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# The degradation of coastal permafrost and the organic carbon balance of the Laptev and East Siberian Seas

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ABSTRACT: Coastal erosion plays an important role in the sediment and organic carbon balance of the Arctic Ocean. Based on new data, the present paper evaluates coastal dynamics of the Laptev and East Siberian Seas. These coasts consist of many different types of sediments including ice-rich deposits, which are characterised by extremely high ice-content, rapid coastal retreat and high concentrations of organic matter. For the studied area the volume of eroded coastal sediment exceeds the river sediment discharge. Based on the estimates of coastal sediment input and on average organic carbon concentrations of the coastal sections, the total organic carbon (TOC) supplied to the Laptev and East Siberian Seas by coastal erosion can be quantified as ca. $4 \times 10^6$ t/yr. Other European, Asian and American Arctic Seas are characterised by considerably lower coastal organic carbon input.

## 1 INTRODUCTION

Shore dynamics directly reflecting the 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. (1988) made calculations for 344 km of Alaska coast in the Colville River area and found that coastal erosion here supplied 7 times more sediments to the Alaskan Beaufort Sea than rivers. Are (1999) suggested that the amount of sediment supplied to the Laptev Sea by rivers and shores is at least of the same order but that the coastal erosion input is probably much more significant than the fluvial input. This finding was supported by Rachold et al. (2000), who concluded that the sediment flux to the Laptev Sea through coastal erosion is twice as large as the input from rivers. 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). This indicates that pronounced regional differences in the ratio between fluvial and coastal erosion sediment input must be taken into account.

The transformations of coastal, onshore and offshore permafrost in the Arctic are very fast and widespread natural processes. Thermal abrasion is the most significant destructive phenomenon in coastal retreat in this region. Among others, the Laptev and East-Siberian Seas are of the greatest interest. Due to the erosion of their coasts a large volume of sediment and carbon organic is supplied to these seas (Fig. 1).

The Laptev and East Siberian coasts consist mainly of different types of Quaternary sediments, including ice-rich deposits, which are characterised by extremely high ice contents, fine-grained particles, rapid coastal retreat (1–7 m/yr) and high concentrations of organic matter (Fig. 2). In a number of coastal sections the thermal abrasion cliffs reach 40–50 m altitude and are predominately composed of polygonal ice wedges from the cliff foot to top (so called Ice Complex).

The organic carbon, which originates from eroded coastal permafrost deposits, could be an important agent for increasing the greenhouse gas flux of the atmosphere.

Numerous publications dealing with coastal erosion of the Laptev and East-Siberian coast are available in the literature:

- Laptev Sea: Toll (1897), Gakkel (1957; 1958), Grigoriev (1966), Kluyev (1970), Are (1980; 1985; 1987; 1999), Grigoriev (1993; 1996), Grigoriev & Kunitsky (2000), Rachold et al. (2000, in press).
- East Siberian Sea: Are (1980), Pavlidis et al. (1988), Grigoriev & Kunitsky (2000), Razumov (2000).
- Russian Arctic (in general): Zenkovich (1962), Kaplin et al. (1971), Archikov et al. (1982), Budyko & Izrael (1987), Lisitzin (1990), Kaplin & Selivanov (1999), Lopatin (1999).

Most of these papers however, deal with coastal retreat rates and sediment input only. Publications considering the organic carbon flux are very limited (Stein & Fahl 2000, Semiletov 1999a; 1999b; 2000, Lisitzin 1990, Ronov 1993). Recently, a comprehensive review

