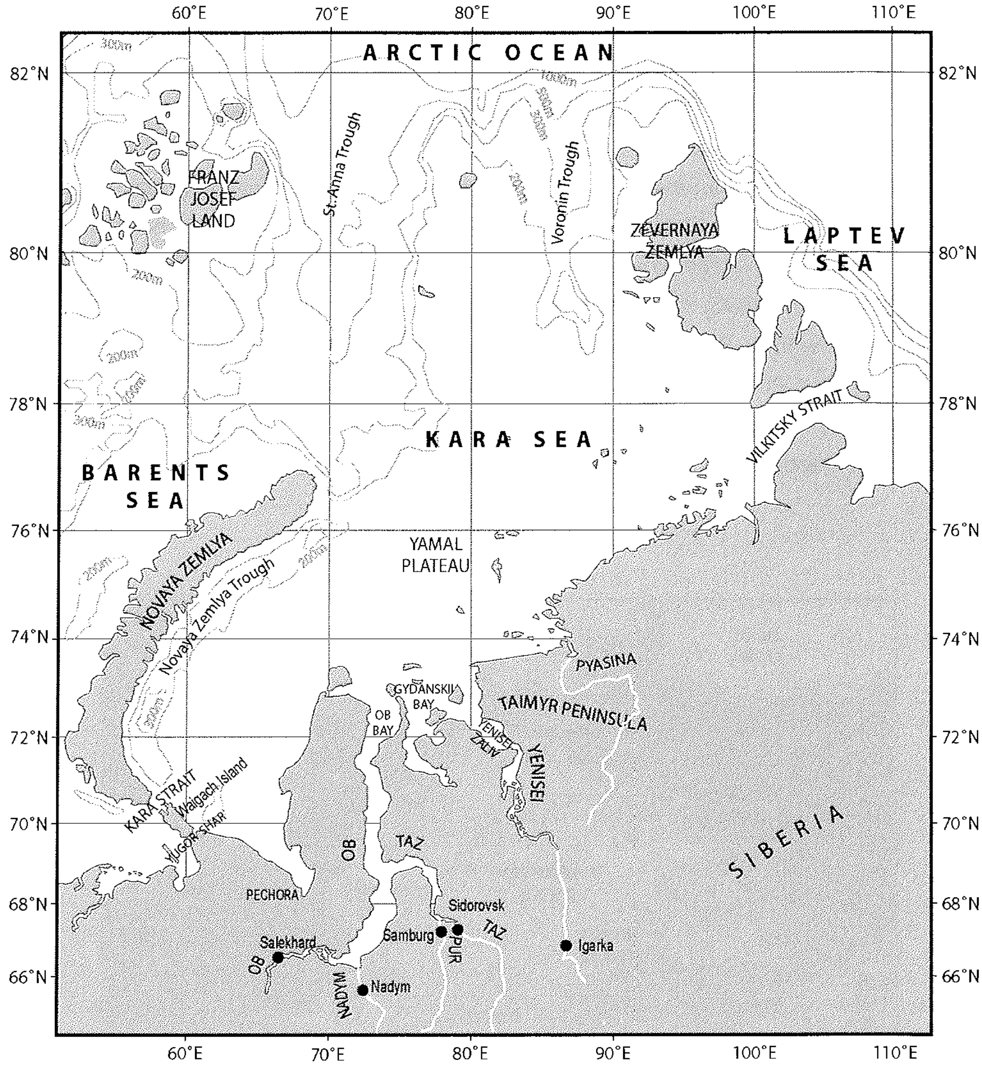


Fig. 1-2: Overview of the Kara Sea

The Ob River is Siberia's third largest river in terms of annual discharge (429 km^3 yr^{-1}; Gordeev, 2000) and is the longest Arctic river (6370 km including the Ob Bay) with the largest catchment area (2.99x10^6 km^2) (Milliman, 1991; Telang et al., 1991). A detailed overview of the Kara Sea shelf and the Ob and Yenisei rivers is given in Chapter 3.2.

1.1 Aims of this thesis

During the last decades, global warming has been one of the main focuses of earth science studies. About $7.7x10^6$ t of carbon dioxide have been released annually into the atmosphere by burning of fossil fuels and by massive changes in land use since the Industrial Revolution (Macdonald et al., 1998). Laxon et al. (2003) relate variations in ice formation directly to increase in summer melt rather than to changes in wind direction and oceanic circulation. Since it receives large amounts of freshwater by rivers draining Northern Eurasia and Northern America (e.g. Yenisei, Lena, Ob, Mackenzie, Yukon and Pechora rivers) that is interacting with the ice formation, the Arctic Ocean indirectly influences physical properties such as atmospheric radiation and heat budget. It is undisputable that the Arctic Ocean plays a major role in the world's ocean system, being one of the major sites of deep water forming. Furthermore, heat transfer from the lower to the higher latitudes is a key mechanism in the world's climate. Climate changes rapidly influence the sensitive Arctic system. Therefore, by improving our understanding of the changes and mechanisms in the Arctic realm (e. g. changing water and sediment discharges of the Arctic rivers and changing sedimentation patterns on the Arctic shelves) we improve our understanding of the world's climate mechanisms.

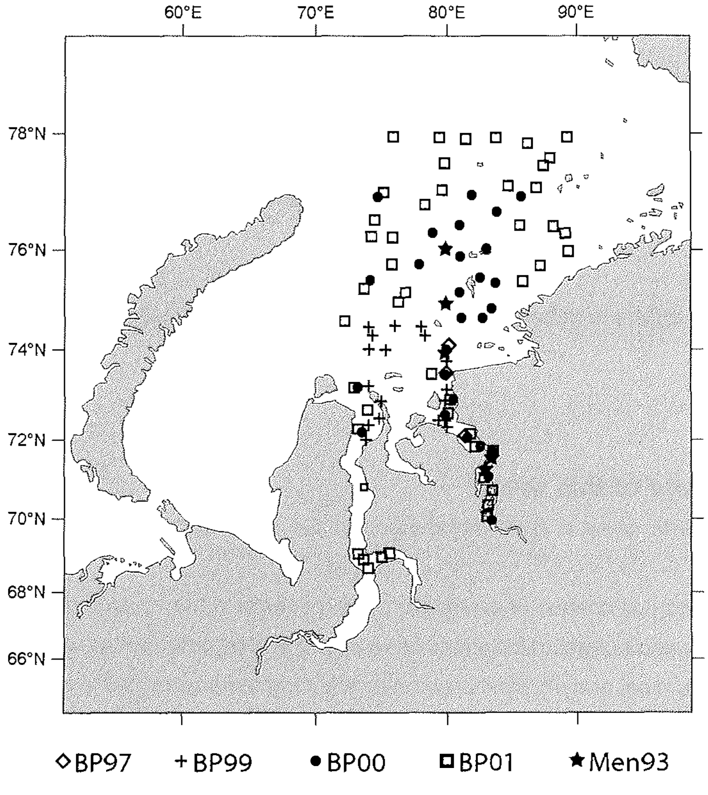


***Fig. 1-3: Overview of the sample stations** of the 1997, 1999, 2000 and 2001 Akademik Boris Petrov cruises and the 1993 Dmitrij Mendeleev cruise of which samples were used in this study.*

In the course of this study, analyses of parameters (e. g. total suspended matter, particulate organic carbon, and particulate nitrogen) were carried out contributing to a detailed understanding of the recent Kara Sea system by (a) allowing estimates of fluxes and sedimentation budgets and (b) giving an insight into the processes at the river-ocean interface. For this purpose, suspended matter and surface sediment samples were collected on four cruises on the Russian research vessel *Akademik Boris Petrov* in 1997, 1999, 2000 and 2001 (Fig. 1-3) within the framework of the German-Russian SIRRO (Siberian River Run-Off) project (Matthiessen and Stepanets, 1998; Matthiessen et al., 1999; Stein and Stepanets, 2000; Stein and Stepanets, 2001; Stein and Stepanets, 2002).

Important open questions can be answered by detailed sedimentological and geochemical investigations. These include the following aspects:

- the recent fluxes of total suspended and organic matter from the Ob and Yenisei rivers into the Kara Sea,
- the recent sedimentation of this material along the river course, the estuaries and the Kara Sea,
- the processes affecting the material fluxes along their way from the rivers into the Kara Sea and
- a comparison of recent conditions with the conditions throughout the late Holocene (last 6,000 years) to understand how recent environmental changes affect the river-Kara Sea system.

This thesis forms part of our efforts to get an integrative and multidisciplinary view of the Arctic system.

1.2 Outline and structure of this thesis

The first chapter of this thesis gives a short introduction to the aims and purposes of this study.

Chapter 2 deals with the historical context of exploration and research in the Kara Sea.

Chapter 3 and 4 present flux and budget calculations of sediment and organic matter, whereas chapter 5 focuses on the chemical and physical processes affecting the suspended load on its way from the rivers into the Kara Sea:

The total suspended matter, particulate organic carbon and particulate nitrogen loads of the

Ob and Yenisei rivers are discussed in chapter 3. The interannual and intraseasonal variability of these parameters is discussed, and flux estimates from the rivers into the Kara Sea are given. Our findings are compared with sediment discharge data published by other authors.

The fourth chapter contains a recent sediment and organic carbon budget for the Kara Sea, calculated on the basis of the suspended matter sampled in the Kara Sea during the 2000 and 2001 SIRRO expeditions. To compare our recent with the late Holocene budget revealed from sediment core data (Stein and Fahl, 2004a), a late Holocene sediment budget was interpolated from our recent budget. Furthermore, our recent Kara Sea budget was compared to late Holocene budgets of the Laptev Sea (Rachold et al., 2002b; Stein and Fahl, 2004b) and to a recent budget of the Beaufort Sea (Macdonald et al., 1998).

The fifth chapter focuses on the processes affecting the suspended load and dissolved elements in the mixing zone of freshwater and marine water, the so-called maximum turbidity zone, of the Yenisei River. The findings are compared with other studies of the Yenisei River marginal filter (Beeskow and Rachold, 2003; Lisitsyn, 1995) and with observations in other rivers.

Chapter 6 gives a general summary of chapters 3 to 5 with special emphasis on answering the questions given in section 1.1.

This thesis contains the original text, figures and tables of three manuscripts that were submitted to international, peer-reviewed, journals. The first manuscript (chapter 3) was accepted in reviewed form by *Marine Geology* (Elsevier, Amsterdam). The second and third manuscripts (chapters 4 and 5) were submitted to *Marine Geology* (Elsevier, Amsterdam) and to *Estuarine, Coastal and Shelf Sciences* (Elsevier, Amsterdam) in December 2003 and February 2004, respectively. Due to its cumulative form, repetitions within the text and the figures (e.g. in the introduction chapters of the single papers) cannot be avoided in this thesis. All data used in this study can be found at http://www.pangaea.de/PangaVista.

2 Historical development of research in the Kara Sea

Through many centuries, the Arctic realm has been a place of adventure, mysteries and unknown perils. Little is known about the first explorers to the Kara Sea. In 1556, the British sailing ship *Searchthrift* under Borough reached the Waigach Island and Novaya Zemlya (Fig. 1-2), but immense masses of ice blocked the way through the Kara Strait into the Kara Sea. For the next 25 years, all further efforts were ceased as unpromising. In 1580, two small British sailing ships (*George* under Pet and *William* under Jackman) were sent out to cross the Kara Sea and find the Northeast Passage to China. Pet crossed the Jugor Shar south of Waigach (Fig. 1-2), but perpetual ice and thick fog in the southwestern Kara Sea hindered his further passage. Jackman never returned (Mirsky, 1953).

The Dutch merchant Brunel built a commerce network with a rich family in Archangel'sk

(Fig. 1-1). He was the first European to advance as far as to the Ob River on country way from Archangel'sk. In 1584 he started an expedition by sea to find the Northeast Passage, but did not succeed. On his way back to Europe he crossed the Kara Sea, but ran aground a sandbar in the Pechora River estuary (Fig. 1-2) and lost all his merchandise as well as his honor (Mirsky, 1953). In 1594, Nai on *Zwaan* and Petgales on *Merkur* as well as Barents on another *Merkur* ventured a new approach of the Kara Sea under Dutch colors. Nai and Petgales entered the Kara Sea through the Kara Strait, but had to turn back due to heavy ice conditions. Barents, however, tried to sail around the northern tip of Novaya Zemlya and enter the Kara Sea from the North. He succeeded in 1596, but was stopped by unfavorable weather conditions and had to overwinter on the eastern shore of Novaya Zemlya. After the hibernation, the *Merkur* was wrecked and he and his crew had to sail with the jollyboats. Barents died on their way back through the Kara Strait towards the Kola Peninsula.

At the end of the 17th century Tsar Peter the Great traveled through France, the Netherlands and England. He noticed the European richness and wealth due to trade with oil, fish, fur and whalebone. Only the Tsar knew that his empire since long reached as far as Comchatka, and that trade with furs and mammoth teeth was flourishing. On his return to St. Petersburg he initiated a major expedition to map the Northern coast of Siberia, and to explore the land gate to America he supposed in the unmapped Chukotka Peninsula. As part of his plans, the Kara Sea coast was to be mapped by three expedition teams. Even though Peter the Great died in 1725, his plans were pursued by his successors. In 1734 the first team entered the Kara Sea through the Kara Strait with coarse wooden boats to map the coastline along the Yamal Peninsula to the Ob River mouth (Fig. 1-2). In the gentle summer of 1737, the team reached the Ob River estuary and entered the Ob Bay. The second team intended to map the coastline between the Ob and the Yenisei river mouths. In 1734/5 the Ob Bay was mapped, and aliment depots as well as lighthouses were built along the Ob River. In 1736, the aliment depots and lighthouses were extended towards the Yenisei River. Eventually, in the gentle summer of 1737, the team managed to sail from the Ob River mouth to the Yenisei River mouth and to map the coastline. The third team's duty was to map the coastline from the Yenisei River mouth towards the northernmost tip of the Taimyr Peninsula (Fig. 1-2). Since the team was unable to do the mapping off-shore, they had to map the region traveling the countryside (Mirsky, 1953).

In 1878, Nordenskjøld started a Swedish Expedition on the steam and sailing ship *Vega* to find the Northeast Passage. His journey led him through the Kara Strait into the Kara Sea. From an expedition on the *Pröven* in 1875 Nordenskjøld was familiar with Novaya Zemlya and the Yamal Peninsula where he had made anthropological observations. While the *Pröven* sailed back to Tromsø, Nordenskjøld and a small crew carried out observations and studies along the Yenisei River. After reaching the small settlement Yenisejsk they returned to Sweden. Only one year later he started a second expedition to the Yenisei River on the *Ymer*. Laden with goods he returned to Sweden, the first European to transport merchandise from northern Asia by sea. On his *Vega* expedition 1878-1880 to find the Northeast Passage he again crossed the Kara Sea. Throughout centuries, explorers had tried to find this legendary passage, but he was the first one to succeed: even though the *Vega* was icebound for almost 300 days only some 115 miles off the Bering Strait, she eventually was released and reached Japan in 1880.

Nansen's famous drift expedition on the *Fram* 1893-1896 led him through the Kara Strait, along the Yamal and Taimyr Peninsula and further through the Vilkitsky Strait into the Laptev Sea (Fig. 1-2) (Nansen, 1904). He carried out detailed bathymetric mapping in the Kara Sea and found that the central Kara Sea is very shallow, in contrast to other Siberian seas. He discovered the Novaya Zemlya Trough and incisions on the Yamal Plateau that nowadays are interpreted as paleovalleys of the Ob and Yenisei rivers (K. Dittmers, unpubl. data). He further observed that during summer the rivers release enormous amounts of freshwater and keep the southern Kara Sea ice-free. He assumed that the land masses absorb large amounts of heat due to their dark color and release this heat into the Kara Sea by runoff, resulting in enhanced ice melting near the coast. He noticed that the ice distribution in the Kara Sea is, nevertheless, not controlled by the heat from land, but driven by wind and ocean currents. By comparing his measurements with measurements from the *Vega* expedition that had taken place 15 years earlier but during the same month, he noticed the high interannual variability that is characteristic for the Kara Sea. He ascribed the much larger amounts of ice and the significantly lower temperatures during his expedition to smaller river runoff of the Ob and Yenisei rivers in 1893 (Nansen, 1902).

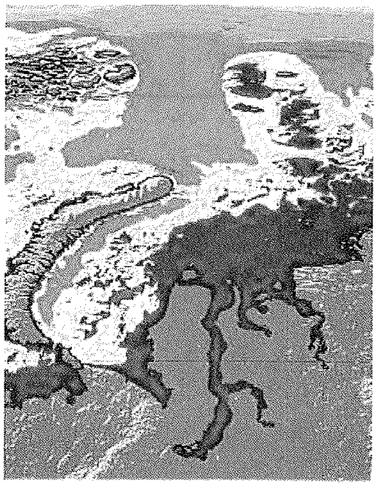
In 1908, Amundsen planned to repeat Nansen's drift with the *Fram*. He was granted the commandership of a second *Fram* expedition, but when it became known that Peary reached the North Pole in 1909, he had to abandon his plans because he could not get any contributions to an Arctic expedition anymore. He decided to lead an expedition to the South Pole instead. After his successful return he resumed his plans, but it soon was clear that the *Fram* was unserviceable for another expedition to the Arctic Ocean. When the First World War broke out in 1914 he again had to abandon his plans. In 1916 he eventually managed to build the ship *Maud*, and started his expedition in 1918. Like Nansen he decided to enter the Kara Sea through the Kara Strait, to sail along the Yamal and Taimyr Peninsulae and to leave the Kara Sea through the Vilkitsky Strait (Sverdrup, 1933).

