THE CONTRIBUTION OF SHORE THERMOABRASION TO THE LAPTEV SEA SEDIMENT BALANCE

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Abstract

A schematic map of Laptev Sea shore dynamics is compiled for the first time, using available published data. It shows the distribution of thermoabrasion shores, mean long-term shore retreat rates, and areas of seabed erosion and accretion. The amount of sediment released to the sea from the 85 km Anabar-Olenyok section of the coast is calculated, as an example, at 3.4 Mt/year. These results are compared with published data on sediment transport of rivers running into the Laptev Sea. Estimates of the Lena River discharge range from 12 to 21 Mt/year, of which only 2.1 to 3.5 Mt may reach the sea. The analysis shows that the input of thermoabrasion at mean shoreline retreat rates of 0.7 to 0.9 m/year is at least of the same order as the river input and may greatly exceed it.

Introduction

Thousands of kilometres of Arctic sea coast retreat at rates 2-6 m/year under the action of thermoabrasion\(^1\) (Are, 1985; Barnes et al., 1991). Tens of square kilometres of Arctic land therefore are consumed by the sea every year. This is a special kind of marine transgression occurring with a constant sea level. Obviously this process has to be taken into account by various economic activities on the coast. It also plays an important role in the evolution of the Arctic environment. Sea level has risen during the past century and is expected to continue rising, reaching most probably 50 cm above the present level by the year 2100 (Climate change..., 1996). Therefore the rate of shore thermoabrasion may accelerate considerably.

The thermoabrasion of shores is considered by permafrost scientists as a separate cryogenic process, but it is an important part of a complicated land-ocean interaction. In particular thermoabrasion is a source of sediment for the sea derived from the land. Therefore it affects the sediment balance of Arctic seas. But the importance of this agent has not been determined reliably until now. The sediment discharge of rivers has long been considered in Russia as the main terrestrial input to the marine sediment balance. More recently, very rough comparisons showed that river and shore input may be of the same order of magnitude (Suzdalsky, 1974; Shuisky 1983). At present it is possible to determine the input from shore thermoabrasion offshore more accurately.

Maps of shore dynamics are needed to solve this problem and others related to climate change impacts. Such maps have been compiled for about 650 km of Alaska northern shores (Reimnitz et al., 1988; Barnes et al., 1991). Mean annual amount of sediments supplied into the sea due to shore thermoabrasion have been calculated and presented. Similar maps may be drawn up for the Arctic shores of Russia. A schematic map of the Laptev Sea shore dynamics is compiled here as a first approach (Figure 1).

Compiling the Laptev Sea shore dynamics map

Very little reliable data are published on Laptev Sea shore retreat rates. Most measurements are from short sections of the coast. Schematic maps of shore dynamics are compiled for Khantaga Bay, for a part of Anabar-Olenyok coast and for Vankina Guba Bay (Zigarev and Sovershaev, 1984; Are, 1985; Novikov, 1984; Grigoryev, 1996; Medkova, 1994). Satisfactory information on the lithology of coastal sediments is derived from geological maps at 1:1,000,000 and larger scales. The Permafrost-landscape map of Yakutia ASSR of 1:2,500,000 scale (1991) gives only a rough idea of the ice content of coastal sediment. The height of the cliffs and nearshore bathymetry were obtained from the

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\(^{1}\) Thermoabrasion is the process of erosion of coast and shoreface, composed of icebonded permafrost or ice, under the combined action of mechanical and thermal energy of the sea. Shores subjected to thermoabrasion are called thermoabrasional (Are, 1988).
topographic maps of 1: 25,000 and other scales. Other information was gathered from numerous scientific publications. All these sources were used to compile the map presented in Figure 1.

The resultant directions of wave energy, directions of longshore sediment movement and areas of sediment accretion in the bays were drawn on the map according to Sovershaev (1980). The directions of sediment transport in the straits of Novosibirsky archipelago were derived from Klyuyev (1967) and maps of surface currents (Atlas of the Arctic, 1985; World Ocean Atlas, 1980).

The stable shores supplying no sediment to the sea, shown on the map with a bold line, represent either stable shores not exposed to the destructive influence of the sea, or those composed of hard rock - liparite, andesite and basalt. Shores where nothing is known are represented by a thin line.