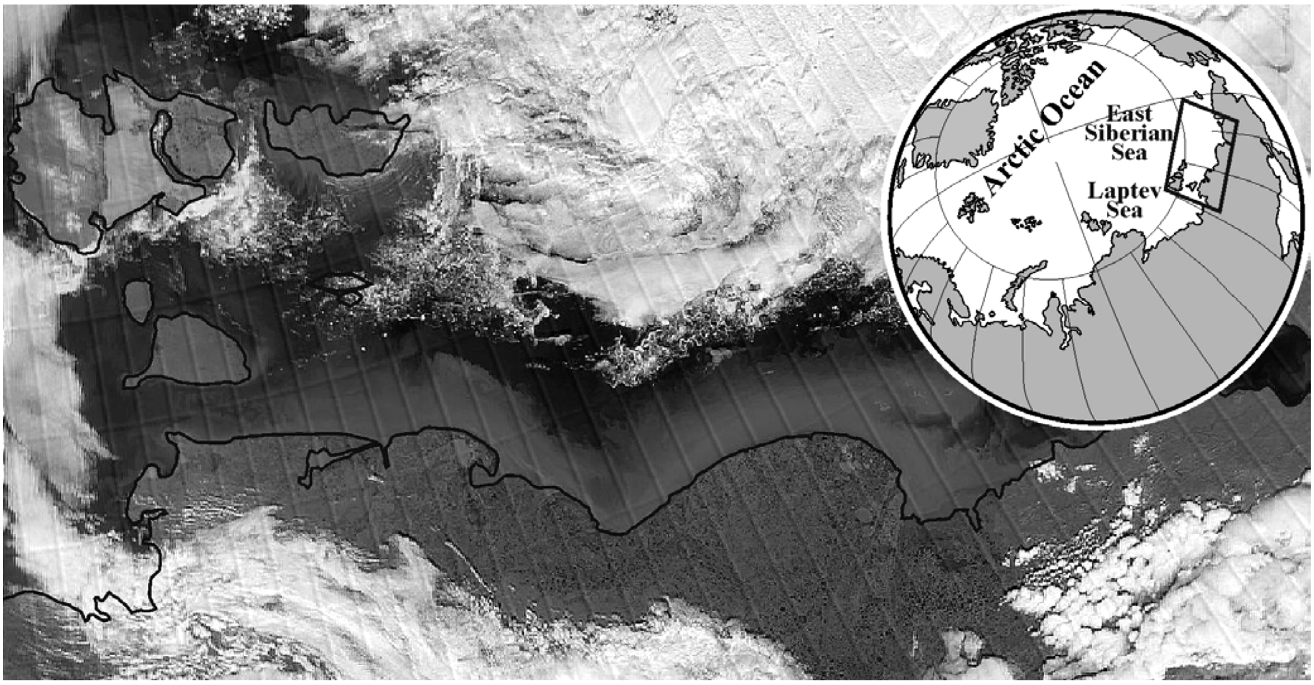


Figure 1. Suspended sediment flux along the coastal zone of the East Siberian Sea as a result of coastal erosion. Satellite image is taken from http//www.visibleearth.nasa.gov.

Figure 2. Thermal abrasion cliff on the northern cape of Muostakh Island in the Buor-Khaya Bay, Laptev Sea. Retreat rates of the cliff at this coastal are 5–13 m/yr.

of the organic carbon fluxes to the Russian Arctic Seas has been presented in Romankevich & Vetrov (2001).

This paper presents a quantitative assessment of the organic carbon input to the Laptev and East Siberian Sea through coastal erosion and utilises this data to compare rates of input with other Arctic Seas. The evaluation is based upon a combination of data on coastal erosion sediment input and organic carbon concentrations of the coastal sections. The focus is on the Laptev Sea and East Siberian Seas, where field studies were performed from 1985 to 2000 (Rachold 1999; 2000, Grigoriev & Kunitsky 2000, Rachold & Grigoriev 2001). Based on the review of existing publications (see above) the quantification will be extended to cover all Arctic Seas. It should be noted that our assessment is based on TOC concentrations of the coastal sediments. Therefore, at present, it is only possible to provide information on the TOC fluxes. Particulate and dissolved organic carbon species cannot be distinguished. Moreover, the reported TOC fluxes correspond to the gross coastal organic carbon input, the amount of organic carbon entering the sea as a consequence of coastal erosion. Subsea erosion and the fate of the organic matter on the shelf will not be evaluated here.

## 2 METHODS AND DATA SOURCES

The methodology used to quantify TOC input through coastal erosion generally involves the following steps:

1. The quantification of coastal retreat rates of representative key sections. This is achieved by long term field measurements, the comparison of topographic maps, satellite images and aerial photographs over a given time period. A detailed description of this method is given in Rachold et al. (2000).
2. The determination of coastal morphology (mainly cliff height and slope) to quantify the volume of material input based on coastal retreat rates.
3. The analysis of the coastal sediments composition, which includes the determination of ice content and the specific density of the sediments. This data is essential to quantify the sediment 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 applied to the entire coastline. This can be achieved by a segmentation of the coast. The basis for dividing the coast into homogeneous segments depends on whether there are substantial changes in sediment texture, ice content, or TOC concentration.

During the last several years 25 key sections of the Laptev Sea coast have been studied to determine coastal retreat rates and the composition of the coastal sediments. These Russian-German expeditions were a component in the framework of the project Laptev Sea 2000 (Rachold 1999; 2000; Rachold & Grigoriev 2001). According to the 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. Additionally, to estimate the TOC flux it is essential to define average TOC concentrations for the coastal sediments.

The Laptev Sea coastline is characterised by the frequent occurrence of ice-rich deposits. Approximately 30% of the coast consists of an ice complex with an ice content of up to 85%. Our studies clearly show that the erosion of the ice complex is of major importance for the sediment budget of the Laptev Sea, accounting for 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 during storms along the cliff base. This results in block failure along ice-wedge polygon intersections of the coast. The blocks that remain frozen are washed away by seawater and the dominant cliff erosion rates are in the range of 1–7 m/yr. Due to thermal denudation of the middle and upper parts of the ice-rich cliffs, the input of sediments into the sea can remain quite high even during temporary attenuation of erosion at the cliff base. According to our estimations, in the Laptev Sea the average retreat rate of coastlines consisting of ice complex and lake-thermokarst deposits is 2.5 m/yr.

