Chapter 2

Modern Terrigenous Organic Carbon Input to the Arctic Ocean

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2.1 General Introduction

The main objective of this chapter is to assess recent fluxes of terrigenous dissolved and particulate organic carbon into the Arctic Ocean. The most important terrigenous sources of organic matter (OM) in the ocean are (1) river and groundwater discharge, (2) coastal erosion, (3) sea-ice input and (4) aeolian material fluxes. The organic carbon fluxes of each of these pathways will be considered separately and a evaluation will be made of their roles in the total balance of OM input to the ocean.

2.2 River Input

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2.2.1. Introduction

Before addressing the question of river discharge and, in particular, its contribution to terrigenous organic carbon input to the ocean, it is necessary first to define clearly what we mean by the Arctic Ocean and its drainage basin. Prowse and Flegg (2000) showed that in the literature evaluations of river water discharges to the Arctic Ocean vary widely. These authors conclude that this variability derives simply from differences in the how the Arctic Ocean has been defined geographically. At the widest scale, Shiklomanov et al. (2000) defined "All Arctic Regions" (AAR) to include "river basins in North America that drain into the Hudson Bay, and the Yukon River (Alaska) and the Anadyr River (Russia) that drain into the north Pacific south of the Bering Strait". Greenland, the eastern edge of Norway and the Canadian Arctic Archipelago are also included in this definition of the Arctic. The total contributing area is 23.7×10^6 km^2 and the total river discharge amounts to 5250 km^3 y^{-1}.

From our point of view it seems more reasonable to follow the definition that was adopted at the NATO Research Workshop of the Arctic Ocean Freshwater Budget – the so-called "Arctic Ocean River Basins – AORB" (Lewis 2000). There, it states that the "Arctic Ocean is defined as being bounded by: the Russian main land, a line across Bering Strait, the north coast of Alaska and the northernmost limit of the islands in the Canadian Arctic Archipelago, then across Kennedy Channel to Peary Land, across Svalbard, down to the Nordkapp of Norway and back to the Russian coast". This definition comprises only the coastal basins that drain directly towards the Arctic Ocean including the northern edges of the Canadian islands and the northern tip of the Greenland ice cap. The total contributing area for the AORB definition is 15.5×10^6 km^2 and the total river discharge amounts to 3299 km^3 y^{-1}, with a range from 3043 to 3546 km^3 y^{-1} (Prowse and Flegg 2000).

2.2.2 River water and suspended matter

River water discharge is particularly important for the Arctic Ocean because, although the this ocean contains only 1.0% of the world ocean water, it receives 11% of the global runoff (Shiklomanov 1998). In Table 2.1 the average multiannual discharges of freshwater, suspended matter (SM), and dissolved organic carbon (DOC), particulate organic carbon (POC) and total organic carbon (TOC) into the Arctic Ocean are summarized. The largest Arctic rivers in terms of water discharge (in km^3 y^{-1}) are: Yenisei – 620, Lena – 525, Ob – 404, Mackenzie – 330, Pechora – 131 and Kolyma – 122. The western rivers (Sev. Dvina, Onega, Mezen) show a maximum discharge in May (Fig. 2.1) whereas the the Siberian rivers, Ob, Yenisei, Lena, Indigirka etc., exhibit their highest discharge in June.

The concentration of SM in the Arctic rivers is low ranging from 8 mg l^{-1} in the Yenisei to 207 mg l^{-1} in the Indigirka. The average SM concentration is 36 mg l^{-1} for the Russian Arctic rivers and 63 mg l^{-1} for all Arctic rivers. The first assessments of SM