The shores composed of soft rock are classed as comparatively stable. These are characterised by a very low rate of retreat, but the cliffs of such shores, if rather high, may supply a considerable amount of sediment to the sea.

Prograding shores are shown on the map along the front of the Lena and Yana river deltas because these deltas are growing according to many hydrological publications. But there is published data for eroding delta shores also. For example Grigoryev (1993) reports that the northern shores of the Lena delta in its eastern part undergo erosion in places. Intensive erosion of shores was observed along the Yana river delta (Grigoryev, 1966). The front of the Yana river delta is framed by two young marine terraces up to 10 km wide according to State Geological Map of 1:1,000,000 scale. So the dynamics of delta shores are rather complicated. Further investigations are needed to understand these processes.

Most shore retreat rates shown on the map are derived from direct field measurements or a comparison of aerial photographs (Sovershaev, 1980; Novikov, 1984; Are, 1985; Grigoryev, 1996). The values shown on the northern and southern coasts of Dm. Laptev Strait are determined in an indirect way. Various published descriptions of these cliffed coasts suggest that their visual appearance has not changed during the last 80 years (Vollosovich, 1915; Romanovsky, 1963; Grigoryev, 1996). These cliffs, composed of an ice complex, have a narrow thermoterrace at the base and a vertical upper part. Preservation of this morphology for many years provides evidence of the equality of the shore retreat rate and of the ice complex\(^2\) thermodenudation rate. The latter is calculated using the seasonal sums of mean daily positive air temperatures (Are, 1985).

The areas of sea floor erosion and sediment accretion in the vicinity of Anabar-Olenyok coast and around Bolshoy Lyakhovsky island are drawn on the map according to Klyuyev (1967, 1970, Klyuyev, Kotyukh, 1985).

The coastal plain between the mouths of the Anabar and Olenyok rivers is composed of an ice complex containing 60-80 % of particles less then 0.05 mm in diameter. According to Klyuyev (1970), the floor of the Laptev Sea in this area is composed of sand in water depths between 4-6 m and 20-25 m. Near the shore and in deeper areas the bottom sediment is silty. Klyuyev (1970) believes that sandy bottoms represent erosional areas of the sea floor. Lindemann (1994) and Benthiern (1994) support this viewpoint and suggest that a sandy bottom in the Laptev Sea marks areas of sea floor erosion, whereas silty and clayey bottom - indicates sediment accretion. This hypothesis is used in compilation of Figure 1 to distinguish the areas of erosion and accretion offshore.

Much of the information contained in Figure 1 is based on several assumptions and its reliability cannot be proven at present, but the reasons for choosing of any designation used may be explained. For example, why was the south-eastern coast section of Taymyr peninsula designated as comparatively stable shore? This part of the coast is composed of loose marine, alluvial and marine-alluvial sediments along half its length according to the State Geological Map at 1:1,000,000 scale. The other half is composed of soft rock in 5 separate sections. The mean shoreface slope out to the 10 m isobath is steeper than typical conditions in the Laptev Sea, suggesting that this part of the shore undergoes wave erosion. The form of the shoreline demonstrates that the blocks of soft rock offer shore protection. These blocks form capes with bays between them. The bays extend as much as 5 km inland. Probably the bays are created by thermoabrasion of shores composed of loose deposits during last 5,000 years when sea level was stable. So the present position of the shoreline in the bays should be near an equilibrium state. If so, the rate of shore retreat should be limited now by the erosion rate of the sections composed of soft rocks. So it seems most reasonable to designate the shore section as a comparatively stable one.

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\(^2\) Perennially frozen ice-rich unconsolidated Quaternary deposits with a large content of ice wedges are called ice complex in Russian permafrost literature. The total ice content of these sediments is as large as 95 % by volume. Ice complex is widespread on Laptev Sea coast.
Figure 1. Schematic map of Laptev Sea shore dynamics. 1 - stable shores supplying no sediments into the sea, 2 - comparatively stable shores built by soft rock, 3 - slowly retreating thermoabrasion shores (<2m/year), 4 - rapidly retreating thermoabrasion shores (>2m/year), 5 - prograding shores of delta, 6 - areas of sea floor erosion, 7 - areas of sediment accretion, 8 - resultant direction of wave energy, 9 - direction of sediment longshore movement, VGB - Vankina Guba Bay, DLS - Dmitry Laptev Strait, BLI - Bolshoy Lyakhovsky Island.
Sediment supplied to the sea by thermoabrasion of Anabar-Olenyok coast