Detailed scientific studies were carried out on the *Vega*, *Fram* and *Maud* expeditions and fill several large volumes (e. g. Bøggild, 1906; Nansen, 1902; Nansen, 1904; Nansen, 1906; Sverdrup, 1933).

Nowadays it is much easier to sail the Kara Sea. Icebreakers are stationed in Murmansk and can reach the Kara Sea within few days, and today's vessels are much more comfortable than the early sailing and steaming ships. But still the Kara Sea has not lost its attraction. Many of the scientific questions have not changed much since the time of Nordenskjøld, Nansen and Amundsen; still salinity, temperature, current speed and directions and water depth are measured. Many of the present observations confirm the early findings and complete their statement, but research has not been stagnant during the last decades to centuries, so some of the early conclusions sound somewhat antiquated. Still the early observations are of great value to compare the late 19th century to early 20th century Kara Sea with the contemporary Kara Sea.

Systematic scientific work in the Kara Sea started in 1921, when the head of the Russian Government – V. I. Lenin – signed a decree about the creation of a "Floating Marine Research Institute" (Kulikov et al., 1999) to explore the White, Barents and Kara Seas. During the Second World War, Russia stopped all scientific investigation of the western Russian Arctic seas. After the Second World War, scientific work was resumed by several Russian marine institutes. During the last years, cruises took place almost every year to the Kara Sea (Kulikov et al., 1999; Tarasov et al., 1999). The joint German-Russian SIRRO (Siberian River Run-Off) project contributed another six cruises on *RV Akademik Boris Petrov* in 1997, 1999, 2000, 2001, 2002 and 2003 (Matthiessen and Stepanets, 1998; Matthiessen et al., 1999; Schoster and Levitan, 2003; Schoster and Levitan, 2004; Stein and Stepanets, 2000; Stein and Stepanets, 2001; Stein and Stepanets, 2002).

Part B:
Accepted and submitted papers



The Kara Sea

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

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

3.1 Abstract

The rivers Ob and Yenisei 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 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 (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.

3.2 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

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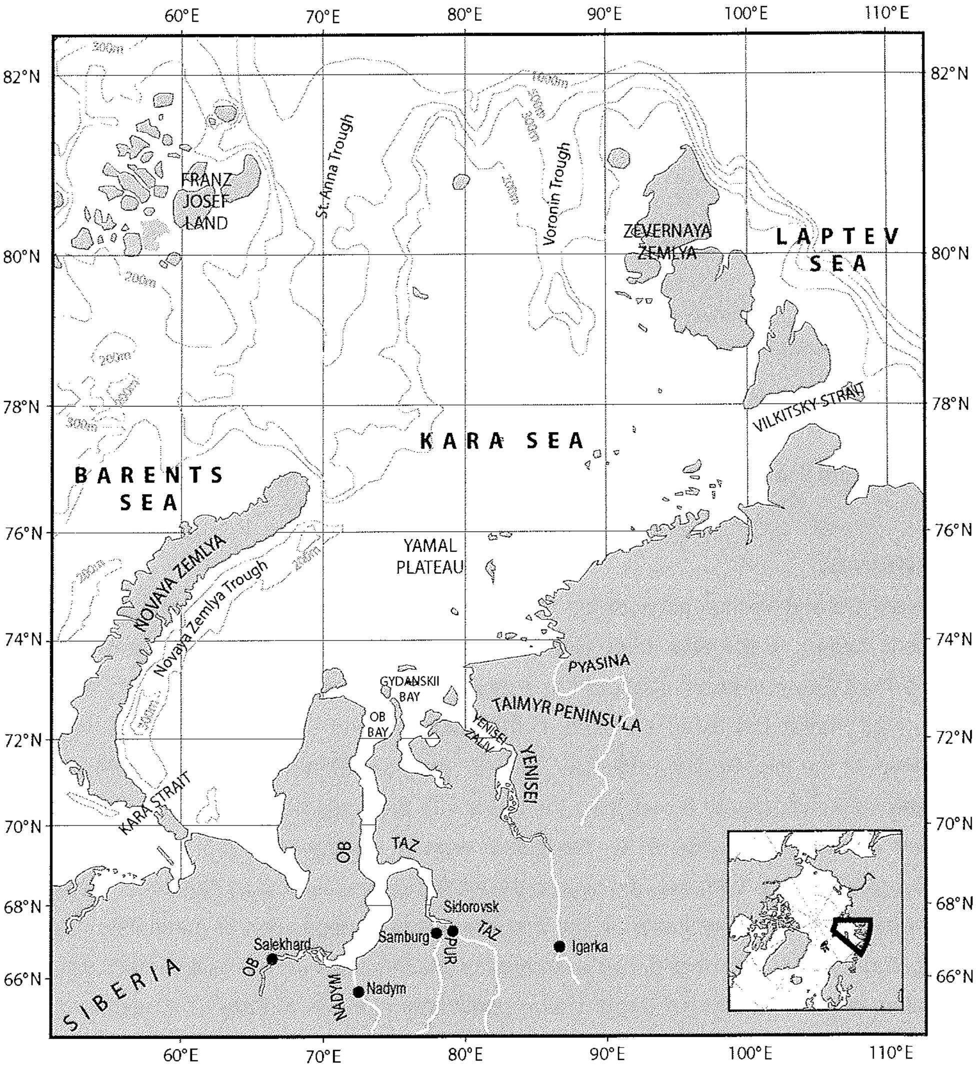

Fig. 3-1: Geographical position of the study area.

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. 3-1). 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 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 to 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 ten 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 yr^{-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 to 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, 2004a; 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, 2004a, 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. 3-1) 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.

3.3 Materials and Methods

3.3.1 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 liter 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. 3-2 and 3-3 indicate the sample stations in 2001 (48 stations, Gebhardt et al., 2002) and 2000 (28 stations, Unger et al., 2001), respectively.

3.3.2 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 mg/l.

3.4 Results

3.4.1 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. 3-2 and 3-3). 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 one to two 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.

3.4.2 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. 3-2 and 3-3).

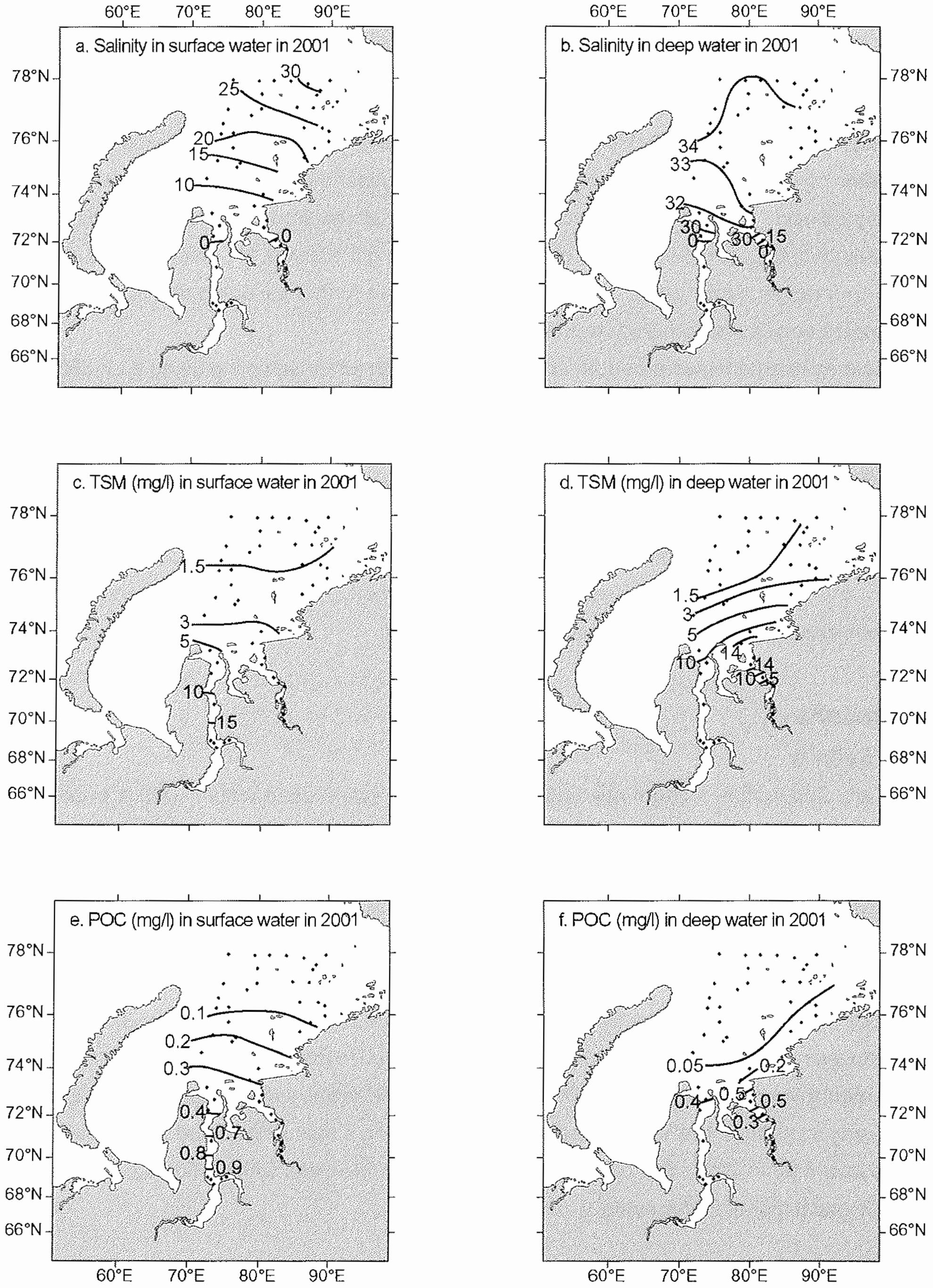

Fig. 3-2: Salinity, TSM and POC concentration in the Ob and Yenisei rivers and the adjacent Kara Sea in 2001*. Left Panel: surface water, right panel: deep water. Salinity is given in a. and b., TSM (mg/l) in c. and d., and POC (mg/l) in e. and f. Dots mark the sampling points.*

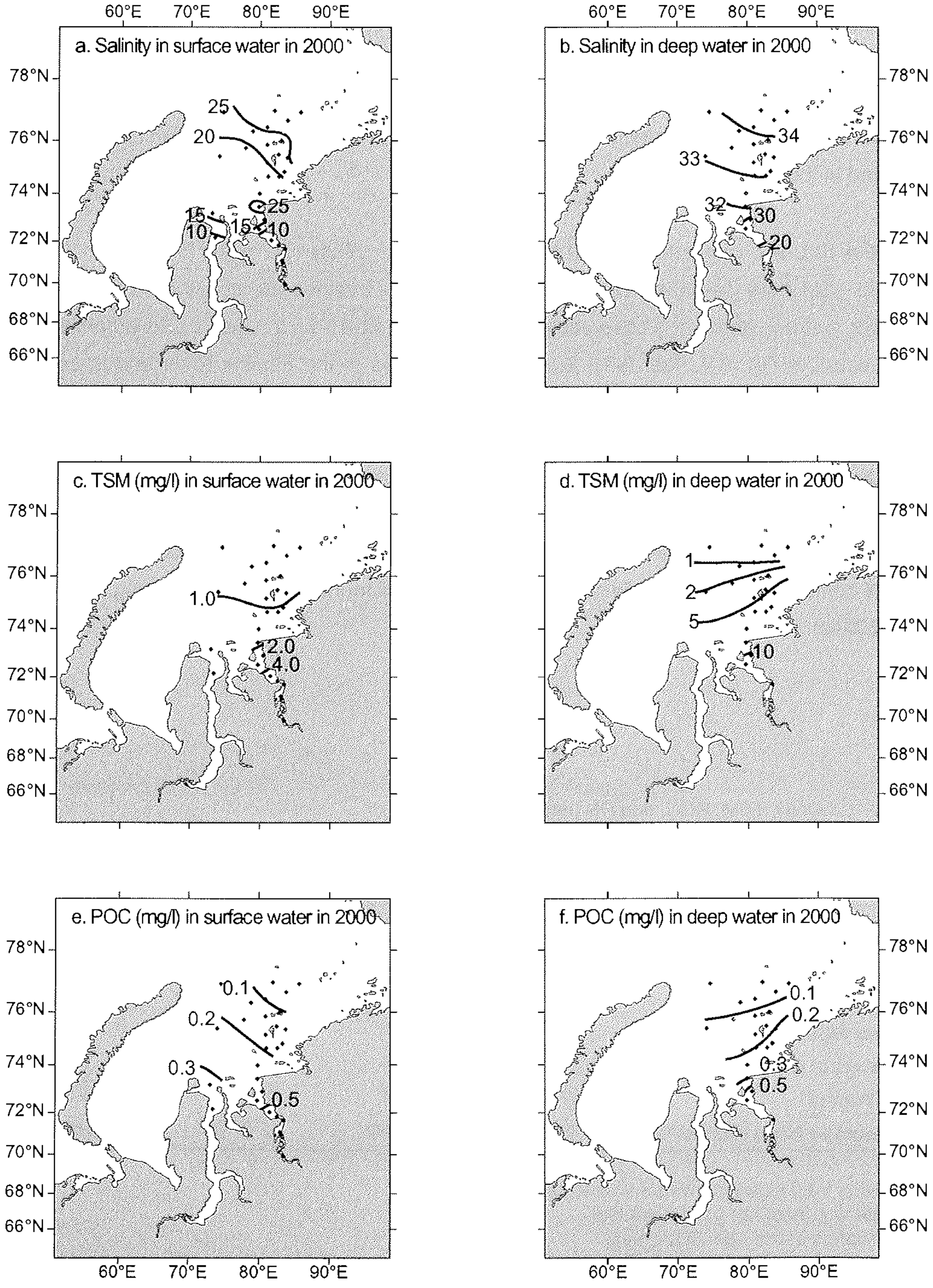

Fig. 3-3: Salinity, TSM and POC concentration in the Ob and Yenisei rivers and the adjacent Kara Sea in 2000. *Left Panel: surface water, right panel: deep water. Salinity is given in a. and b., TSM (mg/l) in c. and d., and POC (mg/l) in e. and f. Dots mark the sampling points.*

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.

3.4.3 Particulate organic carbon (POC) and particulate nitrogen (PN)

Like the TSM data described above, Yenisei River POC values are constant in both years. However, a strong gradient is observable in the Ob River data from the Ob-Taz River confluence to the estuary (Fig. 3-4; Tab. 3-1). 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, 2004a).

Tab. 3-1: Salinity, TSM, POC, and PN measured in 2001.

	Salinity	TSM (mg/l)	POC (mg/l)	PN (mg/l)
Rivers	0-10[d]	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[a]	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[b]	0-30	1.1-5.6	0.05-0.36	0.01-0.053
Gradients in Surface Waters[a,b]	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[a,c]	N to S	SE to NW	SE to NW	SE to NW

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

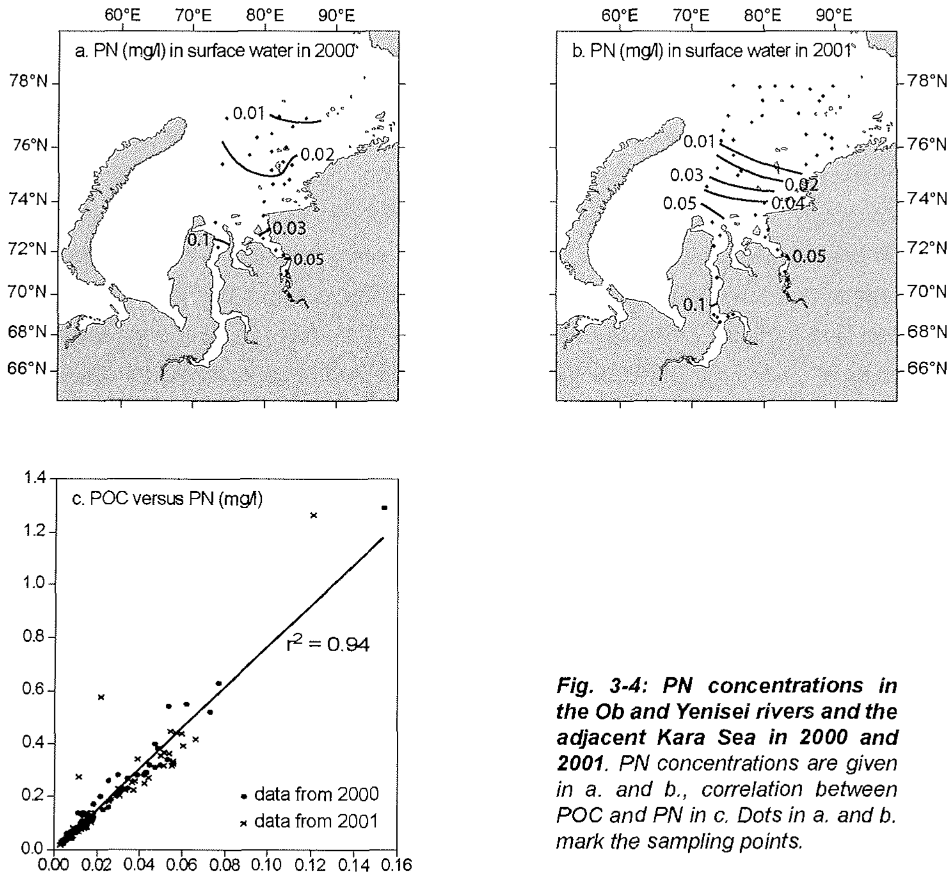

Fig. 3-4: PN concentrations in the Ob and Yenisei rivers and the adjacent Kara Sea in 2000 and 2001. *PN concentrations are given in a. and b., correlation between POC and PN in c. Dots in a. and b. mark the sampling points.*

3.5 Discussion

3.5.1 Interannual and intraseasonal variability

The Ob and Yenisei river 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 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., 2003b). 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. 3-2 and 3-3). 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.