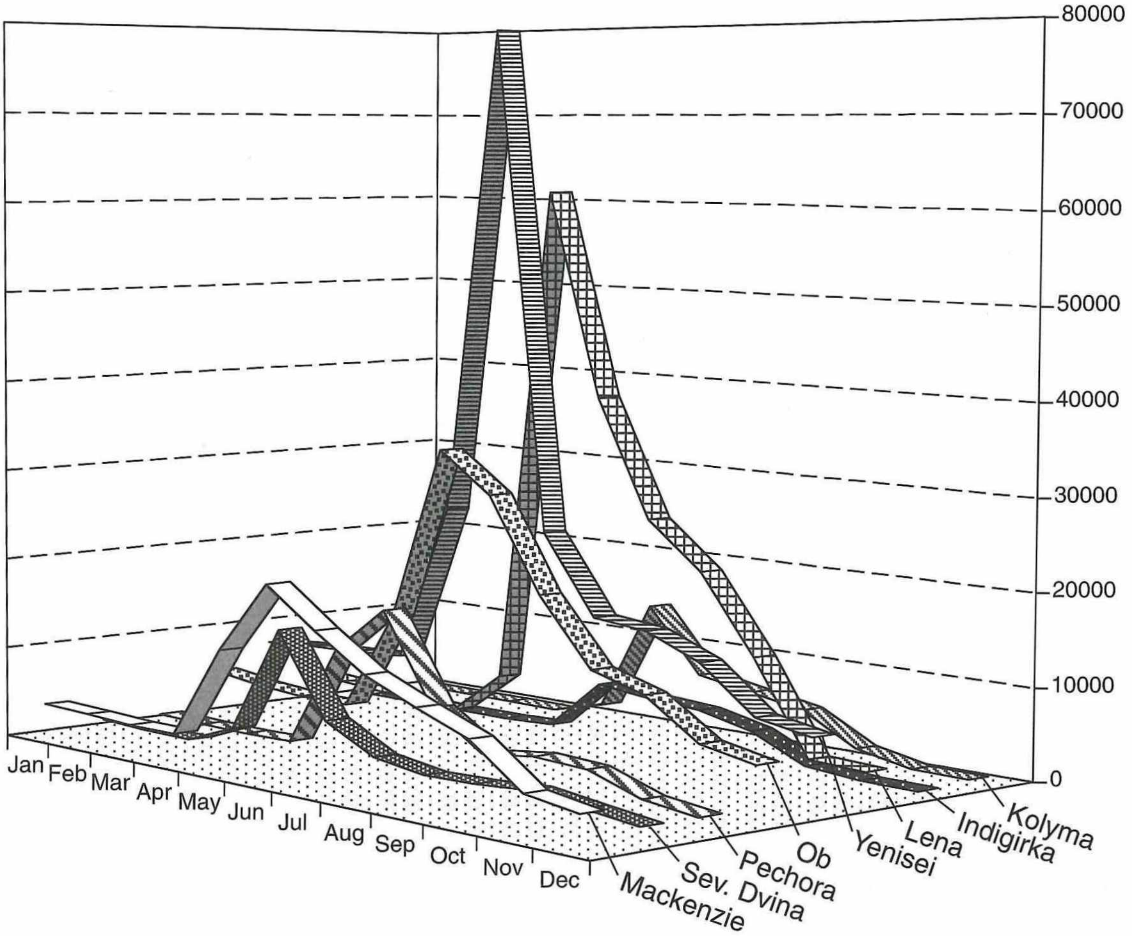

Fig. 2.1. Seasonal variations in water discharge of the largest Arctic rivers. The monthly discharge data are taken from the Regional, Electronic, Hydrographic Data Network For the Arctic Region (http://www.R-ArcticNET.sr.unh.edu/) and represent the average discharges for the years 1980–1993

fluxes of the Russian Arctic rivers appeared at the end of the 1940s (Shamov 1949; Lopatin 1952), based on the Roshydromet data from the 1920s. In North America regular measurements of SM discharge began in the 1970s (US Geological Survey and Water Survey of Environment Canada). Since that time many evaluations of SM fluxes have been published culminating in a pan-Arctic review article synthesizing the sediment fluxes of 8 large Arctic rivers to the Arctic Ocean and coastal seas (Holmes et al., 2002). The best estimates of the contemporary average annual sediment flux in these rivers were provided and are included in Table 2.1. Taking into account corrections made by Holmes et al. (2002), the total SM flux from the Eurasian territory to the Arctic Ocean was reduced from 115×10^6 t y^{-1} (Gordeev et al. 1996) to 102.2×10^6 t y^{-1} (Table 2.1).

The Mackenzie River, which is the fourth largest Arctic river in terms of water discharge (330 km^3 y^{-1}; Macdonald et al. 1998) is the largest river in terms of sediment discharge (124×10^6 t y^{-1} of sediment; Holmes et al. 2002). Thus, using the Arctic Ocean River Basins definition (see above), the Mackenzie River is absolutely dominating in the Canadian Arctic, providing 90 % of the water and 99 % of the SM discharge for that region (Table 2.1).

It is interesting to note that the East Siberian rivers in comparison to the western Russian Arctic rivers (west of the Lena River, which is located at the boundary between the Eurasian and North American tectonic plates) are characterized by lower runoff, higher SM concentration and by significantly lower water mineralization, organic matter and nutrient concentrations. The rivers eastward of the Lena River resemble more closely the North American rivers than the western Russian Arctic rivers (Gordeev et al. 1996).

