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)

It should be noted that our assessment is based on total organic carbon (TOC) concentrations of the bulk, ice-rich, coastal permafrost sediments and does not distinguish between dissolved and particulate organic carbon species. Furthermore, we presently have no information about the fate of the organic matter derived from coastal erosion once it enters the shelf, i. e. whether the organic carbon will be transported in particulate form or whether it will be partly transferred into dissolved species. Therefore, it is possible to provide information only on the TOC fluxes, which correspond to the gross coastal organic carbon input, i. e. the amount of organic carbon entering the sea as a consequence of coastal erosion.

2.3.2
Data sources and methods

Generally, the methodology to quantify TOC input through coastal erosions involves the following steps:

1. The quantification of coastal retreat rates of representative key sections, which can be done by long term field measurements, the comparison of different-time topographic maps, satellite images and aerial photographs or a combination of both. A detailed description of this method is given in Rachold et al. (2000).
2. The determination of the coastal morphology (mainly cliff height and slope) to quantify the volume of material supplied ($m^3\ y^{-1}$) based on linear coastal retreat rates ($m\ y^{-1}$).
3. The analysis of the composition of the coastal sediments, which includes the determination of ice content and specific density of the sediments. These data are essential to quantify the sediment mass input through coastal erosion.
4. The determination of the TOC concentration of the coastal sediments at the key sites to estimate the TOC flux.
5. Finally, the data obtained for key sections must be extrapolated to the entire coastline. This can be done by segmenting the coast into homogeneous segments depending on the locations of substantial changes in sediment texture, ice content, or TOC concentration.

Laptev and East Siberian Sea

Recently, several key sections of the Laptev Sea coast have been evaluated in detail for coastal retreat rates and composition of the coastal sediments during the Russian-German expeditions within the Laptev Sea 2000 project from 1998 to 2000 (Rachold 1999, 2000; Rachold and Grigoriev 2001). Using methodology described above, the coast was divided into segments and the parameters needed to quantify the sediment input through coastal erosion were assigned to each segment as was average TOC concentration for the coastal sediments.

The Laptev Sea coastline is characterized by the frequent occurrence of ice-rich deposits with about 30 % of the coast consisting of the Ice Complex with an ice content of up to 80 %. Our studies clearly show that erosion of the Ice Complex is of major importance for the sediment budget of the Laptev Sea, contributing about 76 % of the coastal sediment flux. A similar situation can be observed in the East Siberian Sea. At many coastal sections the Ice Complex is intensively eroded because wave-cut notches are formed along the bases during storms, which subsequently results in block disintegration of the coast. The still-frozen blocks are washed away by seawater and the dominant erosion rates are in the range of 2–6 $m\ y^{-1}$. Due to thermal denudation of the upper and middle parts of the ice-rich cliffs, coastal retreat rates can remain high even during temporary attenuation of the cliff foot abrasion. We estimate the average retreat rate of coastlines consisting of Ice Complex and Lake-Thermokarst deposits to be 2.5 $m\ y^{-1}$.

Table 2.7 shows average TOC concentrations of thermokarst sediment and the Ice Complex of the Laptev Sea region, which were determined by CNS-elemental analyzer after removal of carbonate carbon. As seen from the table, the TOC values are highly variable ranging from <1 to >30 % and we will use 4 % as an average TOC content for the Ice Complex and thermokarst sediments of the Laptev Sea coast in the following. Other types of coasts must be considered such as ice-poor coasts formed from Pleistocene-Holocene sediments and rocky or other non-icy coasts. The ice-poor and non-icy coasts are characterized by significantly lower TOC concentrations averaging 1 % and 0.3 %, respectively.

Table 2.8 summarizes the characteristics of the main types of coasts in the Laptev Sea region.

Based on the length of each coastal type and the parameters given in the table, we quantify the TOC flux to the Laptev Sea through coastal erosion as 1.8×10^6 $tC\ y^{-1}$. The major portion enters the eastern Laptev Sea (0.9×10^6 $tC\ y^{-1}$), whereas the TOC flux to the central and western Laptev Sea amount to 0.56×10^6 $tC\ y^{-1}$ and 0.34×10^6 $tC\ yr^{-1}$, respectively.

Based on the studies of Grigoriev and Kunitsky (2000) and Razumov (2000), we are able to extend these calculations to the East Siberian Sea (Table 2.9) where ca. 2.2×10^6 $tC\ y^{-1}$ are exported to the shelf by coastal erosion.