3.5.2 TSM and POC in the Ob and the Yenisei rivers

Surface TSM (POC) concentrations decrease from 18 mg/l (0.9 mg/l) 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.

3.5.3 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. 3-2a). 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. 3-5a) 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. 3-5b).

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 to 1300 mg m^{-2} d^{-1} of organic carbon (Gaye-Haake et al., 2003b), and sedimentological stations deployed in the estuaries and the adjacent portions of the Kara Sea during September 1993 revealed POC fluxes of 0.71 to 368 mg m^{-2} d^{-1} (Lisitsyn et al., 1995). Vertical organic carbon fluxes sampled by a 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

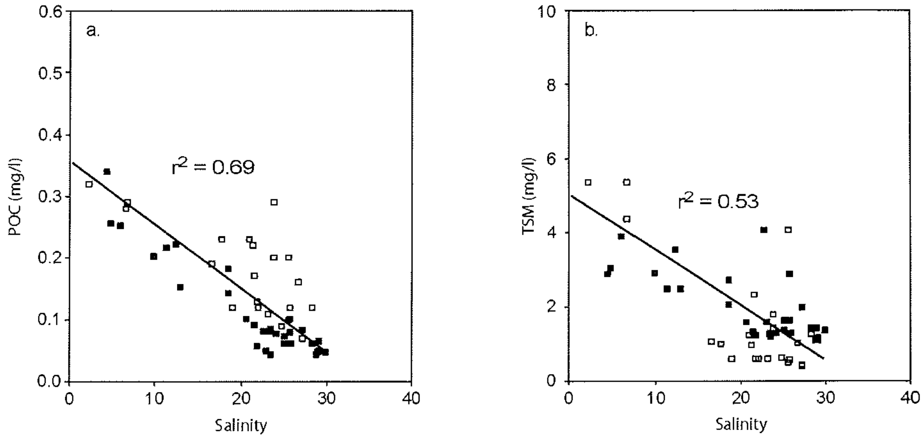

Fig. 3-5: Correlation of POC and TSM with salinity. *Data from the Ob are left out due to high resuspension. a. POC versus salinity, b. TSM versus salinity. Open squares: data from 2000, close squares: data from 2001.*

(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. 3-1) which could additionally influence the concentration and composition of both TSM and POC.

North of 76°N, TSM remains relatively constant at 1.1 to 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. 3-6). Stein et al. (2004a, their Fig. 7.6.22) provide new data about the Holocene sediment

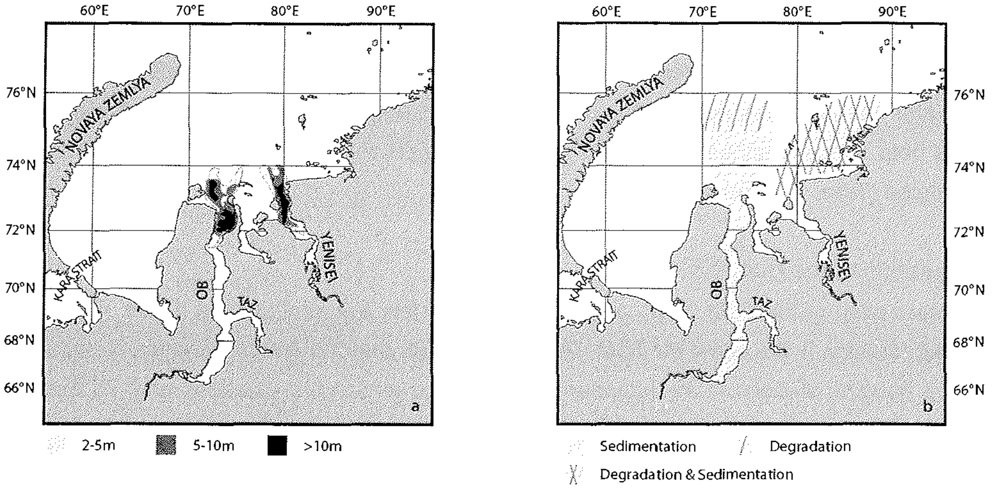

Fig. 3-6: Areas of sedimentation and degradation in the Ob and Yenisei rivers and the adjacent Kara Sea. *Holocene sediment thickness is given in a. (after Dittmers et al., 2003), areas of recent sedimentation and degradadtion in b.*

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 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.

3.5.4 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 (Tab. 3-2). On the basis of these data, modern annual TSM, POC and PN budgets for the Ob and Yenisei rivers were calculated (Tabs. 3-3 and 3-4).

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

Tab. 3-2: Periods of water and sediment discharge data used for calculation of mean monthly water and sediment discharges applied in the TSM, POC and PN budgets.

River	First Year	Last Year	Number of Years	Gaps[c]	Gauging Station (Fig. 3-1)
Ob[a]	1958	1994	37	no	Salekhard
Ob[b]	1960	1987	28	yes	Salekhard
Yenisei[a]	1978	1995	18	no	Igarka
Yenisei[b]	1970	1986	17	yes	Igarka
Pur[a]	1939	1990	52	yes	Samburg
Taz[a]	1962	1994	33	yes	Sidorovsk
Nadym[a]	1955	1990	36	yes	Nadym

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

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

$$C_{TSM_i} = \frac{Q_i}{S_i} \quad . \qquad (1)$$

In this expression:

C_{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:

$$p = \frac{C_{TSM_i}}{m_{TSM_i}} \quad . \qquad (2)$$

Here m_{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:

Tab. 3-3: 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})
Jan	16.16	0.03	0.03	3.32
Feb	14.76	0.03	0.03	3.29
Mar	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
Aug	46.83	0.15	0.15	16.86
Sept	43.94	0.11	0.11	12.19
Oct	37.57	0.09	0.09	10.05
Nov	17.84	0.03	0.03	3.79
Dec	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

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

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:

$$q_i = \frac{m_{POC_i}}{m_{TSM_i}}\ , \tag{4}$$

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_{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 Ob-Taz River confluence

Tab. 3-4: 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})	TSM Budget at the River Mouth[f] (10^3 t month^{-1})	POC Budget at the Ob-Taz Confluence[g] (10^3 t month^{-1})
Jan	13.48	15.51	0.12	0.03	0.08	1.84	4.14
Feb	10.25	11.79	0.09	0.02	0.06	1.41	3.17
Mar	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
Aug	60.69	67.31	2.48	0.53	1.72	38.21	85.97
Sept	36.82	42.79	1.06	0.24	0.77	17.11	38.51
Oct	27.92	33.07	0.56	0.13	0.42	9.28	20.89
Nov	16.70	20.09	0.22	0.05	0.17	3.74	8.41
Dec	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 og 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

in month i (POC_i):

$$POC_i = q \cdot s_i \quad (5)$$

The PN budget was calculated exactly the same way as the POC budget except that in (4) the measured POC values were substituted by the measured PN values.

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. 3-7 and 3-8). 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. 3-2 and 3-3) with an average TSM concentration of 3.2 mg/l (± 0.47 mg/l) and an average POC concentration of 0.36 mg/l (± 0.07 mg/l; measurement points for TSM and POC: 8 stations).

TSM, POC and PN budgets for the Yenisei River were calculated (Tab. 3-3) 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 Tab. 3-5).

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. 3-7 and 3-8). 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 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 occurs, the Ob River floods, and sedimentation and erosion take place on its floodplains. Smith

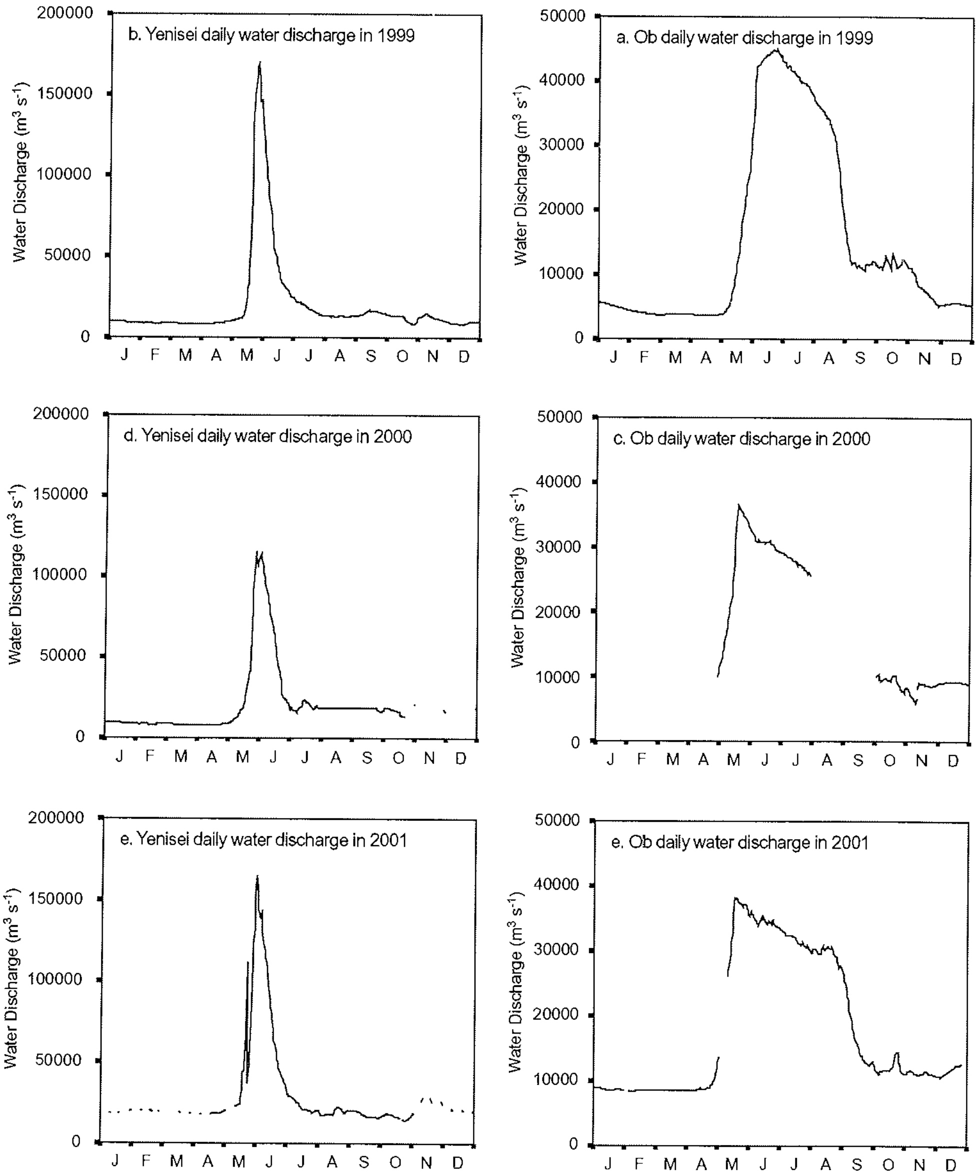

Fig. 3-7: ***Daily water discharge for the Ob and Yenisei rivers in 1999, 2000 and 2001****. Left panel: Yenisei, right panel: Ob. Gaps due to time spans without measurements.*

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. 3-8).

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

Tab. 3-5: Annual TSM, POC and PN discharge of the Yenisei and Ob rivers into the Kara Sea.

River	TSM Discharge (10^6 t yr^{-1})	POC Discharge (10^6 t yr^{-1})	PN Discharge (10^6 t yr^{-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. (1997)
	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. (1997)
	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 confluence

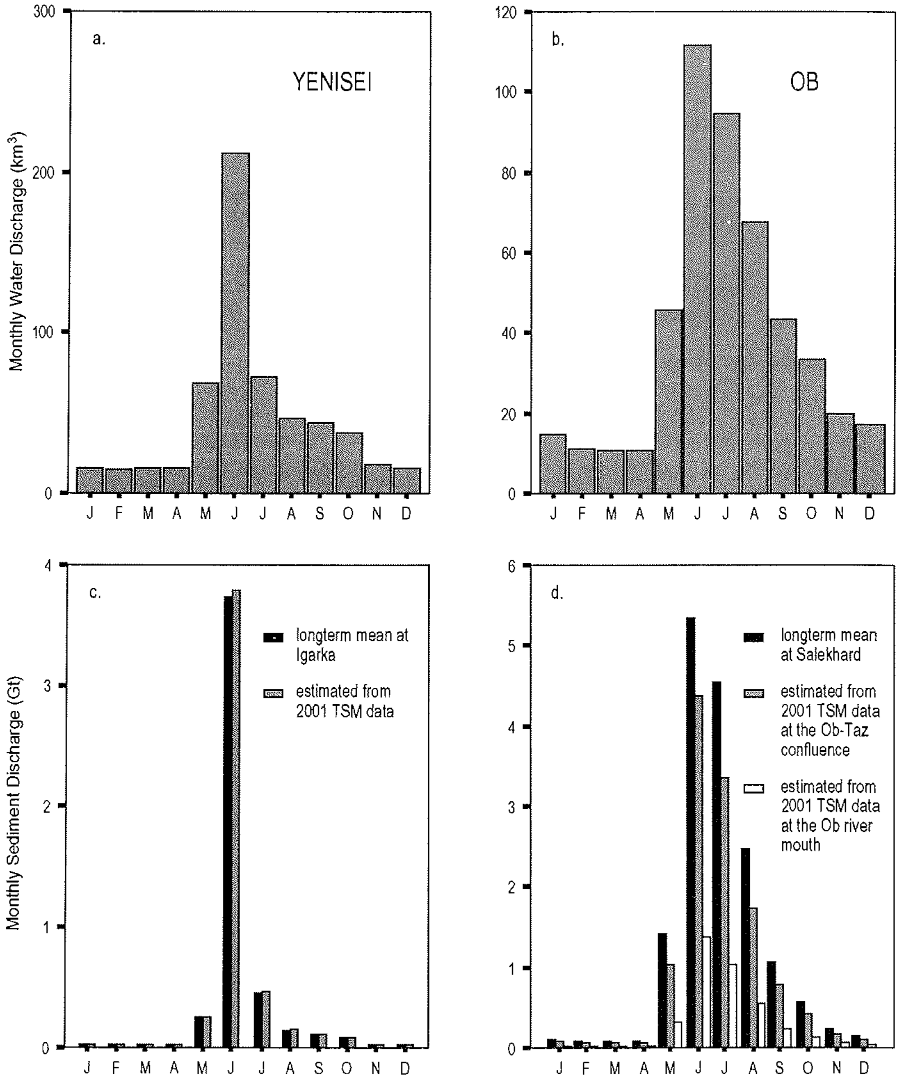

Fig. 3-8: Water and sediment discharge of the Yenisei and Ob rivers. *Long term mean water discharge are given in a. (Yenisei) and b. (Ob incl. Nadym, Pur and Taz), sediment discharge is given in c. (Yenisei) and d. (Ob incl. Nadym, Pur and Taz).*

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. 3-1), 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; Tab. 3-4).

The Ob River delivers 3.76x10^6 t sediment, 0.27x10^6 t POC and 0.027x10^6 t PN to the Kara Sea annually. The Ob-Taz River confluence budget calculation yield 12.21x10^6 t of estimated sediment, 0.61x10^6 t POC and 0.081x10^6 t PN annually (Tab. 3-5). 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 (Tab. 3-6).

Tab. 3-6: 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 (Tab. 3-5) and (b) water discharge data from Lammers and Shiklomanov (2000)

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, 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 $6.3x10^6$ tons per year at Divnogorsk (just downstream of the Krasnoyarsk dam) before the dam closure and $0.2x10^6$ tons per year 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.