Table 2.1. Average multiannual riverine water and suspended matter discharges and fluxes of DOC, POC and TOC to the Arctic Ocean. The majority of data in this table is taken from Gordeev et al. 1996 and Gordeev 2000. Note that sometimes POC + DOC is not equal to TOC because of different sources of data. For the content of TOC, "total" refers to "average concentrations". This average calculated for the large rivers was adopted to "other areas" where no concentration data are available. [1] Holmes et al. (2002); [2] Smirnov et al. 1988; [3] Romankevich and Vetrov 2001; [4] Lobbes et al. 2000; [5] Artemiev 1997; [6] Nesterova 1960; [7] Maltseva et al. 1987; [8] Magritsky 2001; [9] Rachold and Hubberten 1999; [10] Cauwet and Sidorov 1996; [11] Mulholland and Watts 1982; [12] AMAP Report 1998; [13] Macdonald et al. 1998; [14] Spitzy and Leenheer 1991; [15] Degens et al. 1991; [16] based on [6]; [17] based on [4]

River	Area	Water disch.	Tot. susp. matter		Content			Flux			TOC	POC in dry SPM	DOC×100 / DOC+POC
					DOC	POC	TOC	DOC	POC	TOC			
	$10^3 km^2$	$km^3 y^{-1}$	$g m^{-3}$	$10^6 t y^{-1}$		$mg l^{-1}$			$10^6 t y^{-1}$		$t km^{-2} y^{-1}$	wt.%	
White and Barents Seas													
Onega	57	15.9	18	0.30	–	–	20.7[2]	–	–	0.33	5.8	–	–
N. Dvina	357	110	37	4.1[1]	11.6	2.6	15.3[3]	1.28	0.28	1.68	4.7	6.8	76
Mezen	78	27.2	33	0.6[1]	12.1[4]	1.8[4]	7.0[2]	0.25[4]	0.04[4]	0.19	2.4	1.1	–
Pechora	324	131	72	9.4[1]	12.7	0.3	13.0[5]	1.66	0.04	1.70	5.2	0.43	97
Other area	570	179	19	3.5	–	–	13.7	–	–	2.45	4.3	–	–
Total	1386	463	39	17.9[1]	–	–	13.7	4.18[3]	0.45[3]	6.35	4.4	–	–
Kara Sea													
Ob	2545	404	37	15.5[1]	9.1[6]	0.9[6]	7.1[2]	3.68[16]	0.36[16]	2.87	1.1	–	91
Nadym	64	18	22	0.4	–	–	5.0[2]	–	–	0.09	1.4	–	–
Pur	112	34.3	18	0.7[1]	–	–	6.7[1]	–	–	0.23	2.0	–	–
Taz	150	44.3	21	0.7[1]	–	–	–	–	–	–	–	–	–
Yenisei	2594	620	8	4.7[1]	8.5[4]	0.3[4]	7.4[7]	4.86[4]	0.17[4]	4.59	1.8	–	96
Pyasina	182	86	39	3.4	–	–	–	–	–	–	–	–	–
Other area	867	275	20	5.5	–	–	7.2	–	–	1.98	–	–	–
Total	6589	1480	21	30.9[1]	–	–	7.2	–	–	10.6	1.6	–	–
Laptev Sea													
Khatanga	364	85.3	20	1.7	–	–	6.3	–	0.04[9]	0.54	1.5	2.3	–
Anabar	100	17.3	24	0.4	–	–	5.1	–	–	0.09	0.9	–	93
Olenjok	218	32.8	38	1.1[1]	10.2[4]	0.83[4]	7.2	0.32[4]	0.026[4]	0.24	1.1	–	92
Lena	2448	523	39	20.7[1]	6.6[10]	1.1[10]	7.7	3.6[9]	1.2[9]	4.8[9]	1.9	5.8	86
Omoloy	39	7	18	0.04[1]	2.8[4]	0.3[4]	–	0.003[4]	0.001[4]	–	–	5.7	75
Yana	225	31.9	130	4.0[1]	2.8[4]	1.6[4]	6.7	0.085[4]	0.05[4]	0.21	0.9	1.5	64
Other area	197	40.3	16	0.65	–	–	9.2	–	–	0.37	1.9	–	–
Total	3597	738	39	28.6[1]	–	–	9.2	–	–	6.8	1.9	–	–

Table 2.1 (continued)