Average TOC concentrations of lake-thermokarst sediment and the ice complex of the Laptev Sea region were determined by CNS-elemental analysis after removal of carbonates. The TOC concentrations are highly variable, ranging from $<1$ to $>30\%$, with an average value of 4%. Other types of coasts that must be considered, are ice-poor coasts formed from Quaternary sediments and rocky or other types of ice-free coasts. The ice-poor and ice-free coasts are characterised by significantly lower TOC concentrations averaging 1% and 0.3%, respectively.

Table 1 summarises the characteristics of the main types of coasts in the Laptev Sea region. Based on the length of each coastal type, which was determined on the basis of topographical maps (scale 1:100 000 and 1:200 000) and the parameters given in the table, we are able to quantify the sediment and TOC flux to the Laptev Sea through coastal erosion. It should be noted however that the flux data given in Table 1 is based on several parameters, each of which contains a considerable error. Due to the multitude of possible sources of error, these errors cannot be fully quantified, but total error is assumed to account for ca. 30%. The coastal erosion TOC flux therefore amounts to $1.9 \pm 0.6 \times 10^6$ tC/yr. The major portion enters the eastern Laptev Sea ($1 \times 10^6$ tC/yr), whereas the TOC flux to the central and western Laptev Sea amount to $0.56 \times 10^6$ tC/yr and $0.34 \times 10^6$ tC/yr, respectively.

The studies of Grigoriev & Kunitsky (2000), and Razumov (2000) indicate that the parameters described for the Laptev Sea coasts can be applied to the East Siberian Sea as well. In the East Siberian Sea however, the retreat rates of coastal sections consisting of ice complex and lake-thermokarst deposits are slightly higher than in the Laptev Sea, averaging 3 m/yr. Based on these observations we are able to perform the same calculations for the East Siberian Sea. Table 2 summarises the results, which show that

Table 1. Coastal type of the Laptev Sea and their characteristics in regard of TOC flux associated with coastal erosion. See text for explanation.

| | Ice complex and thermokarst deposits | Ice-poor Pleistocene–Holocene coasts | Rocky and other types of of non-icy coasts |
|---|---|---|---|
| Total length of the coast (km) | 2400 | 1600 | 3200 |
| Number of studied key sections | 10 | 14 | 1 |
| Average retreat rate (m/yr) | 2.5 | 1 | 0.05 |
| Average ice content (%) | 50 | 20 | 2 |
| Average cliff height (m) | 10 | 5 | 20 |
| Average TOC concentration (%) | 4 | 1 | 0.3 |
| Coastal sediment flux ($10^6$ t/yr) | 44.4 | 9.5 | 4.5 |
| Coastal TOC flux ($10^6$ t/yr) | 1.78 | 0.1 | 0.015 |

Table 2. 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/yr) | 3 | 1 | 0.05 |
| Coastal sediment flux ($10^6$ t/yr) | 52.5 | 10.9 | 3.1 |
| Coastal TOC flux ($10^6$ t/yr) | 2.1 | 0.1 | 0.01 |

$2.2 \pm 0.7 \times 10^6$ tC/yr are imported to the East Siberian Sea by coastal erosion.

Unfortunately, the other Russian Arctic Seas (White, Barents, Kara and Chukchi Seas) have not been studied in such detail. Some publications on coastal erosion exist but do not follow the methodology given above. The best estimates are summarised in Romankevich & Vetrov (2001), who used all available sources, including data published by the current authors for the Laptev Sea, to evaluate the TOC flux. Although some of their estimates, especially those of the White, Barents and Kara Seas, appear too high, we will utilise the TOC input in the absence of more accurate data.

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

As discussed in Rachold et al. (2000) the best estimate of the coastal erosion sediment input to the Canadian Beaufort Sea ($5.6 \times 10^6$ t/yr) 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 $0.3 \times 10^6$ tC/yr. In further calculations Macdonald et al. (1998) accept an average of $0.06 \times 10^6$ tC/yr for the coastal TOC input, which will be applied to the current calculations.

The coastal sediment flux into the Alaskan Beaufort Sea was quantified by Reimnitz et al. (1988) as $2.3 \times 10^6$ t/yr. Organic carbon concentrations of shallow marine Alaskan shelf sediments have been published by Naidu (1985). In general, the concentrations are low (less than 1–1.4%). Based on this data a maximum TOC input of $0.03 \times 10^6$ tC/yr for the Alaskan Beaufort Sea will be assumed.