3.5.5 Comparison of the budget with other studies

According to our budget, the Yenisei River delivers $5.03x10^6$ t of sediment and $0.57x10^6$ t of POC to the Kara Sea annually (Tab. 3-5). Except for the older sediment discharge data of $14.5x10^6$ t yr^{-1} of Telang et al. (1991) and the $13x10^6$ t yr^{-1} estimate of Lisitsyn (1972), our data are similar to the recent estimates of Bobrovitskaya et al. (1996) who measured a total of $4.2x10^6$ t yr^{-1} sediment discharge at Igarka, and Gordeev et al. (1996) who reported a total suspended matter discharge of $5.9x10^6$ t yr^{-1} (Tab. 3-5). POC discharge data from the literature are lower than our estimate of $0.57x10^6$ t yr^{-1} POC. Köhler et al. (2003) have calculated a POC discharge of $0.31x10^6$ t yr^{-1} from their dissolved organic carbon (DOC) data and the

POC/DOC ratio proposed in Nesterova (1960) (Tab. 3-5). Lobbes et al. (2000) calculated a POC discharge of 0.17×10^6 t yr^{-1} (see Tab.3-5).

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 (2004a) and by Stein et al. (2003a), and 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 $13\text{-}14.5 \times 10^6$ t yr^{-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 t 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 yr^{-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 (Tab. 3-5). 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 yr^{-1}. Telang et al. (1991) proposed a sediment discharge of 13.4×10^6 tyr^{-1}, Lisitsyna (1974) a sediment discharge of 15.0×10^6 t yr^{-1} and Lisitsyn (1972) reported 16×10^6 t yr^{-1}. The estimate by Romankevich et al. (2000b) 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 yr^{-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).

3.6 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 3.76x10^6 t TSM, 0.27x10^6 t POC and 0.027x10^6 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 takes place.

The Yenisei River has changed its depositional regime in recent decades. Prior to the dam closures in its hinterland, it yielded about 9.2x10^6 t sediment per year to the Kara Sea. The present situation is rather complicated to monitor due to the strong seasonality. The calculated 5.03x10^6 t of sediment, 0.57x10^6 t of POC and 0.084x10^6 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 0.8x10^6 t yr^{-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 (2004a) 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.

3.7 Acknowledgements

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

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4.1 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 18.5x10^6 t yr^{-1} of sediments and 0.37x10^6 t yr^{-1} of organic carbon are buried in the estuaries, whereas 18.33x10^6 t yr^{-1} sediment and 0.287x10^6 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. Differences between our and recent Holocene budgets can be explained by changes in the hinterland due to dam constructions, and by differences in the catching effectiveness of the mixing zone ("marginal filter") between fresh riverine and saline marine Kara Sea water.

4.2 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 changes in land use (7.7×10^6 t per year, Mackenzie, 1998), intensifying the natural greenhouse effect and leading to global warming (Albritton et al., 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., 2003; Bobrovitskaya et al., 1997). 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; Canfield et al., 1993b; 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 mineralised 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).

In recent decades, many studies of the sediment and organic carbon budgets of shelf seas have been carried out (e.g. Canfield et al., 1993a; De Haas et al., 1997; De Haas et al., 2002; Frankignoulle and Borges, 2001). 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).

4.3 Overview of the Kara Sea shelf

The Arctic Ocean accounts for only 1.5% of the global ocean (Aagaard, 1994), but contains about 20% (i.e. $5x10^6$ 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. 4-1), 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.

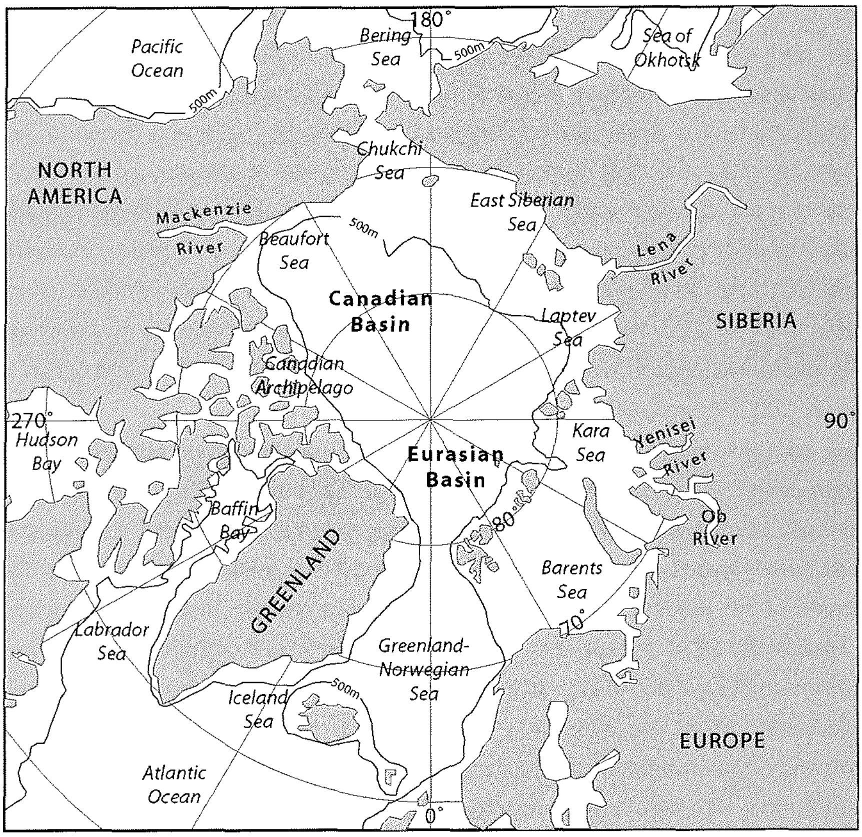


Fig. 4-1: General overview of the Arctic Ocean.

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. 4-2). 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. 4-2). 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 1,060 km^3 including their tributaries (chapter 3). 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 years. The mean residence time of fresh water in Arctic shelf areas has been estimated at about 1 to 3 years by Schlosser et al. (1995) and Hanzlick and Aagaard (1980) propose some 2.5 years. 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

Fig. 4-2: ***Geographical overview of the study area.*** *(after Gebhardt et al., chapter 3, this volume).*

surface hydrography, is strongly seasonally influenced (Fig. 4-3), whereas deep water is much more stable as it is constantly supplied from the central Arctic Ocean.

The water and sediment discharge of the Ob and Yenisei rivers are strongly seasonally influenced (Fig. 4-3). 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. 4-3). The rivers start to freeze in mid-October, and only a small amount of water and sediment is discharged during the winter months.

4.4 Inputs of sediment and organic carbon to the Kara Sea shelf

4.4.1 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., 1997; Bobrovitskaya et al., 1996; 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. 4-2), 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., chapter 3, this volume; 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 (chapter 3). Gebhardt et al. (chapter 3, this volume) 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 5.03×10^6 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. 4-2). 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. (chapter 3, this volume) calculated an annual POC flux

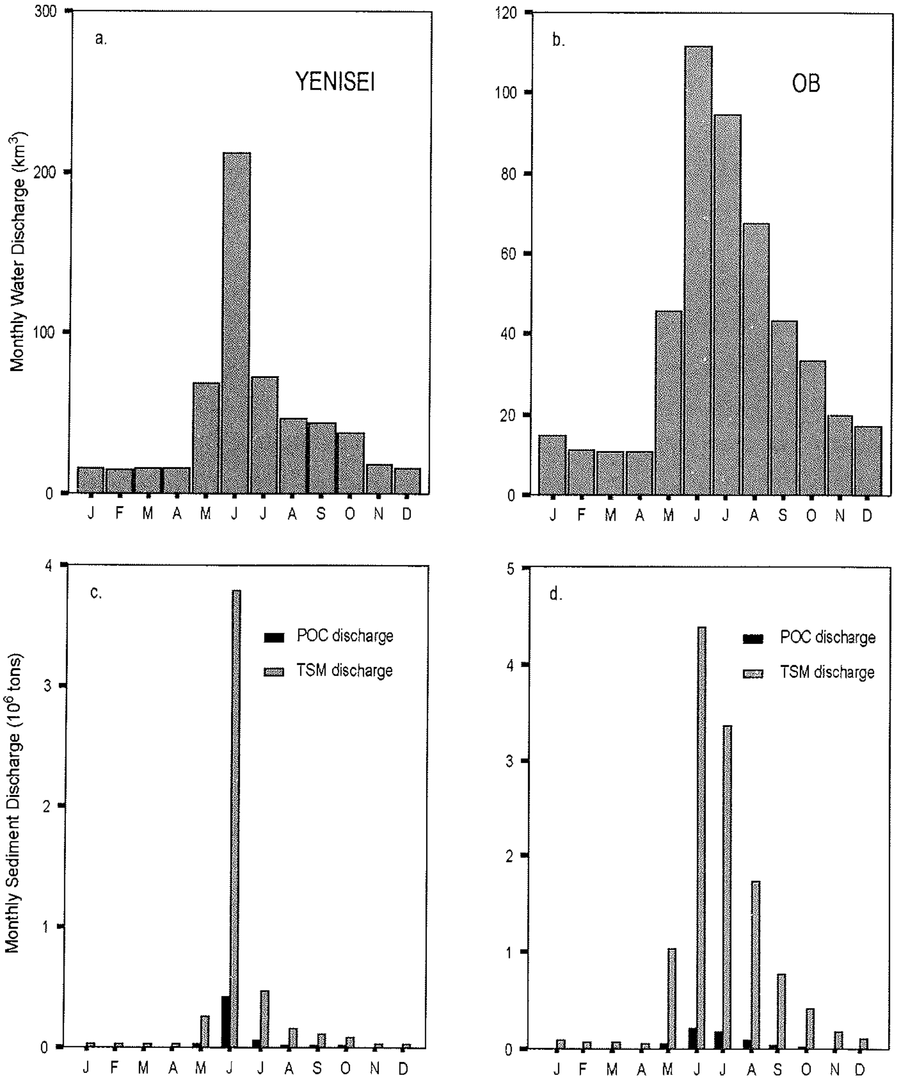


Fig. 4-3: Water and sediment discharge of the Yenisei and Ob rivers. *Long term mean water discharge is given in a. (Yenisei) and b. (Ob incl. Nadym, Pur and Taz), sediment and POC discharge in c. (Yenisei) and d. (Ob incl. Nadym, Pur and Taz). a. and b. from Lammers and Shiklomanov (2000), c. and d. from Gebhardt et al. (chapter 3, this volume).*

of 0.61x10^6 t for the Ob-Taz confluence situated downstream of the gauging station (Fig. 4-2). 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. (chapter 3, this volume).

4.4.2 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 700x10^9 t carbon are stored in dissolved form in the ocean, compared to only 570x10^9 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.

4.4.3 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. 4-2). Data from the Pyasina River are scarce. Gordeev et al. (1996) propose an annual sediment discharge of 3.4x10^6 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.

4.4.4 Coastal erosion in the Kara Sea

Coastal erosion data from the Kara Sea are sparse. Romankevich and Vetrov (2001) report an annual coastal erosion of 109×10^6 t sediment and 1×10^6 t organic carbon. New estimates from A. Vasiliev (pers. comm.) are much lower: 27×10^6 t sediment and 0.5×10^6 t POC. Nevertheless, these values are extrapolated for the whole Kara Sea coast from local estimates, and further investigation is needed to reach a consensus. In this study, we use the new estimates of Vasiliev 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.

4.4.5 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 color measurements) combined with *in situ* measurements. Days without ocean color 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., 2003a).

General estimates of primary production vary greatly. The estimate, by Subba Rao and Platt (1984), of 27 g 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} ± 18.5×10^6 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 (D. Unger, unpubl. data) 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.

4.4.6 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. 4-4) (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. 4-4) (Pavlov and Pfirman, 1995). An annual flow of 1,640 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 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

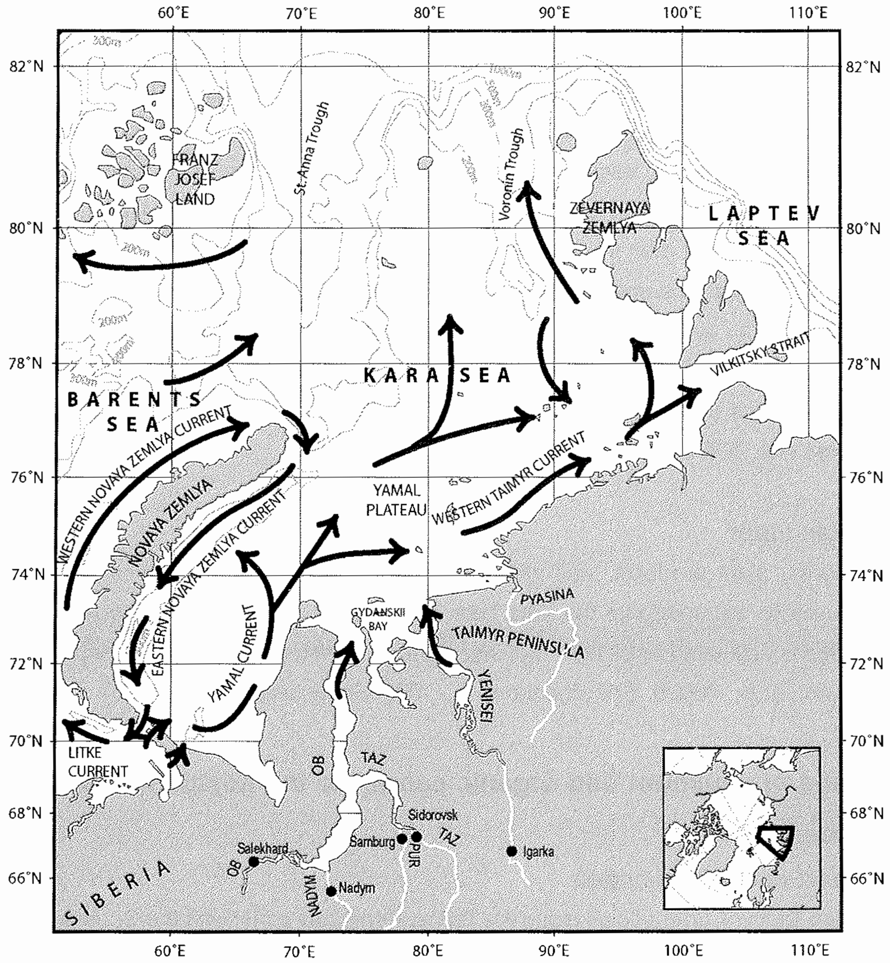


Fig. 4-4: ***General pattern of surface water currents.*** *(after Pavlov and Pfirman, 1995).*

summer concentration to last for about 4 month). This yields an annual flux of 0.82x10^6 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 5,000 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 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 7,500 km^3, which leads to an annual input of 8.75x10^6 t TSM. An annual total net import of 9.57x10^6 t TSM from the Barents to the Kara Sea (0.82x10^6 t through the Kara Strait and 8.75x10^6 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 0.323x10^6 t POC per year. 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).

4.4.7 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 0.1x10^6 t of sediment, comprising 0.044x10^6 t of organic carbon (Romankevich et al., 2000b; Shevchenko et al., 1999; Shevchenko et al., 1996).

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

4.5.1 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. 4-4). The annual water flow from the Kara Sea into the Laptev Sea through Vilkitsky Strait is estimated to be 4,900 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. (chapter 3, this volume; Figs. 3-2 and 3-3) 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 TSM and 0.025 mg/l POC. Furthermore, we use a mean annual water outflow of 7,950 km^3 to estimate the annual export through Vilkitsky Strait. This results in estimated annual exports of 3.18x10^6 t TSM and

0.194×10^6 t POC through Vilkitsky Strait.

4.5.2 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. (chapter 3, this volume); we assume a fourfold dilution of TSM and a fivefold dilution of POC (0.5 mg/l TSM and 0.03 mg/l POC) that, with an average water outflow of 20,500 km^3, results in an estimated annual export of 10.25×10^3 t TSM and 0.615×10^6 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, the 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 value overestimates the present downslope transport of sediment. De Haas et al. (2002) found that only on rather small shelf seas with distinct riverine input is sediment transported further than the inner shelf, and Eisma et al. (1985) pointed out that only 7 to 10% of riverine material reaches the deep sea globally. Therefore, the ratio of 17% of the input being transported to the Arctic Ocean by turbidity flows seems rather high for the wide Kara Sea shelf. Macdonald et al. (1998) calculated a ratio of 13% for the small Beaufort Sea including sediment transported by turbidity flows as well as incorporated in ice. We apply a mean value of about 8%, referring to the 7 to 10% suggested by Eisma et al. (1985), to calculate sediment transport down the shelf edge in the Kara Sea. The total annual sediment input into the Kara Sea can be calculated as 57.24×10^6 t (20.57×10^6 t by the rivers, 0.1×10^6 t by eolian input, 27×10^6 t by coastal erosion and 9.57×10^6 t through the Kara Strait), giving an estimated annual downslope sediment transport of 4.58×10^6 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 0.046×10^6 t organic carbon from the Kara Sea to the Arctic Ocean by turbidity flows.