Table 2.7. TOC concentrations of coastal sediments of the Laptev Sea region (in %)

Location	TOC max	TOC min	TOC stn. dev.	TOC avg.
Big Lyakhovsky Island				
Ice Complex (right section)	17.5	0.9	3.3	3.2
Ice Complex (left section)	38.2	3.1	8.4	11.9
Alas deposits (right section)	3.1	1.2	0.5	2.0
Alas deposits (left section)	7.1	1.5	2.1	3.8
Bykovsky Peninsula				
Alas deposits	16.5	0.8	4.3	6.3
Ice Complex	21.5	1.3	3.4	4.1
Olenyok Channel (Lena Delta), Nagym Section				
Ice Complex	21.5	0.2	6.4	4.3
Olenyok Channel (Lena Delta), Buor-Khaya Section				
Ice Complex	21.6	1.1	6.8	9.2
Average ice-rich coast				4.0

Table 2.8. Coastal types of the Laptev Sea and their characteristics in regard to TOC flux associated with coastal erosion

	Ice Complex and thermokarst deposits	Ice-poor Pleistocene-Holocene coasts	Rocky and other types of non-icy coasts
Total length of the coast (km)	2400	1600	3200
Average retreat rate (m y^{-1})	2.5	1	0.0001–0.1 (avg. 0.05)
Average ice content (%)	50	10–30 (avg. 20)	0–4 (avg. 2)
Average cliff height (m)	10	5	10–30 (avg. 20)
Average TOC concentration (%)	4	1	0–1 (avg. 0.3)
Coastal sediment flux (10^6 t y^{-1})	44.4	9.5	4.5
Coastal TOC flux (10^6 t y^{-1})	1.78	0.1	0.015

Table 2.9. Coastal types of the East Siberian Sea and their characteristics in regard of TOC flux associated with coastal erosion

	Ice Complex and thermokarst deposits	Ice-poor Pleistocene-Holocene coasts	Rocky and other types of non-icy coasts
Total length of the coast (km)	2400	1600	1900
Average retreat rate (m y^{-1})	3	1	0.0001–0.1 (avg. 0.05)
Average ice content (%)	50	10–30 (avg. 20)	0–4 (avg. 2)
Average cliff height (m)	10	5	10–30 (avg. 20)
Average TOC concentration (%)	4	1	0–1 (avg. 0.3)
Coastal sediment flux (10^6 t y^{-1})	52.5	10.9	3.1
Coastal TOC flux (10^6 t y^{-1})	2.1	0.1	0.01

White, Barents, Kara and Chukchi Seas

Unfortunately, the other Russian Arctic Seas are have not been studied in such detail. Publications on coastal retreat erosion, where they exist, do not follow the methodology given above. The best estimates are summarized by Romankevich and Vetrov (2001), who used all available sources to evaluate the TOC flux. Although some of their estimates, especially those of the White, Barents and Kara Seas, seem too high, in the following we will use their TOC input estimates because more accurate data are not available at present.

Note that the Chukchi Sea data given by Romankevich and Vetrov (2001), which are in fact taken from Lisitzin (1990), refer to the Asian Sector only. To roughly quantify the sediment and TOC flux to the entire Chukchi Sea we multiply their value by a factor of 2.