## 3 RESULTS

Table 3 summarizes the estimates of the sediment and TOC flux to the Arctic Ocean through coastal erosion. In total, ca. $430 \times 10^6$ t of sediment per year and $6.7 \times 10^6$ tC/yr enters the Arctic Ocean. 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, although 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. The satellite image of the East Siberian Sea (Fig. 1) clearly shows the major sources of sediment. High turbidities, which are related to coastal sediment input, are observed along the coastline.

Table 3. Sediment and TOC flux to the Arctic Ocean through coastal erosion.

| | Sediment flux ($10^6\,t\,yr^{-1}$) | TOC flux ($10^6\,t\,yr^{-1}$) |
|---|---|---|
| White Sea[1] | 60 | 0.3 |
| Barents Sea[1] | 59 | 0.5 |
| Kara Sea[1] | 109 | 1 |
| Laptev Sea[2] | 58.4 | 1.9 |
| East Siberian Sea[2] | 66.5 | 2.2 |
| Chukchi Sea[3] | 70 | 0.8 |
| Beaufort Sea[4] | 7.9 | 0.09 |
| Total | 430.8 | 6.79 |

[1] Romankevich & Vetrov (2001), [2] this study, [3] refers to the entire Chukchi Sea (twice the value of Romankovich & Vetrov (2001) given for the Asian sector of the Chukchi Sea only; [4] sum of Canadian Beaufort Sea (according to Macdonald et al. 1998) and Alaskan Beaufort Sea (based on Reimnitz et al. 1988 and Naidu 1985).

Semiletov (1999a; 1999b) stated that in the marginal seas of the Russian Arctic 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/yr (Semiletov 1999b; 2000). Based on our estimation given in Table 2.8, the sum of the TOC input of the Laptev Sea, East Siberian Sea and the Asian sector of the Chukchi Seas is quantified as $4.4 \times 10^6$ tC/yr. This is in general agreement with Semiletov's data and

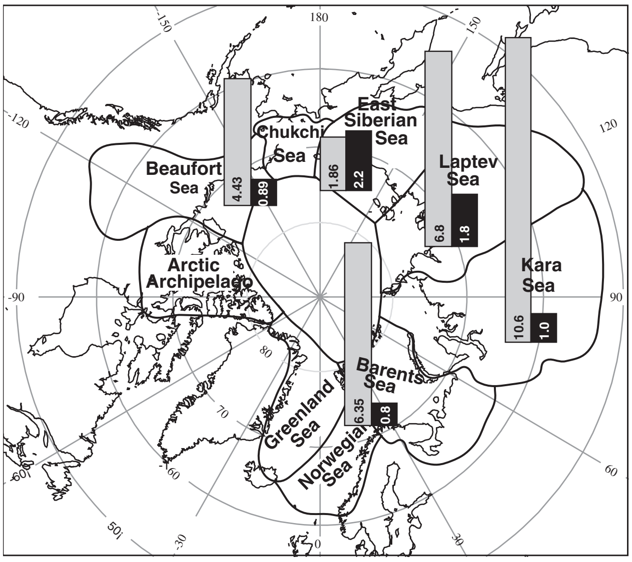


Figure 3. Riverine and coastal TOC fluxes to the Arctic Ocean ($10^6$ t/yr). Grey bars refer to river input and black bars to coastal erosion. Note that the sum is shown for Beaufort and Chukchi Sea and that Barents Sea input data include White Sea.

underpins the importance of coastal TOC input in the Siberian Arctic.

## 4 CONCLUSIONS

Figure 3 illustrates the distribution of river and coastal TOC fluxes in the individual Arctic Seas. River data is from Gordeev & Rachold (in press). Despite the overall dominance of the river discharge, in some regions coastal erosion TOC input is comparable to the river TOC flux. In contrast to all other Arctic Seas, the East Siberian Sea supplies more TOC from coastal erosion than from rivers. This is due to the absence of large rivers, and the dominance of ice complex deposits along the coastline. Ice complex deposits are characterised by high TOC concentrations and rapid erosion rates mainly due to their high ice content. In the Laptev Sea, where ice complex deposits are also widespread, the coastal erosion TOC input is comparable to that of the East Siberian Sea. The strong inflow of the Lena River however, produces a considerably larger TOC flux.

The most interesting conclusion which can be drawn from the calculations concerns the sediment budget of the Arctic Ocean. The total coastal erosion sediment input of ca. $430 \times 10^6$ t/yr (Fig. 3, see Table 3) is almost twice as high as the total riverine suspended matter discharge of ca. $230 \times 10^6$ t/yr (Gordeev & Rachold, in press). It must be noted that the coastal erosion data are best estimates and do, with the exception of the well studied Laptev and East Siberian Seas, include a considerable error. Nevertheless, this finding indicates that coastal erosion is one of the main processes which controls sediment delivery to the Arctic Ocean.

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