4.5.3 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 if IRS in the ice drift (e.g. Harms et al., 2000, and references therein; Pfirman et al., 1995; 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 sea floor 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).

Pavlov and Pfirman (1995) estimate an annual ice export of about 454 km^3 from the Kara Sea to the adjacent seas. Mean sea-ice sediment concentrations ranging from 10 to 157 mg/l were measured for the Arctic Ocean (an overview is given in Harms et al., 2000). For calculation of the Beaufort Sea IRS, a mean concentration of 13 mg/l was assumed (Macdonald et al., 1998). 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. This leads to a mean IRS concentration of 5.3 mg/l which is somewhat lower than the value used in the Beaufort Sea or the values measured in the Arctic Ocean.

4.6 Sedimentation within the estuaries and on the Kara Sea shelf

4.6.1 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 accumulation and storage do not take place in the same area. Accumulation takes place throughout the entire Ob Bay (chapter 3), 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 (chapter 3). 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., in press; 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 (chapter 3). Sediment presently accumulates at a more northerly location than during the Holocene. Dittmers et al. (2003) calculated average Holocene sediment accumulations of 14.3×10^6 t and 9.2×10^6 t in the Ob and Yenisei river marginal filters annually, 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 5.03×10^6 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 13.95×10^6 t and 0.55×10^6 t for the Ob River and 4.56×10^6 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. 4-2) can be summed up as 18.51×10^6 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 2.07×10^6 t and 0.12×10^6 t per year, 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).

4.6.2 Sediment and organic carbon accumulation on the Kara Sea shelf

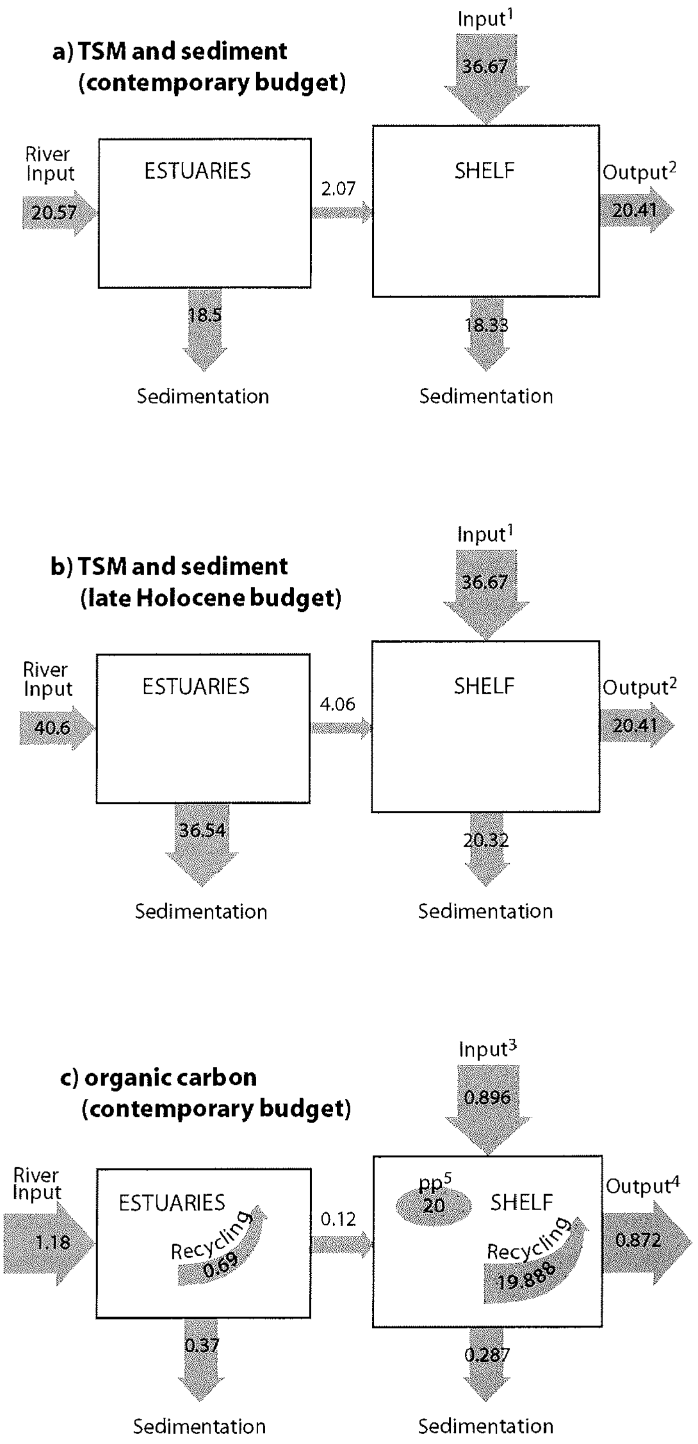
In a first step, 38.74x10^6 t sediment (2.07x10^6 t river input, 0.1x10^6 t eolian input, 27x10^6 t due to coastal erosion and 9.57x10^6 t from the Barents Sea) and 0.987x10^6 t organic carbon (0.12x10^6 t river input, 0.044x10^6 t eolian input, 0.5x10^6 t due to coastal erosion and 0.323x10^6 t from the Barents Sea) are brought annually to the Kara Sea shelf. About 10.25x10^6 t sediment and 0.615x10^6 t POC are transported further to the Arctic Ocean by suspension, 4.58x10^6 t sediment and 0.046x10^6 t POC by high-saline brines, resuspension and debris flows, 2.4x10^6 t sediment and 0.017x10^6 t by IRS, and 3.18x10^6 t sediment and 0.194x10^6 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 18.33x10^6 t and a terrestrial organic carbon accumulation of 0.175x10^6 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 0.287x10^6 t TOC accumulated on the Kara Sea shelf, which means that about 0.112x10^6 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 123x10^6 t sediment and 1.38x10^6 t organic carbon (i.e. 1.15x10^6 t of terrigenous and 0.23x10^6 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 109x10^6 t yr^{-1} sediment and 1x10^6 t yr^{-1} organic carbon which recently was shown to be far too high (A. Vasiliev, Earth Cryosphere Institute RAS, Moscow, pers. comm.: 27x10^6 t yr^{-1} sediment, 0.5x10^6 t yr^{-1} POC); therefore, we think that they overestimate the Kara Sea shelf sedimentation.

4.7 Preliminary budget for the shelf

4.7.1 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. 4-5a). We estimate that 90% of the river input is accumulated within the estuaries. With mass balance calculations we estimate that 38.74x10^6 t sediment are brought to Kara Sea shelf annually, of which 17.23x10^6 t (44%) are transported further to the Arctic Ocean (2.4x10^6 t by ice, 10.25x10^6 t by suspension and 4.58x10^6 t by saline brines, resuspension and debris flows down the shelf edge). About 3.18x10^6 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 18.33x10^6 t (47% of the total input into the Kara Sea).


a) TSM and sediment (contemporary budget)
Input¹
36.67
River Input
20.57
ESTUARIES
2.07
SHELF
Output²
20.41
18.5
18.33
Sedimentation
Sedimentation
b) TSM and sediment (late Holocene budget)
Input¹
36.67
River Input
40.6
ESTUARIES
4.06
SHELF
Output²
20.41
36.54
20.32
Sedimentation
Sedimentation
c) organic carbon (contemporary budget)
Input³
0.896
River Input
1.18
ESTUARIES
Recycling
0.69
0.12
pp⁵
20
SHELF
Recycling
19.888
Output⁴
0.872
0.37
0.287
Sedimentation
Sedimentation

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

Stein and Fahl (2004a) suggest that sedimentation conditions during the last 6,000 years 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 (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. 4-5b).

4.7.3 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. 4-5c). 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 0.69×10^6 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 1.047×10^6 t POC to the Kara Sea shelf (0.12×10^6 t by river input, 0.044×10^6 t by eolian input, 0.5×10^6 t through coastal erosion and 0.323×10^6 t from the Barents Sea). A loss of about 0.872×10^6 t POC (0.017×10^6 t by ice, 0.046×10^6 t to the Arctic Oceans by saline brines, resuspension and debris flows, 0.615×10^6 t to the Arctic Ocean by suspension and 0.194×10^6 t through the Vilkitsky Strait to the Laptev Sea) can be estimated. About 0.175×10^6 t organic carbon are permanently

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Fig. 4-5 (left side): 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, 27×10^6 t yr^{-1} input due to coastal erosion and 9.57×10^6 t yr^{-1} from the Barents Sea*

[2] *Output: 2.4×10^6 t yr^{-1} by ice, 3.18×10^6 t yr^{-1} to the Laptev Sea, 10.25×10^6 t yr^{-1} to the Arctic Ocean by suspension and 4.58×10^6 t yr^{-1} as sediment downslope the shelf edge to the Arctic Ocean*

[3] *Input: 0.44×10^6 t yr^{-1} eolian input, 0.5×10^6 t yr^{-1} input due to coastal erosion and 0.232×10^6 t yr^{-1} from the Barents Sea*

[4] *Output: 0.017×10^6 t yr^{-1} by ice, 0.194×10^6 t yr^{-1} to the Laptev Sea, 0.615×10^6 t yr^{-1} to the Arctic Ocean by suspension and 0.046×10^6 t yr^{-1} as sediment downslope the shelf edge to the Arctic Ocean*

[5] *pp = primary production*

buried on the shelf. Of the annual primary production of $20x10^6$ t, about $19.888x10^6$ t are recycled and only $0.112x10^6$ t (0.56%) are permanently stored on the Kara Sea shelf.

4.8 Discussion

4.8.1 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 (Tab. 4-1). 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 2,000 years conditions have changed and that accumulation rates suggest an increase in effectiveness of the marginal filter. (b) A large difference of about $82x10^6$ t yr^{-1} is obvious in the coastal erosion data used for the budgets (Tab. 4-1). As discussed above, recent data by A. Vasiliev (pers. comm.) 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 $75x10^6$ 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. 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.

4.8.2 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 ($127x10^6$ t sediment and $2.1x10^6$ t POC annually) and coastal erosion is of minor importance in the Beaufort Sea ($5.6x10^6$ t per year, 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

Tab. 4-1: 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	36.54	-8.74
Coastal Erosion	109	27	82
Sedimentation on the Shelf	95.2	20.32	74.88

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 26x10^6 km^2 and the hypothetical amount of about 0.3x10^6 t organic carbon buried annually on the Beaufort Sea shelf. As 1.4x10^6 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 3.85x10^6 t of organic carbon. As we estimate a total burial of 0.657x10^6 t (0.37x10^6 t in the estuaries and 0.287x10^6 t on the shelf), the Kara Sea shelf seems to be an area of lower-than-average carbon burial.

4.8.3 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 5,000 years, about 60.8x10^6 t sediment was deposited annually on the Laptev Sea shelf according to Rachold et al. (2002b).

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), 40.5x10^6 t of sediment and 0.67x10^6 t of organic carbon are annually accumulated on the Laptev Sea shelf; another 17x10^6 t of sediment and 0.17x10^6 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 44% are transported further to the Arctic Ocean (6% by ice and 38% by currents and gravitational flow), and 8% 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, not more 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; Stein and Fahl, 2004b).

4.9 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 0.657x10^6 t organic carbon (i.e. 32% of the organic carbon brought to the Kara Sea by rivers and coastal erosion) is annually buried in the Kara Sea (0.545x10^6 t of terrestrial and 0.112x10^6 t of marine origin), and about 0.872x10^6 t organic carbon are transported further into the Arctic Ocean. 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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5 The turbidity maximum zone of the Yenisei River (Siberia) and its impact on organic and inorganic proxies

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Keywords: mixing zone, turbidity maximum, carbon cycle, Arctic Ocean, Kara Sea

5.1 Abstract

A general overview of the processes taking place in the summer mixing zone of the fresh Yenisei River water and the marine waters of the Kara Sea is given in this study, with special emphasis on bulk (total suspended matter), inorganic (Fe, Mn) and organic (suspended organic carbon, suspended nitrogen) proxies. Within the mixing zone, a zone of enhanced turbidity (maximum turbidity zone) was observed comparable to studies in other rivers. Flocculation of particles due to changes in salinity and hydrography cause this maximum turbidity zone, and resuspension additionally enhances the turbidity in the near-bottom layers. Organic matter behaves conservatively in the mixing zone in terms of its percentage within the suspended matter, but, nevertheless, undergoes degradation as revealed from amino acid data. Inorganic, redox- and salinity-sensitive, proxies (Mn, Fe) behave non-conservatively. Dissolved iron is removed at low salinities (<2) due to precipitation of iron-oxyhydroxides, and dissolved manganese is adsorbed on suspended particles, enhancing the Mn/Al ratio of the suspended matter in the same zone. At higher salinities within the mixing zone, Fe/Al and Mn/Al ratios of the suspended particles are depleted due to resuspension of sediment with lower Fe/Al and Mn/Al ratios. Dissolved manganese concentrations are significantly higher in the near-bottom layers of the mixing zone due to release from the anoxic sediment. All things considered, the Yenisei River mixing zone shows patterns similar to other world's rivers.

5.2 Introduction

Estuaries occupy less than 10% of the ocean's surface (Lisitsyn, 1995), but play an important role in the global cycle of divers substances (e.g. organic matter, nutrients, metals). Estuaries and coastal areas trap significant quantities of suspended and dissolved matter and, thus, act as filter between the terrestrial and the marine realm. In the course of mixing between riverine freshwater and marine saline water, changes in physicochemical properties lead to physical, chemical and biochemical processes affecting the dissolved and suspended load of the river. Only during the late 1970s, a broad interest arouse concerning the processes taking place in the mixing zone (e.g. Cronin, 1975; Kennedy, 1980; Kennedy, 1982; Kennedy, 1984; Wiley, 1976; Wiley, 1978), and since then, estuarine and coastal research has been well established. Nevertheless, the processes going on in estuaries are still not well understood. Some proxies seem not to be affected by the processes, whereas others are trapped or mobilized in the mixing zone. This ability of estuaries to remove or retain material in solution and suspension makes estuaries important in terms of environmental questions.

During the last decades, studies about the removal and mobilization processes were carried out in several estuaries (e. g. Lena River, Cauwet and Sidorov, 1996, Gordeev and Shevchenko, 1995; Fly River, Wolanski and Eagle, 1991, Wolanski and Gibbs, 1995; St. Lawrence River, Bewers and Yeats, 1978, 1979, Cossa and Poulet, 1978, Gobeil et al., 1981, Hamblin, 1989, Lucotte, 1989; Changjiang River, Cauwet and Mackenzie, 1993, Jiufa and Chen, 1998, Milliman et al., 1985). A zone of maximum turbidity is generally observed in estuaries at the convergence of the downstream flowing surface water and the upstream flowing salt wedge of marine water (Bowden, 1984). This zone is characterized by high concentrations of suspended matter, higher than upstream in the river or downstream in the estuary. The estuarine circulation pattern has an effect on the location and strength of the turbidity maximum zone. This site of high suspended matter concentrations provides an ideal site for physical, chemical and biological reactions between dissolved and particulate species as well as interactions amongst particulate species. As a result, the turbidity maximum acts as a filter between rivers and oceans.

Lisitsyn (1995) calculated that in what he calls the "marginal filter", about 93 to 95% of the suspended and about 20 to 40% of the dissolved riverine material is deposited worldwide. He slightly modified his statement for the Polar Regions where rivers are more influenced by seasonal variations, e.g. by ice cover and snow during winter. Furthermore, these rivers drain areas of permafrost. Lisitsyn (1995) distinguishes between two different marginal filter regimes in the Ob and the Yenisei rivers: (i) a short summer regime with the main part of water and solid material delivered to the Kara Sea and (ii) a rather long winter regime with low water and suspension discharges. He further introduces a so-called ice marginal filter: during ice production, the saline water forms dense plumes sinking in the water column and transporting some of the marginal filter sediment away from its initial position.

In this study, we intend to characterize the processes taking place in the Yenisei River estuary and compare these findings with rivers from other regions. However, as all our data origin from the short Arctic summer period, we are only able to evaluate the summer situation.

5.3 Study area

The Kara Sea is one of the Arctic shelf seas of Northern Siberia (Fig. 5-1). The central and the eastern parts of the Kara Sea are dominated by the Ob and Yenisei estuaries (=Yamal Plateau) with a characteristic depth of 25 to 30 m. More than one third of the total freshwater discharge to the Arctic Ocean is into the Kara Sea, mainly via Ob and Yenisei rivers (Aargard and Carmack, 1989).

The Yenisei River draining into the Kara Sea is Siberia's largest river with a drainage area of 2.58×10^6 km^2 and a length of 3844 km (Gordeev, 2000; Milliman, 1991; Milliman and Meade, 1983; Telang et al., 1991). The Yenisei bed crosses igneous basement rocks and fills two large reservoirs in its upper reaches, and flows through the West Siberian Plain in regions of permafrost in its lower reaches. Along the banks, the taiga is gradually replaced by forest tundra. The freshwater discharge to the Kara Sea is highly seasonal with the main discharge occurring during spring and summer, 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). During the summer months, deep water supplied from the central Arctic Ocean forms a stable salt wedge having salinities >30 in the Yenisei River.