River	Area	Water disch.	Tot. susp. matter		Content			Flux			TOC	POC in dry SPM	DOC × 100 / DOC + POC
					DOC	POC	TOC	DOC	POC	TOC			
	$10^3 km^2$	$km^3 y^{-1}$	$g m^{-3}$	$10^6 t y^{-1}$		$mg l^{-1}$			$10^6 t y^{-1}$		$t km^{-2} y^{-1}$	wt.%	
East Siberian Sea													
Indigirka	360	54.2	207	11.1[1]	4.8[4]	3.5[4]	7.7	0.24[4]	0.17[4]	0.42	1.2	1.6	58
Alazeya	68	8.8	80	0.1[1]	–	–	–	–	–	–	–	–	–
Kolyma	647	122	83	10.1[1]	4.6[4]	3.1[4]	8.1	0.46[4]	0.31[4]	0.99	1.5	3.0	60
Other area	252	48.2	80	3.85	–	–	8.0	–	–	0.38	1.5	–	–
Total	1327	233	110	25.15[1]	–	–	8.0	–	–	1.86	1.4	–	–
Chukchi Sea (excluding Alaska)													
Amguema	29.6	9.2	6	0.05	–	–	6.7	–	–	0.06	2.0	–	–
Other area	64.6	11.2	58	0.65	–	–	6.7	–	–	0.07	1.1	–	–
Total	94.2	20.4	34	0.7	–	–	6.7	–	–	0.13	1.4	–	–
Total Eurasian Arctic													
	12987	2932	36	102.2[1]	6.6[4]	1.3[4]	8.8	19.4[17]	3.81[17]	25.7	2.0	–	–
Chukchi Sea (Alaska) and Beaufort Sea													
Kobuk	24.7[11]	–	–	–	–	–	–	–	–	0.04[12]	–	–	–
Kuparuk	8.11[11]	–	–	–	–	–	–	–	–	0.014[12]	–	–	–
Mackenzie	1787[12]	330[13]	168	124[1]	5.2[14]	7.2[15]	12.5[15]	1.3[13]	2.1[13]	4.1	2.1	3.3	62
Other area	726	37	–	1.1	–	–	–	0.19	0.055	0.24	–	–	–
Total Canadian Arctic													
	2513	367	–	125.1[1]	5.1	5.8	11.6	1.9	2.15	4.3	1.7	2.1	48
Total Arctic													
	15500	3299	63	227.3[1]	–	–	9.1	–	–	30.0	1.9	–	–

2.2.3 Fluxes of organic carbon

The estimation of riverine DOC and POC fluxes into the Arctic Ocean has long attracted the attention of many investigators. In the Russian Arctic rivers systematic measurements of organic matter (OM) were started in the mid-1930s (Maltseva et al. 1978). Most of the data, which were collected by the Roshydromet System, were obtained on unfiltered water samples using permanganate oxidation in an acidic medium and by dichromate oxidation in an acidic medium followed by recalculation into TOC concentrations based on correction coefficients that were specific for the various geographic zones and seasons (Sawyer and Semenov 1971; Semenov 1977). Only a few hundred determinations of DOC and POC were made after filtration of river water through GF/F and GF/C filters by means of wet combustion with colorimetric recording of the liberated CO_2, or by means of photochemical oxidation with infrared spectroscopic recording of CO_2 (Romankevich and Artemiev 1985; Artemiev 1997).

The first assessments of TOC discharge for the Russian Arctic rivers were obtained by Skopintsev and Krylova (1955) and Alekin and Brazhnikova (1964). A summary of the Roshydromet data for the period from 1936 to 1965 and later up to 1980 (Table 2.2) was provided by Maltseva et al. (1978, 1987), Maltseva (1980) and Smirnov et al. (1978, 1988). Two decades later new estimates of OM discharge from the Russian territory to the Arctic Ocean appeared in Artemiev (1997), Gordeev et al. (1996), Gordeev and Tsirkunov (1998) and Gordeev (2000). The most recent work by Romankevich and Vetrov (2001) is an important summary of all available information on the carbon cycle in the Russian Arctic Seas including the riverine discharge of OM.

Several articles published in English are available on the riverine OM input to the World Ocean, in which Arctic rivers are considered to some extent (Duce and Duursma 1977; Schlesinger and Melack 1981; Meybeck 1982, 1993; Michaelis et al. 1986; Degens et al. 1991). The transport of organic carbon to the oceans by the North American rivers was summarized in the work of Mulholland and Watts (1982). During the last few years several new studies on the topics of discharge and origin of riverine OM and its distribution in the Arctic Ocean have been presented (Ittekkot 1988; Telang et al. 1991; Cauwet and Sidorov 1996; Macdonald et al. 1998; Lara et al. 1998; Opsahl et al. 1999; Rachold and Hubberten 1999; Kattner et al. 1999; Lobbes et al. 2000).

Based on a review of the existing information, Table 2.1 presents our best estimates of DOC, POC and TOC fluxes from rivers of the Eurasian and Canadian Arctic. It has to be noted that in this section we evaluate only the riverine OM discharge to the Arctic Ocean or so-called gross river flux, i.e. the amounts of substances transported by the river to the land/sea boundary. In the river/sea mixing zone riverine material, including OM, is subject to intensive change in quality and quantity. However, it is not the objective of this section to consider the behavior of riverine OM at the river/sea boundary which is discussed in detail in Chapter 4.