The following data are needed to calculate the amount of sediment supplied to the sea by thermoabrasion: the shore retreat rate \( V \), m/year or shore advance rate, the height of the cliffs \( H \), m, position of the lower boundary of shoreface (average maximum wave base \( h_{\text{max}} \), m), lithology of sediments composing the coast and shoreface, volumetric ice content of these sediments and their dry bulk density \( B \), t/m\(^3\).

Among the parameters needed, the least studied and understood is lower boundary of the shoreface, which corresponds to the maximum depth of wave influence on the bottom \( (h_{\text{max}}, m) \). This boundary is usually well-defined geomorphologically for deep seas (depths \( > h_{\text{max}} \) ) along the abrasion coasts composed of sand, coarse-grained sediments or rock. In such situations the wave base is marked by the edge of an underwater accretion terrace (Zenkovich, 1962). In shallow seas, the lower boundary of the shoreface may be associated with the isobath where the comparatively steep slope of shoreface changes into a rather gentle slope of transition zone. However, in some beach profiles the change of inclination is indistinguishable. In some areas the boundary between the shoreface and the transition zone may be indicated by a change in bottom sediment from sandy on the shoreface and to silty in the transition zone (Reineck and Singh, 1980).

About a half of the Laptev Sea is shallow. Waves rework the sea floor everywhere up to several hundred kilometres from the shore. This impact is so strong that during severe fall storms the waves throw sand and silt onto the deck of ships (Klyuyev, 1970). Obviously it is unreasonable to consider erosion of the sea floor at such distances from the coast as shore erosion. In this situation the notion of shoreface becomes meaningless. However it is necessary to locate the boundary between shore erosion and sea-floor erosion in order to calculate the amount of sediment volume supplied to the sea by destruction of these shores. At present it is possible to use only assumed values of \( h_{\text{max}} \), which cannot be substantiated reliably.

The Anabar-Olenyok coast is one of the longest and best studied sections of the Laptev Sea shores retreating because of thermoabrasion. The mean retreat rate of a section of this 85 km long coast (Figure 1, dotted line box) is 2 m/year, as determined by comparing aerial photographs taken in 1949 and 1971 (Are, 1985).

Erosion of the shallows occurs everywhere in this area out to the 5 m isobath at a distance of 6-8 km from the shore. The erosion rate is as high as 4 cm/year (Klyuyev, 1967, 1970; Klyuyev, Kotyukh, 1985). Therefore the value \( h_{\text{max}} = 5 \) m was taken for the calculations of sediment amount. According to Klyuyev (1970) the shoreface retreats parallel to itself implying that retreat of the shore is continuous.

A part of this coast, 69.5 km long, is composed of ice complex or thermokarst depression deposits. The latter consist mainly of thawed and subsided ice complex. Therefore the height of the cliffs crossing thermokarst depressions can be considered as a product of thaw settlement of ice complex. This implies that the quantity of sediment supplied to the sea by thermoabrasion of cliffs composed of ice complex and thermokarst depression deposits (per metre of shoreline) is equal. Therefore all shores composed of ice complex or thermokarst depression deposits are considered in calculations as having the height of cliffs in thermokarst depressions (10 m). Other parts of the coast 15.5 km long are composed of sediments having zero thaw settlement and cliffs about 1 m high.

Little is known about the thickness of ice complex in this area. In some places the lower ends of ice-wedges are below sea level. As a first approximation it is assumed that thaw settlement of all deposits which occur below sea level is zero. The dry bulk density of silty sands is approximately 1.5 t/m\(^3\).

Using the data listed and methodology of calculations developed and described in detail by the author (Are, in press) the volume of sediment supplied to the sea by thermoabrasion along 85 km of the Anabar-Olenyok coast is as follows.