Large amounts of river suspension have built up thick packages of sediments mostly in the outer estuary and the southernmost Kara Sea (Dittmers et al., 2003; Stein and Fahl, 2004a). It has been assumed that the major amount of organic carbon deposited in the Kara Sea is of riverine origin (Stein and Fahl, 2004a, and references therein).

5.4 Data used for this study

In order to get detailed information on the processes taking place in the mixing zone, we combine different data from the Yenisei River estuary. Most of the data were obtained within the framework of the German-Russian SIRRO project (Siberian River Run-Off) on three *RV Akademik Boris Petrov* cruises between 1997 and 2000 (Matthiessen and Stepanets, 1998; Matthiessen et al., 1999; Stein and Stepanets, 2000; Stein and Stepanets, 2001). Additionally, sediment surface samples from the international *RV Dmitriy Mendeleev* expedition in 1993 (Lisitsyn and Vinogradov, 1995) were used in this study. All suspended and dissolved matter

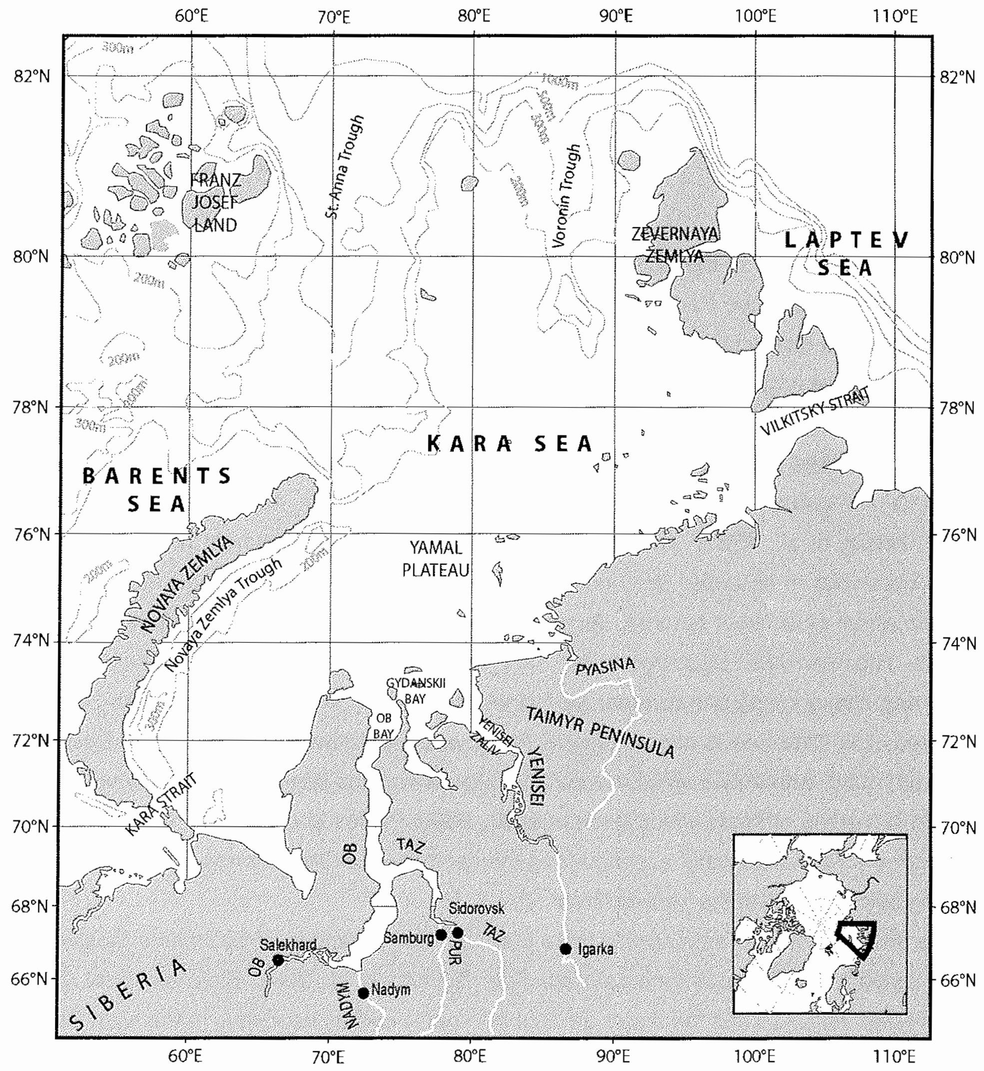

Fig. 5-1: ***General overview of the study area.*** *(after Gebhardt et al., chapter 3, this volume).*

samples are from the Akademik Boris Petrov 2000 cruise in order to avoid effects due to different conditions in different years. Nevertheless, surface sediment samples originate from different years as the surface sediment is not affected by interannual variations.

Sampling and laboratory procedure for total suspended matter (TSM), particulate organic carbon (POC) and particulate nitrogen (PN) are given in Gebhardt et al. (chapter 3, this volume), details of amino acid analyses, calculation of the Reactivity Indes (RI) as well as total organic carbon of surface sediment (TOC) can be found in Unger et al. (subm.). Analytical procedure for preparation of suspended Mn/Al and Fe/Al as well as dissolved Mn and Fe are given in Beeskow and Rachold (2003), surface sediment Mn/Al and Fe/Al data originate from Schoster et al . (2000). Salinity is always given as a ratio (Practical Salinity Scale).

For investigation of the processes being active in the estuary and, in particular, in the mixing zone between riverine freshwater and marine saline water we chose a transect from 70°N in the southern part of the Yenisei River (salinity=0) to 76.4°N in the central Kara Sea (salinity=29.1) (Fig. 5-2).

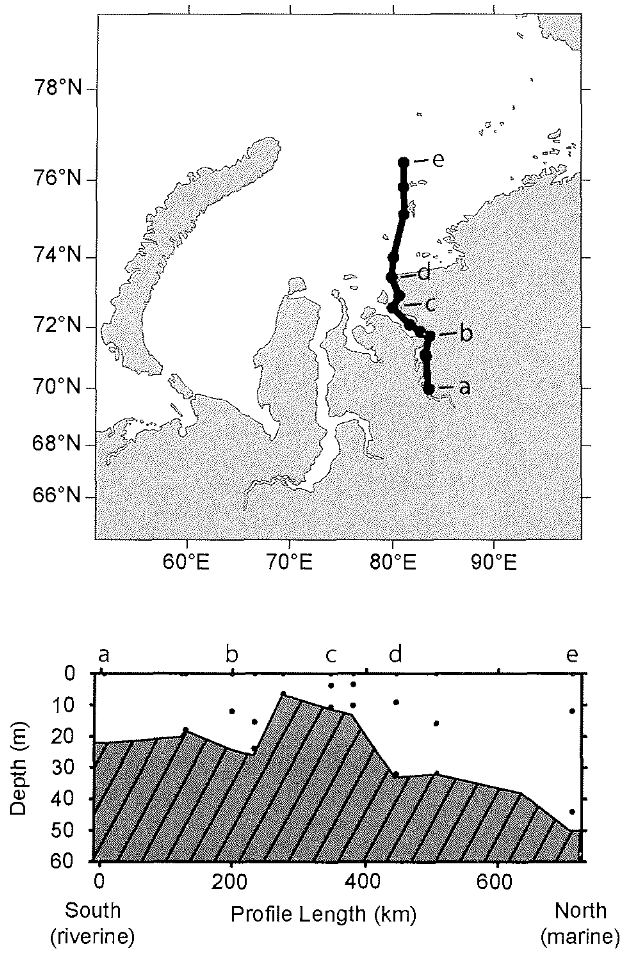

Fig. 5-2: Yenisei River profile used in this study. *Dots mark the sampling points; hatched area corresponds to the river bed.*

5.5 The marginal filter of the Yenisei River

5.5.1 Salinity and TSM

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) (Fig. 5-3a). River run-off forms a plume of low saline water north of the two river estuaries (Fig. 5-4a). Water with salinities of 20 to 30 enters the estuary as salt intrusions, forming a stable salt wedge in the Yenisei River which penetrates as far south as a narrows at 71.6°N, as revealed by a supposed left-over of the salt intrusion that previously reached further south than it did during the sampling period. A lens of highly saline surface water (about 25) was observed just north of the Yenisei estuary.

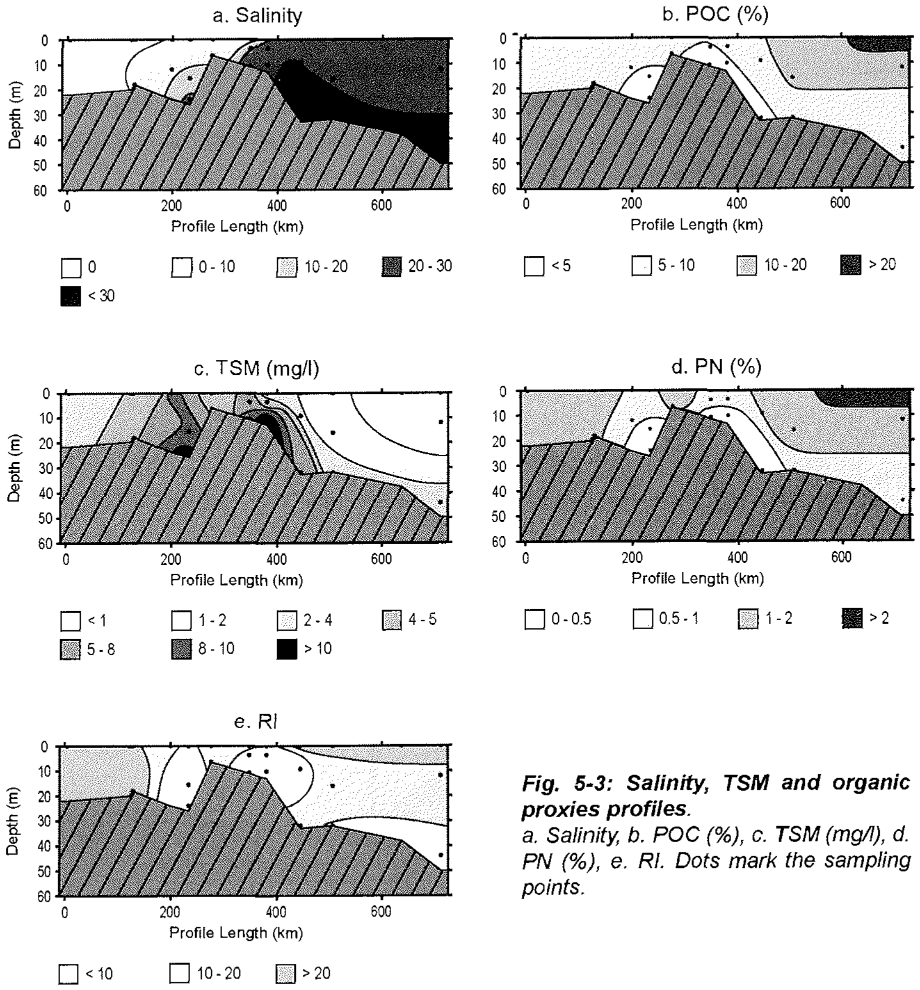

Fig. 5-3: Salinity, TSM and organic proxies profiles.
a. Salinity, b. POC (%), c. TSM (mg/l), d. PN (%), e. RI. Dots mark the sampling points.

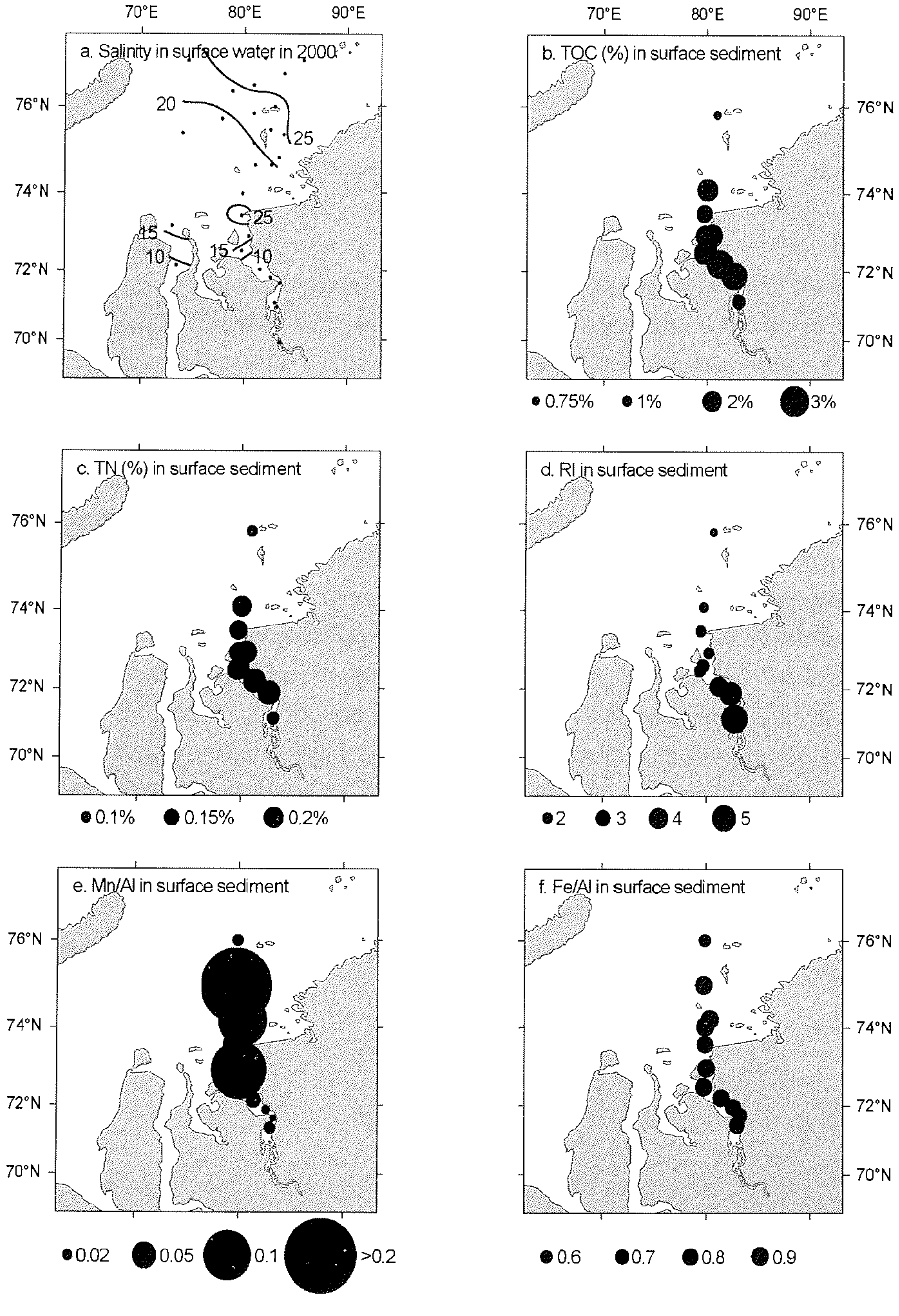

Fig. 5-4: Salinity and surface sediment geochemistry maps*. a. Salinity of surface water, b. TOC (%) of surface sediment, c. TN (%) of surface sediment, d. RI of surface sediment, e. Mn/Al of surface sediment, f. Fe/Al of surface sediment. Dots mark the sampling points.*

Zones of TSM concentration maxima (TSM concentrations >10 mg/l) are found in two areas at the river bottom (Fig. 5-5): (i) where the narrows at 71.6°N widens towards north and (ii) at the Yenisei River-Kara Sea interface. Both areas are characterized by hydrographic changes: (i) flow speed is high at the narrows functioning as a funnel for the Yenisei water. Where the narrow widens, the flow speed changes and vortices cause resuspension of bottom material. (ii) At the opening of the river to the Kara Sea, marine deep water intrudes into the river mouth. This water mass of marine origin and initially marine composition causes turbulences at its interface to the river bottom, resulting in resuspension of sediment. Furthermore, at the interface between the overlying riverine water and the deep marine water where the pycnocline develops, the shear stress is enhanced due to the diametrical current directions.

Kranck (1984) points out that large flocs with higher settling velocities sink to the river bottom where they are destructed due to different settings, and resuspended as smaller particles, forming part of the turbidity maximum. While enhanced TSM concentrations at the river bottom can be explained by resuspension, enhanced values within the surface water must be caused by different processes. A distinct increase in surface TSM concentration from values <5 mg/l to values between 5 and 8 mg/l is observed in the mixing zone of riverine freshwater and marine water at salinities between 0.1 and 10. Electrochemically induced precipitation and flocculation of colloidal as well as dissolved material play important roles in the removal of substances such as iron and manganese as well as fine suspended matter (Kranck, 1984). It is still not clear whether the salinity change or the change in hydrography is the main reason for aggregation and disaggregation of particles (e. g. Burban et al., 1989; Burban et al., 1990; Lick et al., 1993; Serra et al., 1997; Thill et al., 2001; Winterwerp, 2002). As changes in hydrography and salinity occur at the same locations in the Yenisei River, it is not clearly distinguishable what process eventually is responsible for the flocculation of suspended matter in this river.