At present, reliable TOC data are available for most rivers whereas only major rivers have been studied separately for DOC and POC concentrations. Table 2.1 shows the existing data and the fluxes calculated on the basis of these analytical data where, if possible, the DOC and POC components are separated. Unfortunately, the existing database is not sufficient to distinguish between DOC and POC for each shelf area and in some cases only TOC fluxes can be reported. POC fluxes have been published by Romankevich et al. (2000). However, it has to be noted that their flux data are not based on analytical POC values but, rather, were quantified based on the assumption that the organic carbon concentration comprises 2% of the total suspended matter for each river.

We estimate that total TOC discharge to the Eurasian Arctic Ocean is 25.7×10^6 tC y^{-1}. The implied average TOC concentration of 9.1 mg l^{-1} in the Arctic rivers is similar to the world-wide average of 9.9 mg l^{-1} (Meybeck 1993), and the TOC flux to the

Table 2.2. TOC fluxes of the former USSR territory (1936–1980) (Maltseva et al. 1987) (* OM was recalculated to TOC as 2:1)

Sea	Area 10^3 km^2	Water discharge km^3 y^{-1}	TOC flux 10^6 tC y^{-1}	Specific TOC flux t km^{-2} y^{-1}
White and Barents	1250	418	5.52	4.4
Kara	6200	1337	12.52	2.0
Laptev	3670	799	8.52	2.3
East Siberian	1390	238	1.70	1.2
Chukchi	102	28.6	0.90	1.0
Total	12612	2808	28.36	2.2

Arctic accounts for ca. 8.1% of the global TOC flux (370×10^6 tC y^{-1}, Meybeck 1993). A recent estimate of the TOC flux to the seas of the Russian Arctic (Romankevich and Vetrov 2001) is 23.5×10^6 tC y^{-1}, which is 10% lower than our value of 25.7×10^6 tC y^{-1}. However, both studies report practically the same TOC concentration in river water of the Russian Arctic (8.6 and 8.8 mg l^{-1}, respectively) and the difference between the two evaluations is mainly explained by the difference in total water discharges: 2730 km^3 y^{-1} estimated by Romankevich and Vetrov (2001) and 2932 km^3 y^{-1} used in this study.

What are the main sources of OM in the rivers? Riverine OM is generally derived from allochthonous sources (eroded soil and plant material) with a much smaller component from autochtonous sources (freshwater aquatic production) (Meybeck 1982; Ittekkot 1988; Lobbes et al. 2000). C/N ratios and stable carbon isotope ratios are useful in distinguishing between autochthonous and allochthonous sources, and studies in the Lena River indicate that POC is formed mainly from allochthonous detrital organic material (Lara et al. 1998; Rachold and Hubberten 1999; Lobbes et al. 2000), which is in general agreement with the small phytoplankton biomass in the Lena River (Sorokin and Sorokin 1996) and the relatively old average radiocarbon age of OM of the Laptev Sea bottom sediments (Kuptsov and Lisitzin 1996). Figure 2.2 shows the relationship between δ^{13}C values of POC and reciprocal POC concentrations in the water volume (POC [mg l^{-1}] = SPM [mg l^{-1}] · TOC [%] · 10^{-2}) of the Lena, Yana, and Khatanga basins. The linear correlations suggest two endmember mixing with the two hypothetical endmembers being detrital and autochthonous organic matter (Rachold and Hubberten 1999). In boreal forests like the Arctic taiga about 84% of the terrestrial carbon is stored in soils and 16% in living vegetation (Dixon et al. 1994). It can be expected that the thawing of permafrost due to global warming will elevate the amount of soil-derived terrigenous DOM discharged into the Arctic Ocean (Opsahl et al. 1999).

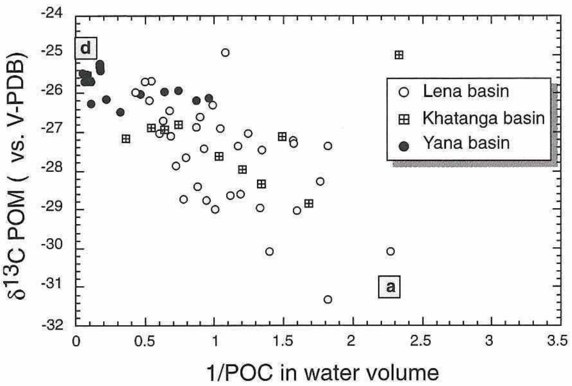

Fig. 2.2. δ^{13}C values of POC vs. 1/POC concentrations in the water volume (POC [mg l^{-1}] = SPM [mg l^{-1}] · TOC [%] · 10^{-2}) of the Lena, Yana, and Khatanga basins. The linear correlations suggest two-endmember mixing. Hypothetical detrital [d] and autochthonous [a] endmembers are presented (Rachold and Hubberten 1999)

It has to be noted that POC (and TOC) fluxes (Table. 2.1) refer to the suspended matter only and do not include the river bedload. The transport of bedload and the relationship between the amount of SM and bedload in the Arctic rivers is still poorly understood. Lopatin (1952) noted that field measurements of bedload by "device-catchers", especially in large rivers during freshet, did not provide adequate results for volume and regime of bedload transport. In agreement with observations in the Mackenzie River (Carson et al. 1998), in the first approximation it is assumed that in the plain rivers the bedload does not exceed 5–10% of the SM flux. Taking into account that the bedload consists mainly of sand with an organic carbon content of 0.5–1.0%, a rough evaluation of the bedload carbon input to the Arctic Ocean is $0.05\text{-}0.2\times10^6$ tC y^{-1} (average: 0.13×10^6 tC y^{-1}). This value is negligible compared with the total TOC flux.