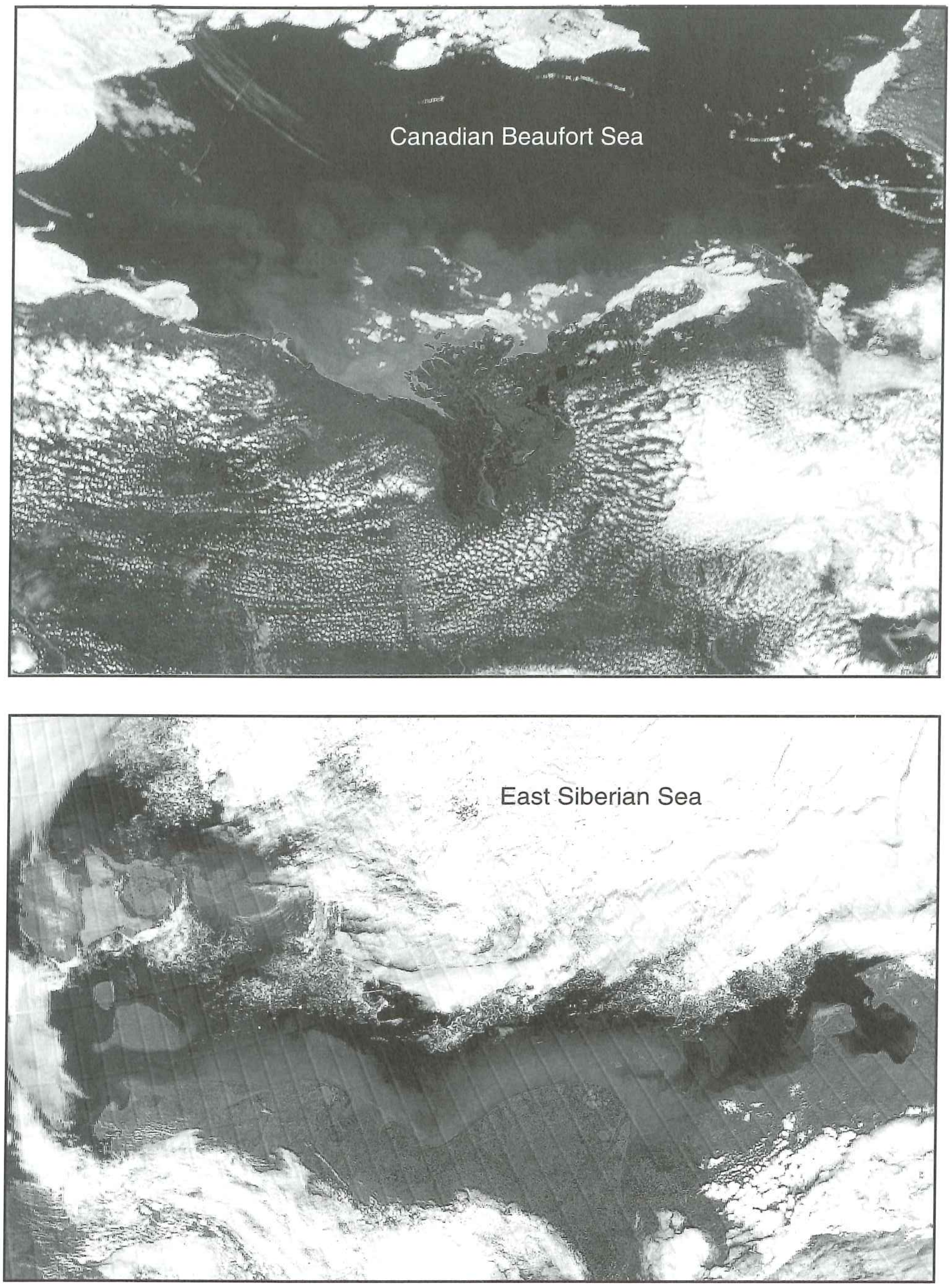

Fig. 2.5. Satellite images of the East Siberian and Beaufort Sea showing the distribution of suspended sediments. The strong river plume of the Mackenzie River is clearly seen in the Beaufort Sea, whereas in the East Siberian Sea very high turbidities are observed along the coastline. Images are taken from http://www.visibleearth.nasa.gov

Beaufort Sea

As discussed in Rachold et al. (2000) the best estimate of the coastal erosion sediment input to the Canadian Beaufort Sea (5.6×10^6 t y^{-1}) was published by Hill et al. (1991). Based on this value and on an average TOC concentration of the coastal sediments of up to 5% Macdonald et al. (1998) estimate a maximum coastal TOC input into the Canadian Beaufort Sea of 0.3×10^6 tC y^{-1}. In their further calculations Macdonald et al. (1998) accept an average of 0.06×10^6 tC y^{-1} for the coastal TOC input, which will be applied in our calculations.

The coastal sediment flux into the Alaskan Beaufort was quantified by Reimnitz et al. (1988 a) as 2.3×10^{6} t y^{-1}. Organic carbon concentrations of shallow marine Alaskan shelf sediments have been published by Naidu et al. (1985). In general, the concentrations are low (less than 1–1.4 %). Based on these data we will use a maximum TOC input of 0.03×10^{6} tC y^{-1} for the Alaskan Beaufort Sea.