Altogether, two processes – associated with each other – can be observed regarding the

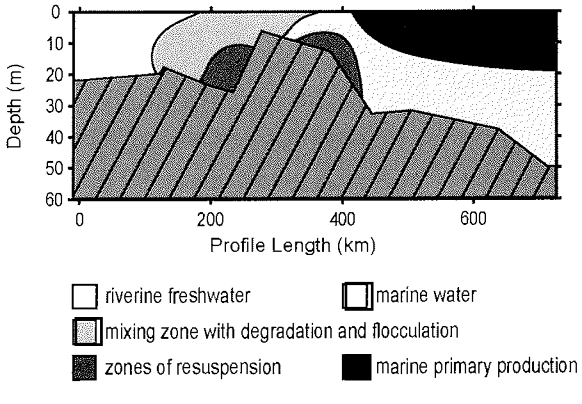

Fig. 5-5: Simplified model of the Yenisei River profile.

distribution of TSM concentration: (i) centers of high TSM concentrations at the river bottom caused by resuspension of settled and broken large flocs and surface sediment and (ii) flocculation of suspended matter within the water column due to both changes in the hydrographic regime and an increase in salinity.

5.5.2 Organic proxies

To study the effect of estuarine processes on organic matter, particulate and total organic carbon (POC and TOC) as well as particulate and total nitrogen (PN and TN) were studied. Percentages rather than absolute concentrations were used to avoid concentration-dependent phenomena. Amino acid data (in particular the RI index) was used to determine the degradational state of the organic matter.

POC percentages are relatively constant between 5 and 10% from the southernmost point of the river to the river mouth (Fig. 5-3b). Nevertheless, POC values are lower in the areas of resuspension indicated by enhanced TSM concentrations. Sediment has much lower TOC concentrations of about 2 to 2.5% (Fig. 5-4b), and if sediment of lower TOC is resuspended, it dilutes the POC content of the original suspended matter; this phenomenon observed in these areas in turn confirms the process of resuspension. PN behaves relatively similar to POC, with zones of decreased PN percentages due to resuspension of sediment with lower TN content (Figs. 5-3d and 5-4c). Both POC and PN concentrations are not enhanced in the surface mixing zone. This confirms that (i) resuspension barely affects the surface layers of the Yenisei River, and (ii) precipitation of dissolved organic matter is of minor importance as already reported by Köhler et al. (2003).

Amino acid data, in particular the reactivity index (RI), give information about the degradational state of organic matter (Jennerjahn and Ittekkot, 1997; Jennerjahn and Ittekkot, 1999). RI is high in the freshwater of the Yenisei River with values >20 (Fig. 5-3e). In the resuspension zones, where sediment of low RI (<5, Fig. 5-4d) is suspended and mixed with the freshwater RI signal, RI decreases to values below 10 (Fig. 5-3a). Furthermore, RI is somewhat lower in the surface layers of the mixing zones (10 to 20) compared to the riverine freshwater. This is most likely caused by the degradation of organic matter in this zone. At about 73°N, surface water RI abruptly increases to values >20 in the upper layers, pointing at production of fresh marine organic matter.

5.5.3 Inorganic proxies

The behavior of manganese and iron as redox- and salinity-sensitive proxies was investigated in the Yenisei River transect. In order to avoid concentration-depending effects, Mn/Al and Fe/Al ratios were used for particulate matter and surface sediments. Dissolved manganese and iron,

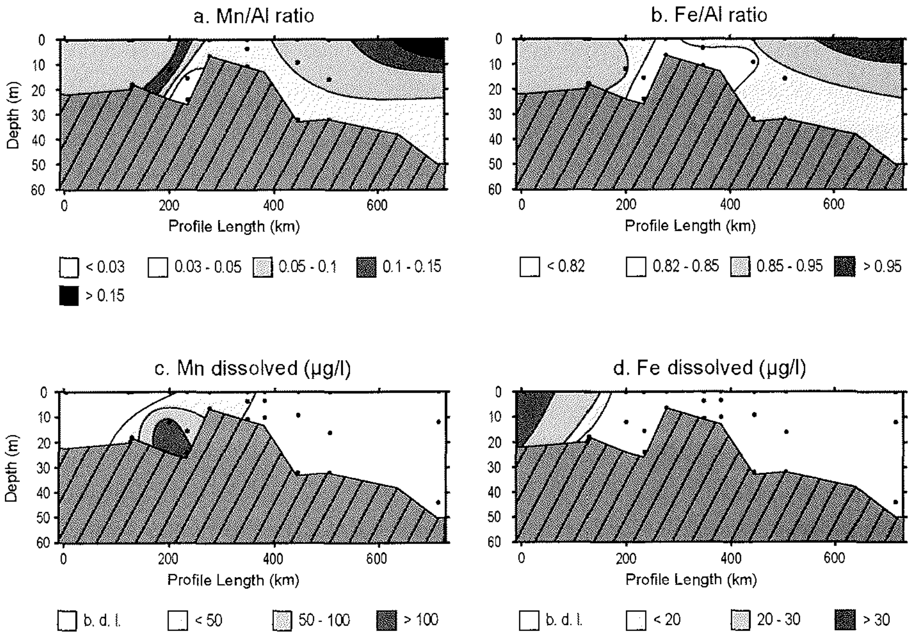

Fig. 5-6: Inorganic proxies profiles. *a. Mn/Al of particulate matter, b. Fe/Al of particulate matter, c. dissolved Mn (µg/l), d. dissolved Fe (µg/l). Dots mark the sampling points.*

in contrast, are given in concentrations.

In the suspended matter, Mn/Al is rather constant in the freshwater part of the Yenisei River. A maximum in Mn/Al occurs with the increase in salinity (Fig. 5-6a). Depletion takes place in the area characterized by resuspension. In the Kara Sea suspension, Mn/Al is rather high and even higher than in the freshwater part of the river. Dissolved manganese concentration is low (below detection limit) both in the freshwater part of the river and in the marine waters of the Kara Sea. It is significantly higher near the river bottom in the mixing zone. Sediment cores from the mixing zone show characteristics of anoxia in the sediment while the overlying water column is oxic. The high concentration of dissolved manganese near the bottom in the mixing zone most likely can be ascribed to early diagenetic processes affecting manganese in the surface layers of the anoxic sediment, releasing reduced manganese into the overlying water column. As the water column is not totally anoxic in contrast to the sediment (benthic fauna is sparse, but existent; H. Deubel (AWI Bremerhaven), pers. comm.), the dissolved manganese is re-oxidized and withdrawn of the dissolved phase.

Similar to Mn/Al, Fe/Al in suspended matter decreases in the mixing zone. Nevertheless, the Fe/Al ratio starts to decrease at lower salinities than Mn/Al, but changes in Fe/Al are small compared to Mn/Al changes. Both Mn/Al and Fe/Al are depleted in the centers of resuspension, most likely due to dilution with suspended sediment of lower Mn/Al and Fe/Al, respectively. Dissolved iron is observed only in the southernmost part of the river at salinities of 0, most probably originating from the surrounding soils (Lisitsyn, 1995). As soon as the salinity is above 0, dissolved iron is withdrawn from the water column by coagulation and precipitation of Fe-oxyhydroxides, and concentrations drop below detection limit (Beeskow and Rachold, 2003).

Enhanced Mn/Al and Fe/Al ratios in the Kara Sea north of about 73°30'N can be ascribed to the production of fresh marine organic material and associated scavenging of manganese. Iron and manganese are analyzed in phytoplankton (Martin and Knauer, 1973), and iron in particular is important for the function of photosynthesis in phytoplankton (Tung-Yuang Ho et al., 2003). Therefore, these elements are enriched in the suspended matter in the upper water column of the northern Yenisei Estuary and the southern Kara Sea.

5.5.4 The "marginal filter" of the Yenisei River

In general, estuarine filters are selective for different species: (i) some parts of the material (dissolved and particulate) are just diluted by the mixing of freshwater with marine water of different concentrations (conservative behavior); (ii) some particulate matter flocculates within the zone of increasing salinity; (iii) some dissolved material is removed from the water column making the turbidity maximum a filter zone, and (iv) some is adsorbed to suspended matter before entering but mobilized within the turbidity maximum (positive and negative non-conservative behavior).

(i) In our study, conservative behavior was observed in PN and POC percentages. These proxies are only affected by changes in hydrography and, therefore, resuspension of surface sediment in the estuarine mixing zone. However, even though percentages of suspended organic matter do not change within the mixing zone, organic matter is affected by degradation, as revealed from RI. This degradation takes place exactly in the mixing zone at salinities above 0 but below 20. Köhler et al. (2003) report an almost conservative behavior of dissolved organic carbon; the conservative behavior of particulate organic matter pointed out in this study further confirms the findings of Köhler et al. (2003) that interaction between dissolved and particulate phases of organic matter is quantitatively insignificant.

(ii) Particles of terrestrial origin are flushed out to sea if their settling rates are sufficiently low and allow them to remain in the net seaward-moving surface layers. TSM is affected by flocculation processes due to changing salinity, increasing its settling speed with increasing flocculation. At low salinities just above 0, flocculation is initiated (Figs. 5-2a and 5-2c). At salinities higher than 20, dilution of TSM due to mixing with marine water of lower TSM concentration is observed and the TSM concentration behavior is conservative (Gebhardt et al., chapter 3, this volume).

Flocculation produces large flocs with high settling rates; due to changing conditions in shear, these flocs tend to break once they reach the river bottom and are readily resuspended, forming part of the turbidity maximum (Kranck, 1984).

(iii) According to Sharp et al. (1984), the effectiveness of the filter is revealed by an abrupt drop in the concentrations of some dissolved materials in the low salinity regions. Dissolved iron is observed only in the freshwater part of the Yenisei River with concentrations of up to 35 µg/l (average concentration in rivers: 40 µg/l; Haese, 2000, and references therein). At the interface between pure freshwater and brackish water, dissolved iron precipitates as Fe-oxyhydroxides due to increasing destabilization of the mixed iron oxides-humic matter colloids (Sholkovitz, 1978), and is withdrawn from the water column. A strong removal of dissolved iron at the freshwater end of the marginal filter was also observed by Dai and Martin (1995).

(iv) Mobilization of species formerly adsorbed to particulate matter was not observed in the mixing zone. However, mobilization of manganese takes place in the anoxic sediments underlying the mixing zone. This is reflected in enhanced dissolved manganese concentrations in this area. As the water column is – at least temporarily – oxic even above the anoxic sediment, manganese is soon re-oxidized and withdrawn from the water column. Nevertheless, this withdrawal is not observable as the dilution of particulate Mn/Al by resuspension is superimposed. Mobilizing of dissolved iron from the anoxic sediment is not observed. This can be explained by the fact that manganese is more mobile and more slowly oxidized than iron and, therefore, migrates more easily. Iron, in contrast, is more readily deposited. The redox potential of the Yenisei River mixing zone sediments is not high enough to reduce iron and release it into the water, whereas manganese is sensitive enough to experience early diagenesis. Release into the water column as well as removal from solution may be temporary (what is the case for manganese in the Yenisei River), and materials may be released from the particulate matter back into solution; this may occur in the water column or after the particles have been accumulated (e. g. Cochran, 1984; Sharp et al., 1984). This leads to a cycling of reduced and oxidized manganese.

However, the mixing zone of the Yenisei River does not affect all substances analyzed here. Many species (e.g. organic matter) behave rather conservatively and are only affected by dilution, e.g. due to resuspension of surface sediment with different species concentration. Only substances that are highly sensitive to changes in ionic strength of the water (e.g. dissolved iron, TSM) show changes in concentration due to precipitation and flocculation.

5.5.5 Comparison with other marginal filter studies

Comparison with earlier studies from the Yenisei River

Many studies on proxies potentially affected by the changing conditions in the marginal filter have been carried out in the Yenisei River (e.g. Dai and Martin, 1995; Gurevich et al., 1995;

Kravtsov et al., 1995; Kuptsov et al., 1995; Lebedeva and Shushkina, 1995; Lisitsyn et al., 1995; Lukashin et al., 1999; Makkaveev, 1995; Paluszkiewicz et al., 2001; Schoster et al., 2000), but in many cases the spatial distribution of data is too small to define the processes and interactions. A detailed study on inorganic proxies was carried out by Beeskow and Rachold (2003) forming the basis of our inorganic dataset. Considering not only inorganic but additionally organic proxies and biological data, we agree with most of their findings about processes taking place in the mixing zone between riverine and marine water. Only for manganese, we propose a slight modification of their conclusion: Beeskow and Rachold (2003) conclude that the dissolved manganese maximum in the near-bottom layer of the mixing zone results from dissolution of suspended manganese due to anoxic or suboxic water. Even though there is evidence of low oxygen concentrations (<4mg/l) as well as low pH and high ammonium values during an earlier cruise (Kravtsov et al., 1995), we think that the water is not totally anoxic (Benthic fauna is sparse in this area, but existent; H. Deubel (AWI Bremerhaven, Germany), pers. comm.). Kravtsov et al. (1995) report maximum concentrations of dissolved heavy metals within the bottom horizon of deep water and suggest a diffusive flux from the sediment to the near-bottom waters. Furthermore, enhanced fluxes of dissolved manganese in the same layers were observed. We, therefore, propose that manganese is released from the anoxic sediment, forms a maximum of dissolved manganese in the near-bottom layer and is soon re-oxidized in the water column. Beeskow and Rachold (2003) suggest that microbial oxidation of organic matter is the main reason for anoxic water in this zone. If this were to be true, a POC loss should be observed in the water column, but is not observed in the surface layer (Fig. 5-3b), and also DOC is reported to behave conservatively (Köhler et al., 2003). However, a change in RI is observed and indicates that degeneration takes place, probably associated with oxygen consumption. During the occasionally occurring oxygen deficits in the overlying water, dissolution of suspended manganese is likely to be a contributing mechanism, but not the main mechanism.

A more general study was carried out by Lisitsyn (1995), describing the marginal filter of the world's rivers with special emphasis on the marginal filter in the Ob and Yenisei rivers as examples of Arctic rivers. Extremely high fluxes of TSM are reported (1,321 and 22,156 mg m^{-2} d^{-1} for the Ob and Yenisei rivers, respectively; Lisitsyn et al., 1995), resulting in fluxes within marginal filters that are higher than those outside by factors of 100 to 1000 (Lisitsyn, 1995). In a worldwide compilation, about 90% to 95% of the suspension discharged by rivers into the mixing zone, 80% of the dissolved and 90% of the suspended iron and about 20% of the dissolved manganese do not reach the pelagic zone (Lisitsyn, 1995). However, the marginal filter of Arctic rivers behaves differently due to the strong seasonality of these rivers: the spring/summer period with the main river runoff has a time span of around 4 months, and only during this short time span, the marginal filter is comparable to rivers in lower latitudes. During the long autumn/winter period, only small amounts of river runoff are released into the Kara Sea, and, furthermore, the rivers and the adjacent Kara Sea are ice-covered. The ice cover prevents the water column from mixing, allowing the winter runoff to spread and distribute widely its suspension load (Lisitsyn, 1995). Additionally, high saline brines are formed during ice production. These brines sink to the Kara Sea floor due to their high density and transport the marginal filter material along the channel incisions towards the Arctic Ocean (Lisitsyn, 1995).

Lisitsyn (1995) observed two "plugs" within the marginal filter: a "silt plug" at salinities around 2 where flocculation and coagulation of clay, organic acids and iron coincide in space, and a "elementorganic plug" at salinities around 5 due to flocculation of organic matter and oxyhydroxides. In our study, iron precipitates at low salinities just at the beginning of the marginal filter, and TSM has its maximum flocculation at slightly higher salinities. Particulate manganese maximum is found at even higher salinities than the TSM maximum concentrations. The flocculation of organic matter as postulated by Lisitsyn (1995) to occur at salinities around 5 was not observed in our study.

Lisitsyn (1995) proposes that the main part of dissolved manganese (about 80%) escapes the marginal filter. The riverine input of dissolved manganese into the marginal filter of the Yenisei River is small (i.e. below detection limit), and so is the output into the Kara Sea. We, therefore, cannot estimate the amount of dissolved manganese that escapes the marginal filter; we only observe that the manganese released into the water column within the marginal filter zone does not leave it. Nevertheless, we notice that – even though the dissolved manganese concentrations are below detection limit in the riverine freshwater, precipitation of dissolved manganese occurs at low salinities as revealed from higher Mn/Al in the suspended matter.