There are very few data available on seasonal variations of DOC, POC and TOC concentrations and fluxes in Arctic rivers. A review of Roshydromet data on seasonal variation of TOC discharge into the Arctic Seas, which was published by Maltseva et al. (1987), indicates that 58 to 78% of the total TOC is discharged during freshet (Table 2.3) and that the portion of TOC transported to the Arctic seas during this period increases from west to east. Let us consider a more recent example of the seasonal variations in TOC concentrations and fluxes in the lower reaches of the Lena River (Fig. 2.3; data taken from Cauwet and Sidorov 1996). Minimum TOC concentrations are observed in winter (3.1–4.8 mgC l^{-1}) while maximum concentrations occur during freshet in June–July (9.6–

Table 2.3. TOC flux in different seasons, in % of annual volume (Maltseva et al. 1987)

Sea	Spring flood	Summer-autumn	Winter
White and Barents	58	34	8
Kara	63	26	11
Laptev	75	22	3
East Siberian	73	24	3
Chukchi	78	21	1

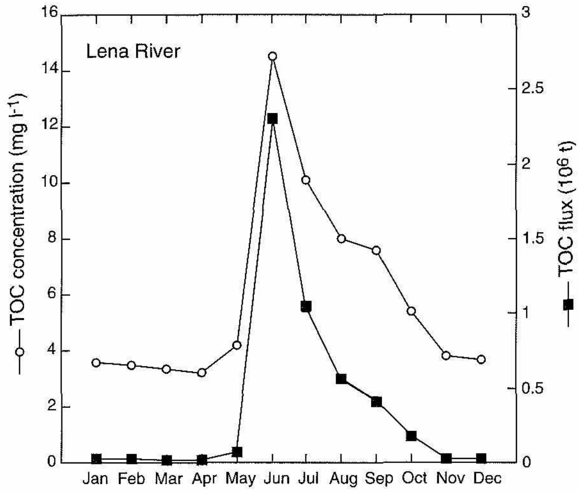

Fig. 2.3. Seasonal variations of TOC concentrations (data from Cauwet and Sidorov 1996) and TOC fluxes in the lower reaches of the Lena River. The TOC fluxes are based on the TOC concentrations given by Cauwet and Sidorov (1996) and the water discharge data for the period of 1980–1993 taken from the Regional, Electronic, Hydrographic Data Network For the Arctic Region (http://www.R-ArcticNET.sr.unh.edu/)

14.4 mgC l^{-1}). This pattern is even more pronounced for the TOC fluxes (TOC concentration multiplied by water discharge), which reveals that during winter the TOC flux of the Lena River is almost negligible (Fig. 2.3). Consequently, the average seasonal TOC concentrations and fluxes to the Laptev Sea (Table 2.4) show that freshet accounts for more than 50% of the annual TOC discharge of the Lena River while the total winter TOC export does not exceed 4% of the annual value. A similar pattern has recently been observed for the DOC transport of the Yenisei and Ob Rivers (Fig. 2.4; Köhler et al. 2003). The comparison with the Lena River (Fig. 2.3) clearly shows that the proportion of OM transported during freshet increases from west to east (Ob < Yenisei < Lena) as previously suggested by Matseva et al. 1987 (see above). Note that for the Lena TOC is shown whereas for the Ob and Yenisei DOC are displayed.

Groundwater discharge

The flux of dissolved OM with groundwater constitutes one of the pathways of terrigenous organics to the Arctic Ocean. A review of the chemical composition of groundwaters of the upper hypergenesis zone of various areas of the Earth has shown