For the section composed of ice complex and thermokarst depression deposits

\[
M = B \cdot V \cdot H \cdot D + B \cdot V \cdot h_{\text{max}}
\]

\[
D = 1.5 \cdot 2 \cdot 10 \cdot 69500 + 1.5 \cdot 2 \cdot 5 \cdot 69500 = 2085000 + 1042500 = 3127500 \text{ t/year.}
\]

where \( D \) - is the length of the coast section. The first term in the equation represents input of shore area above sea level and the second one - that below sea level (shoreface). For the sections with low cliffs

\[
M = 1.5 \cdot 2 \cdot 0.5 \cdot 15500 + 1.5 \cdot 2 \cdot 5 \cdot 15500 = 23250 + 232500 = 255750 \text{ t/year}
\]

and the total supplied from all 85 km of coast about 2108250 + 1275000 = 3.4 Mt/year.
Sediment discharge from rivers draining into the Laptev Sea

The results of calculations of sediment input from the Anabar-Olenyok coast can be compared with the data on sediment discharge from the rivers. Monitoring of water and sediment discharge from the main rivers (Anabar, Khatanga, Lena, Olenyok, Yana) has been carried out during the last 50 years. It is found that about 75% of the total riverine water input into the Laptev Sea is supplied by the Lena River. The sediment discharge from this river represents about 80% of the total discharge from all the rivers (Alabyan et al., 1995). The quantitative evaluations of Lena sediment discharge by different investigators range from 11.8 to 21 Mt/year (Doronina, 1962; Alabyan et al., 1995; Ivanov and Piskun, 1995; Ivanov and Piskun, in press; Waterways ... , 1995). No explanation for the diversity of results is given. All data published characterise the sediment yield upstream from the delta. V.V. Ivanov and A.A. Piskun (1995) believe that special full-scale investigations are needed to determine the amount of sediments coming into the sea. Alabyan et al. (1995) state that only 2.1-3.5 Mt/year of the total Lena River suspended sediment discharge enters the sea. But unfortunately in the publication cited no reason is given for this extremely important statement. No data on bed load discharge are available. So it seems that the riverine input into the sediment balance of the Laptev Sea is no better studied than the input of sediment from shore thermoabrasion. Therefore only a rough and conservative comparison of thermoabrasion and river input is appropriate at this stage.

Nevertheless the calculations and data on Lena River sediment discharge cited above demonstrate that the input of thermoabrasion into the sediment balance of the Laptev Sea cannot be neglected; furthermore the two inputs should be considered of the same magnitude at least.

According to the map in Figure 1, the total length of Laptev Sea shore undergoing thermoabrasion is estimated to be in the range 1000-1300 km (Khatanga bay shores excluded). The 85 km length of Anabar-Olenyok coast represents only 6-8% of it. If only 2.1-3.5 Mt/year of river sediment discharge enter the sea as stated by Alabany et al. (1995), the total input of shore erosion prevails. Another way of supporting this statement is as follows.

Let us calculate the shore retreat rate needed to supply into the sea an amount of sediment equivalent to the maximum estimate of Lena River sediment discharge (21 Mt/year, 80% of total riverine input) using the foregoing methodology. The mean values \( H = 5 \) m and \( h_{\text{max}} = 10 \) m seem to be reasonable for this calculation.

\[
V = \frac{M}{B \cdot D \cdot (H + h_{\text{max}})} = \frac{21,000,000}{1.5 \cdot 1,000,000 \cdot (5 + 10)} = 0.9 \text{ m/year}.
\]

Taking the shoreline length as 1300 km gives \( V = 0.7 \) m/year. From the author’s experience, 0.7-0.9 m/year would not be an exaggerated estimate for the mean retreat rate of Laptev Sea thermoabrasion shores.

Conclusions

A schematic map of Laptev Sea shore dynamics is drawn up for the first time using available published data. The map indicates the current state of understanding and demonstrates that our knowledge of Laptev Sea shore evolution is quite poor. The map may be used for planning future investigations.

Calculation of the sediment amount supplied to the Laptev Sea from shore thermoabrasion of Anabar-Olenyok coast and comparison of this amount with the sediment yield of the Lena River shows that the inputs of shore thermoabrasion and river yield to the sediment balance of the Laptev Sea are at least of the same order. It is very likely that the contribution of thermoabrasion is greater than the contribution of rivers.

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