2.3.3
Coastal organic carbon input

In total 431×10^{6} t yr^{-1} of sediment and 6.7×10^{6} tC y^{-1} enter the Arctic Ocean (Table 2.10). Approximately 60 % of the total TOC flux originates in the Laptev and East Siberian Seas. The predominant sources are Ice Complex deposits, which are widespread in Northeast Siberia. The highest coastal TOC flux is observed in the East Siberian Sea, even though the Laptev Sea coastline is considerably longer. This is due to the dominance of the Ice Complex along the coastline of the East Siberian Sea. Satellite images of the East Siberian and the Beaufort Sea (Fig. 2.5) clearly show the major sources of sediment: the strong river plume of the Mackenzie River is visible in the Beaufort Sea, whereas in the East Siberian Sea high turbidities, which are related to coastal sediment input, are observed along the coastline.

Semiletov (1999a, 1999b) stated that in the Russian Arctic marginal seas, the transport of organics (in the form of particulate matter) induced by coastal erosion has a value similar to that of the DOC transport of the rivers. Semiletov´s evaluation shows an annual flux of particulate organic carbon along the Yakutian coast (from eastern Taymyr to Chukotka) of $3.5–7.0 \times 10^{6}$ tC y^{-1} (Semiletov, 1999 b, 2000). Based on our estimation given in Table 2.10, the sum of the TOC input of the Laptev Sea, East Siberian Sea and the Asian sector of the Chukchi Seas is quantified as 4.4×10^{6} tC y^{-1}, which is in general agreement with Semiletov´s data and underscores the importance of coastal TOC input in the Siberian Arctic.

Table 2.10. Sediment and TOC flux to the Arctic Ocean through coastal erosion. [1]Romankevich and Vetrov (2001), [2]this study, [3]refers to the entire Chukchi Sea (twice the value of Romankovich and Vetrov (2001) given for the Asian sector of the Chukchi Sea only; [4]sum of Canadian Beaufort Sea (according to Macdonald et al. 1988) and Alaskan Beaufort Sea (based on Reimnitz et al. 1988a and Naidu et al. 1985)

	Sediment flux (10^{6} t y^{-1})	TOC flux (10^{6} t y^{-1})
White Sea[1]	60	0.3
Barents Sea[1]	59	0.5
Kara Sea[1]	109	1
Laptev Sea[2]	58.4	1.8
East Siberian Sea[2]	66.5	2.2
Chukchi Sea[3]	70	0.8
Beaufort Sea[4]	7.9	0.09
Total	430.8	6.69

2.4
The Role of Arctic Sea Ice in Transporting and Cycling Terrigenous Organic Matter

H. Eicken

2.4.1
Introduction

The role of sea ice in the Arctic Ocean's budget of terrigenous organic carbon (tOC) is presently not well understood. While it is obviously not a source of tOC as such, the ice cover can potentially be of great importance in providing the fastest, most effective means for basin-wide transport as well as export of tOC from the Arctic into the European Nordic (in particular Greenland and Barents) Seas. In contrast with other ocean basins, Arctic surface waters exhibit unusually high concentrations of terrigenous dissolved organic carbon (tDOC), such that the basin-scale transport of tOC is dominated by the dispersal of riverine tDOC (Opsahl et al. 1999; Lobbes et al. 2000). Whereas sea ice may have slightly elevated levels of tDOC (Thomas et al. 1995; Opsahl et al. 1999), and has been attributed with a significant fraction of the flux of tDOC out of the Arctic Basin through Fram Strait, it is of much greater importance for the transport of particulate organic matter.

Evidence has accumulated over the past two decades demonstrating that entrainment of sediments into sea ice (at particulate concentrations of tens to hundreds of mg l^{-1}) is a common phenomenon in the Arctic and particularly widespread over the broad, shallow Eurasian shelves (e.g., Reimnitz et al. 1994; Pfirman et al. 1997; Eicken et al. 2000). Terrigenous particulate organic matter (tPOM) deposited on the shelves may thus potentially be removed and transported over large distances with sea ice moving with the Transpolar Drift away from the Siberian Arctic across the Pole and into the Greenland Sea (Pfirman et al. 1997). Given that the flux of tPOM into the central Arctic and the Nordic Seas is greatly limited due to the inefficiency of transport in the water column and the bathymetric isolation of the central basins from shelf-slope transport, sea ice input could thus even come to