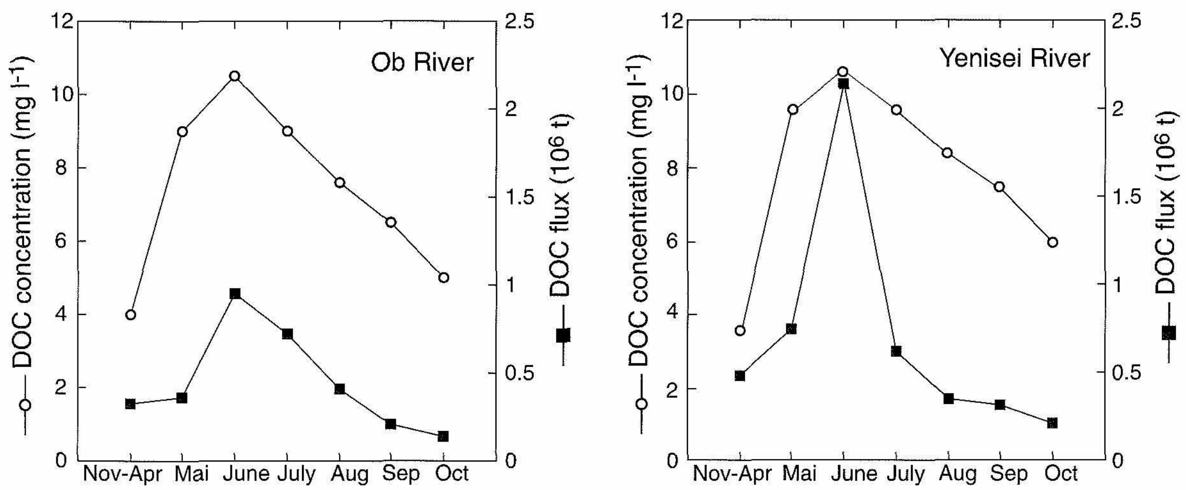

Fig. 2.4. Seasonal variations of DOC concentrations and fluxes of the Ob and Yenisei Rivers (data from Köhler et al. 2003)

Table 2.4. Average concentrations and fluxes of TOC to the Laptev Sea (Cauwet and Sidorov 1996). 1- flood; 2- summer and autumn; 3- winter; 4- average (sum for fluxes)

	Head of the delta				Mouth of the delta			
	1	2	3	4	1	2	3	4
Concentration, mgC l^{-1}	12.6	7.4	3.6	10.2	11.8	8.4	3.7	10.0
Flux, 10^3 tC yr^{-1}	3930	1300	130	5360	3680	1480	140	530

Table 2.5. River and groundwater discharges to the Arctic Seas (in $km^3\ y^{-1}$) according to Gordeev et al. (1999)

Sea basin River	River water discharge (RWD)	Groundwater discharge (GWD)	GWD/RWD %
Barents and White Sea			
Northern Dvina	110	27.8	25.3
Onega	15.9	3.5	22.0
Mezen	27.2	3.74	13.75
Pechora	131	5.0	38.5
Other area	179	26.8	15.0
Total	463	68	14.7
Kara Sea			
Ob	429	76	17.7
Pur	34.3	1.7	5.0
Taz	44.3	1.6	3.6
Yenisei	620	39	6.3
Other area	333	33	9.9
Total	1478	152	10.3
Laptev Sea			
Anabar	17.3	0.91	5.3
Olenyok	36	3.1	8.6
Lena	525	37	7.0
Yana	34	3.3	9.7
Other area	133	12.7	9.5
Total	745	57	7.65
East Siberian Sea			
Indigirka	61	4.6	7.5
Kolyma	132	8.5	6.4
Other area	57	4.4	7.7
Total	250	16.9	6.8
Total Eurasian Arctic			
(excluding Chukchi Sea)	2936	294	10.0

that the DOC concentration averages ca. 5.9 mg l^{-1} (Shvets 1973). From the available data on DOC in river waters of the Arctic for the period of winter low flow, Romankevich and Vetrov (2001) accepted a figure of 6.5 mgC l^{-1} as an average concentration.

Gordeev et al. (1999) sought a relationship between the river discharge and groundwater discharge and their associated transport of dissolved inorganic nutrients to the Arctic Seas. The groundwater discharge for each watershed was evaluated by taking the groundwater discharge module from the map (Kudelin 1975). The small area between the hydrological station located closest to the shore line and the shore line itself were not included due to the absence of data. The calculations show that the ratio between river and underground water discharge averages 10:1. For selected rivers and seas the following proportions of river vs. underground water discharges were quantified (in $km^3\ y^{-1}$) (Table 2.5): Sev. Dvina – 110:27.8, Pechora – 130:5, White and Barents seas – 463:68 (14%); Ob – 429:76, Yenisei – 620:39, Kara Sea – 1478:152 (10%); Lena – 525:37, Laptev Sea – 745:57 (7.6%), Indigirka – 61: 4.6, Kolyma – 132:8.5, East Siberian Sea – 250:16.9 (6.7%), all Eurasian Arctic (without Chukchi Sea) – 2936:294 (10%). The numbers in brackets correspond to the percentages of groundwater discharge relative to river discharge. During winter, river discharge is supported mainly by underground water input to the main river stream (Gordeev and Sidorov 1993). For this reason, DOC and nutrient concentrations in groundwaters were assumed to be equal to their concentrations in river water during very low runoff in winter (Gordeev et al. 1999). Based upon these assumptions the DOC underground flux to the Eurasian part of the Arctic Ocean is evaluated as 1.9×10^6 tC y^{-1}. Considering the proportion between the Eurasian and Canadian