For many proxies, we agree with the definition of the marginal filter sensu Lisitsyn (1995). However, not all postulated processes are observed in the Yenisei River: particulate organic matter behaves rather conservatively even though degradation occurs within the mixing zone. Furthermore, not all processes result from changes in salinity: flocculation of particulate matter is also induced by changing hydrographic conditions (e. g. Burban et al., 1989; Burban et al., 1990; Lick et al., 1993; Winterwerp, 2002), and the release of dissolved manganese within the mixing zone originates from redox processes within the anoxic sediment.

Comparison with other rivers

Lena River (Siberia)

The Lena River drains into the Laptev Sea (Siberia) and is comparable to the Yenisei River in its size and geographical position. However, the Lena River forms a delta with several distributaries and islands in contrast to the Yenisei River characterized by an estuary. Gordeev and Shevchenko (1995) found conservative behavior of iron and some trace elements in the mixing zone, indicating a low affinity for biogenic matter. Nevertheless, the small dataset does not allow a reliable conclusion. However, the dataset of Cauwet and Sidorov (1996) does not show any evidence for consumption of POC on its way through the marginal filter. The authors assume that only a small part of the terrestrial POC undergoes degradation whereas the marine POC is recycled almost *in situ*. This is quite similar to the conservative behavior of POC observed in the Yenisei River. Conservative behavior was also postulated for the Lena River DOC (Cauwet and Sidorov, 1996) similar to the study on the Yenisei River DOC (Köhler et al., 2003).

Fly River (Papua New Guinea)

The Fly River in Papua New Guinea drains one of the wettest places on earth, with a relief of up to >4000 m in its hinterland (Wolanski and Gibbs, 1995). Its yield is extremely high compared to large rivers as the Amazonas, Mississippi and Ganges rivers. The Fly River is well mixed with vertical isohalines, a salt wedge is not found. The turbidity maximum was observed at the landward extent of the salinity intrusion (Wolanski and Eagle, 1991). Wolanski and Gibbs (1995) observed that the suspended particle size was larger at the bottom layers than at the surface waters, and were larger at lower than at higher salinities. The flocs were silt-dominated and, thus, weak and went through a cycle of breakage and re-flocculation through the tidal cycle. Wolanski and Gibbs (1995) concluded that the flocs are forming at the river bottom layer, but are destructed when advecting to the surface layer.

A very similar situation was found in the Yenisei River: the highest concentrations of TSM are found in the near-bottom layer. It is most likely that even in the Yenisei River flocculation takes place in the deep layers and many of the flocs do not reach the surface layer. Flocculation and resuspension probably are associated processes.

St. Lawrence River (North America)

The St. Lawrence River consists of a series of banks, channels and basins, with water depths reaching 150 m in the deepest basin. The turbidity maximum of the upper St. Lawrence River is a prominent feature of about 180 km length and 2 to 24 km width (Gobeil et al., 1981). Non-conservative behavior of dissolved Fe (removal) and dissolved Mn (input from sediment) was observed by Bewers and Yeats (1978; 1979) similar to our observations in the Yenisei River. Furthermore, lower content of e. g. Mn in the particulate matter was observed and interpreted as desorption by Cossa and Poulet (1978). Gobeil et al. (1981) observed decreasing Mn/Al ratios at the landward end of the turbidity front, being not related to salinity as this feature was found also when the turbidity maximum occurred in freshwater. Nevertheless, this feature was also not related to TSM concentrations as it was very stable throughout the tidal cycle with differing TSM concentration (10 to 220 mg/l over the observed tidal cycle). Gobeil et al. (1981) pointed out that the Mn/Al ratio was influenced by bottom processes, being frequently higher in near-bottom samples than at the surface. Furthermore, Fe/Al decreased in the turbidity zone and did not reflect the addition of Fe to the solid phase by the precipitation of dissolved iron. Gobeil et al. (1981) and Hamblin (1989) showed (i) that salinity was not the main process causing the distinct changes in geochemical composition of dissolved and particulate matter in the turbidity maximum, and (ii) sedimentological and hydrological processes to be much more important. In our study, decoupling of salinity-driven and hydrological-sedimentological-driven processes is not easy. Nevertheless, we showed that resuspension due to changes in hydrological conditions plays an important role in the Yenisei River.

Lucotte (1989) investigated the particulate organic matter in the upper St. Lawrence estuary, and found (i) a perfect dilution line between the riverine and the marine $\delta^{13}C$ pool, pointing at both a negligible influence of estuarine bioproduction and a negligible geochemical transformation of POC, and (ii) a residence time of POC of about 6 to 12 months of the particles already in suspension with a slow replacement by new particles. Also the Yenisei River POC shows conservative behaviour even though degradation within the maximum turbidity zone points at enhanced residence time.

Changjiang (=Yangtze) River (China)

The Changjiang River is the fourth largest river in terms of sediment discharge and average water discharge with a large intraseasonal and interannual variability (Milliman et al., 1985, and references therein). The river is characterized by a mesotidal, partially mixed estuary divided by islands into several branches and arms and finally opening into four mouths. The turbidity maximum in the Changjiang River is fed by resuspension and erosion of the river bed (Jiufa and Chen, 1998). Settling velocities of the suspended matter is increased due to flocculation, and during periods of weak tidal currents the massive settling often gives rise to formation of fluid muds. Jiufa and Chen (1998) carried out a lab experiment on the flocculation of suspended matter in the Changjiang River, showing that the flocculation of different particle sizes depends on the flow velocity of the water. It is likely that at a certain flow velocity a certain grain size starts to flocculate, what might result in a maximum turbidity area and even in fluid mud layers due to changes in hydrography without changes in salinity. The authors further showed that the occurrence of the turbidity maximum in the deep layer normally is associated with the reversal of the tidal currents. An area of zero net transport and, therefore, accumulation was detected as a combined effect of tidal asymmetry, runoff and density circulation. Jiufa and Chen (1998) point out that the major processes favoring the transport of suspended matter consist of tidal pumping and advective terms.

It is likely that even in the Yenisei River, flocculation occurs at zones where the velocity is favorable for certain grain sizes. Nevertheless, accumulation of sediment does not take place in the same area as flocculation; the thick sediment packages most probably are laid down in an area of zero net transport as in the Changjiang River.

Cauwet and Mackenzie (1993) carried out a study on organic matter in the Changjiang River. They show that DOC is not influenced by salinity as in the Yenisei River, but in contrast to what was found in the Yenisei River, DOC is sometimes enhanced in the near-bottom layer in the Changjiang River. This was interpreted to occur due to resuspension of interstitial water enriched in DOC.

5.6 Conclusion

In this study, we focused on the summer situation in the Yenisei River mixing zone. Flocculation and resuspension of particulate matter was observed in the mixing zone, forming the maximum turbidity zone, what in turn enhances the flocculation and disaggregation processes due to higher concentrations of particles (e. g. Burban et al., 1989; Burban et al., 1990; Lick et al., 1993). Resuspension was observed in areas of changing hydrographic conditions, and it mainly affected the near-bottom layers. Organic suspended matter (POC, PN) behaves conservatively in the mixing zone in terms of its percentage within the suspended matter even though it undergoes degradation as revealed from RI data. As shown by Köhler et al. (2003), dissolved organic carbon (DOC) also behaves conservatively, supporting the observed conservative behavior of suspended organic matter and the fact that suspended and dissolved organic matter do not interact considerably in the Yenisei River marginal filter.

Non-conservative behavior was observed considering the redox- and salinity-sensitive elements (Fe, Mn). Dissolved iron is withdrawn of the water column at the landward edge of the mixing zone due to precipitation of Fe-oxyhydroxides. A decrease in Fe/Al is observed in the mixing zone and can be ascribed to resuspension of sediment with lower Fe/Al ratio. Dissolved manganese concentrations are below detection limit in the freshwater of the Yenisei River. At the landward edge of the marginal filter, however, Mn/Al increases due to adsorption of the sparse dissolved manganese present in the freshwater. Within the mixing zone, however, Mn/Al is depleted similarly to Fe/Al due to resuspension. Dissolved manganese is largely enhanced in the near-bottom layers within the maximum turbidity zone, which can be ascribed to release of manganese from anoxic sediments into the water column. This process may be enhanced due to resuspension of sediment and associated interstitial water with enhanced dissolved manganese concentrations.

Fe/Al and Mn/Al as well as POC and PN are high in the marine surface waters of the Kara Sea.

We propose that this is due to the enhanced production of marine organic matter in this area; the enhanced production of marine organic matter is revealed by biological data (e. g. Nöthig et al., 2003) as well as by amino acid proxies (Unger et al., subm.).

Differentiation of processes causing the observed effects in the maximum turbidity zone is not always clear in the Yenisei River. Salinity changes are not the main reason for processes taking place in the marginal filter, nor does salinity induce a zonation within the marginal filter as proposed by Lisitsyn (1995). Resuspension of bottom material takes place due to hydrological changes in the river flow, and the mobilization of dissolved manganese in the near-bottom layers in the marginal filter is caused by reducing conditions in the sediment. However, precipitation of dissolved iron at the landward edge of the mixing zone as well as the increase of Mn/Al in suspended matter of the same zone is induced by increasing salinity.

Altogether, the summer situation of the Yenisei River marginal filter is well comparable to rivers of other latitudes (e.g. Fly River in Papua New Guinea, St. Lawrence River in North America). However, for better differentiation between the processes taking place in the marginal filter of the Yenisei River, a better spatial and temporal resolution, e.g. during a full tidal cycle and during winter conditions, is needed.

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Part C:
Synthesis

"HEUREKA! HEUREKA!
I found it! I found it!"
Archimedes (285 - 212 B. C.)

6 Synthesis

This chapter outlines the main results of the previous chapters, with special emphasis on the questions and aims of chapter 1.1. It further summarizes the main outstanding problems and possible guidelines for future projects.

6.1 Key results

- Recent fluxes of the rivers into the Kara Sea

Recent fluxes of total suspended matter (TSM), particulate organic carbon (POC) and particulate nitrogen (PN) were calculated in chapter 3 for the situation in 2001. Fluxes of the Yenisei River reveal a bypass system from the northernmost gauging station in the hinterland (Igarka) to the Yenisei River mouth. Flux calculations for the Ob River, in contrast, show that about three quarters of the sediment discharge measured at the northernmost gauging station (Salekhard) is lost on its way to the river mouth. Seismic data reveal thick sediment packages at both river mouths (Dittmers et al., 2003), whereas sediment thicknesses are low within the rivers. This points at secondary transport processes of sediment from the Ob River towards the Kara Sea (e. g. by resuspension, or incorporated in newly built ice). We could show that the fluxes calculated for 2001 are well usable as general flux estimates for the Ob River and as maximum estimate for the Yenisei River.

- Sedimentation within the rivers and on the Kara Sea shelf

The sedimentation of the riverine sedimentary discharge within the Kara Sea was studied, leading to a recent sediment and organic carbon budget for the investigated area (chapter 4). Other sources of material (coastal erosion, eolian input) were considered, and outflows into the adjacent seas were estimated. The recent sediment and organic carbon budgets were compared to a recent budget calculated for the Beaufort Sea by Macdonald et al. (1998), showing that (i) the much smaller Beaufort Sea is dominated by river sediment discharge, whereas the Kara Sea – outside of the estuaries – is dominated by input due to coastal erosion. Furthermore, it was shown that the Kara Sea buries lower-than-average organic carbon (chapter 3), whereas the Beaufort Sea is an area of higher-than-average organic carbon burial (Macdonald et al., 1998). A late Holocene sediment and organic carbon budget was interpolated from our data in order to compare the recent with the late Holocene sedimentation system as revealed by geological data (Stein and Fahl, 2004a). Differences between the late Holocene budget by Stein and Fahl (2004a) and our interpolated late Holocene budget are striking, but may be reduced to two main factors: (i) Stein and Fahl (2004a) use old coastal erosion data that are by far too high, resulting in a much higher total sedimentation on the Kara Sea shelf, and (ii) the effectiveness of the marginal filter of the mixing zone between riverine and marine water is higher today than during the average late Holocene. This results in higher amounts of sediment caught in the river mouths today compared to the late Holocene.

- Processes affecting the material fluxes along the river course into the Kara Sea

Processes affecting the material discharged by the rivers were studied in detail using summer 2000 organic and inorganic data of the Yenisei River (chapter 5). Changes in hydrography and salinity result in flocculation, precipitation, and resuspension processes; sediment anoxia leads to fluxes of dissolved elements from the sediment to the near-bottom layers of the water column. Differentiation of processes causing the observed effects in the Yenisei River is not always clear. Salinity changes, nevertheless, are not the main reason for the processes taking place in the mixing zone as was proposed by Lisitsyn (1995). Comparison with other rivers reveals that the Yenisei River marginal filter situation during summer is well comparable to the situations in lower latitudes.

- Changes in the past – changes in the future

Changes from the late Holocene to the recent situation were best shown with the comparison between a late Holocene budget revealed from the geological record (Stein and Fahl, 2004a) and our interpolated budget. The most striking features were probable changes in coastal erosion from much higher values in the past to low values today, and changes in the retention effectiveness of the marginal filter. Probably the coastal erosion will change considerably in near future by changes in the permafrost regime due to increasing temperatures. Changes in the river runoff e. g. due to processes in the hinterland as dam constructions and different land use will affect the marginal filter processes and, therefore, its effectiveness. It was shown that the Yenisei River already changed from a sedimentation to a bypass regime due to changes in hydrography caused by dam constructions in its hinterland. All these parameters have a great influence on whether the Kara Sea will act as a sink or source for organic carbon in future. Nevertheless, to give a significant outlook on the future Kara Sea situation, further investigations to improve our understanding of the recent situation is needed as proposed in chapter 6.2.

6.2 Outstanding problems and future perspective

Spatial resolution

The spatial resolution of data in the river-Kara Sea system is remarkably good for geological studies. Nevertheless, suspended matter data from the mixing zone do not resolve this area well enough to give a clear differentiation between the main recent processes taking place:

(i) Data from the Ob River do not resolve the mixing zone of the river. Data are concentrated either on the riverine part or on the marine part of the river. This is mainly due to the fact that during the 2001 cruise – the cruise with the best resolution of the Ob River suspension – the salt wedge and freshwater discharge situation changed significantly during the days of work within the river. Even though samples were recovered in a reasonable spatial resolution, they did not resolve the full interval between salinity 0 and 10 due to the moving freshwater front.

(ii) Data from the Yenisei River recovered during the 2000 cruise resolve the mixing zone quite well. Nevertheless, in order to get a clear differentiation between the salinity-induced and the hydrologically-induced processes, a much higher resolution would be necessary, mainly for the landward edge of the saline intrusion.

Furthermore, data from the northern and western Kara Sea would improve our recent sediment and organic carbon budget.

Temporal resolution

One of the main unsolved problems in the river-Kara Sea system is the winter situation of both the river runoff and the processes taking place in the estuaries and on the shelf. As the Kara Sea is ice-covered during about 8 to 9 months, investigations are only possible during the short summer period. It is well known that the Kara Sea undergoes a high seasonality; data from the winter months would, therefore, improve our recent budgets of fluxes and sedimentation process and our understanding of the winter marginal filter processes. Long term sediment traps were recently installed and successfully recovered and will be the first step to bring the winter situation to light.

Additionally to the high seasonality in the Kara Sea, interannual variations driven by both variations in freshwater discharge and ice conditions are remarkably high (Bobrovitskaya et al., 1997). An annually high-resolution survey of the suspended load of both rivers would improve our understanding of the sedimentation and degradation processes within the rivers and our estimates of fluxes into the Kara Sea. This would give a well-established guideline for comparison with future changes.

Proposal for future activities

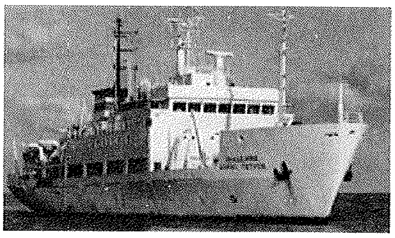
For future research in the river-Kara Sea system, two main focuses are proposed:

a) Additional work to better resolve the marginal filter:

A high-resolution survey of the rivers is proposed, with a higher resolution in terms of salinity as well as in terms of time. For example, stationary work during a tidal cycle would reveal the resuspension processes as driven by changing currents; high resolution sampling at the landward edge of the salt intrusion would reveal the succession of salinity-induced processes as flocculation and precipitation of dissolved matter; current speed measurements within the mixing zone would probably improve the differentiation between salinity-driven and hydrographically-driven processes.

b) Additional work to improve the recent sediment and organic carbon budget of the Kara Sea: The recent Kara Sea budget still contains many interpolated estimates. Fluxes from and to the adjacent seas are widely unknown, and the recent estimates on coastal erosion are not yet well-established. Additional work in the marginal areas of the Kara Sea is required in order to reveal the exchange between the Laptev, Barents and Kara Seas and the Arctic Ocean; measurements of coast retreats are necessary to estimate the contemporary coastal erosion (this is one of the main focuses of the Arctic Coastal Dynamics project, Rachold et al., 2002a).

Part D:
Acknowledgements, References



RV Akademik Boris Petrov

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