Arctic ($12987:2513 \times 10^3$ km^2) the groundwater discharge from the Canadian Arctic amounts to ca. 48 km^3 yr^{-1} corresponding to a TOC flux of 0.37×10^6 tC y^{-1}. This very rough estimate yields a total Arctic groundwater DOC flux of about 2.3×10^6 tC y^{-1}. The POC flux from groundwater is assumed to be negligible.

2.3 Organic Carbon Input to the Arctic Seas Through Coastal Erosion

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2.3.1 Introduction

Shore dynamics directly reflecting complicated land-ocean interactions play an important role in the balance of sediments, organic carbon and nutrients in the Arctic basin. Nevertheless, the contribution of coastal erosion to the material budget of the Arctic Seas has often been underestimated. In recent years, however, several studies have underlined the importance of coastal erosion for the sediment budget of the Arctic Seas. Reimnitz et al. (1988a) made calculations for 344 km of Alaska coast in the Colville River area, finding that coastal erosion supplied 7 times more sediments to the Alaskan Beaufort Sea than did rivers. Are (1999) suggested that the amount of sediment supplied to the Laptev Sea by rivers and shores are at least of the same order of magnitude but that the coastal erosion input is probably much larger than the input of the rivers. This finding was supported by Rachold et al. (2000), who concluded that the sediment flux to the Laptev Sea through coastal erosion is two times larger than the river input. In the Canadian Beaufort Sea on the other hand, the Mackenzie River input is the dominant source of sediments and coastal erosion is much less important (Macdonald et al. 1998), which indicates that pronounced regional differences in the ratio between riverine and coastal erosion sediment input have to be considered.

Numerous studies addressing coastal erosion in various Arctic Seas have been published in the literature (Table 2.6). However, most of these papers deal only with coastal retreat rates and sediment input and publications considering the organic carbon flux are limited to Macdonald et al. (1998), Yunker et al. (1991, 1993) for the Canadian Beaufort Sea; Stein and Fahl (2000) for the Laptev Sea; Semiletov (1999a, 1999b, 2000) for the Laptev, East Siberian and Chukchi Seas; and Lisitzin (1990), Ronov (1993) in general. Recently a review of the organic carbon fluxes to the Russian Arctic Seas has been presented in Romankevich and Vetrov (2001).

In the following we present a quantitative assessment of the organic carbon input to the Arctic Seas through coastal erosion. It must be cautioned that these are the best available estimates of the contribution of coastal erosion to sediment and organic carbon input and may contain considerable error. The evaluation is based upon a combination of data for coastal erosion sediment input and organic carbon concentrations of the coastal sections. Emphasis will be laid on the Laptev Sea and East Siberian Seas, where our own field studies have been performed from 1998 to 2000 (Rachold 1999, 2000; Grigoriev and Kunitsky, 2000; Rachold and Grigoriev 2001). Based on published information listed above, quantification will be extended to cover all Arctic Seas.

Table 2.6. Published information on coastal erosion

Region	References
Canadian Beaufort Sea	Mackay (1963), Harper et al. (1985), Harper (1990), Hill et al. (1986, 1991), Dallimore et al. (1996), Macdonald et al. (1998), Wolfe et al. (1998)
Alaskan Beaufort Sea	Hume et al. (1972), Reimnitz and Barnes (1982), Naidu et al. (1984), Reimnitz et al. (1988a)
White Sea and Barents Sea	Zenkovich (1962), Suzdal'sky (1974), Medvedev (1972), Velikotsky (1998)
Kara Sea	Popov et al. (1988), Vasiliev (1995), Sovershaev (1996), Koreisha et al. (1997)
Laptev Sea	Toll (1897), Gakkel (1957, 1958), Grigoriev (1966), Kluyev (1970), Are (1980, 1985, 1987, 1999), Grigoriev (1993, 1996), Grigoriev and Kunitsky (2000), Rachold et al. (2000, 2002)
East Siberian Sea	Pavlidis et al. (1988), Grigoriev and Kunitsky (2000), Razumov (2000)
Chukchi Sea	Shuisky and Ogorodnikov (1981), Shuisky (1983, 1986), Pavlidis et al. (1988)
Russian Arctic (in general)	Zenkovich (1962), Kaplin et al. (1971), Arkhikov et al. (1982), Budyko and Izrael (1987), Lisitzin (1990), Kaplin and Selivanov (1999), Lopatin (1999)