Polarforschung 64 (3): 123–131, 1994 (erschienen 1996)

Dynamics of the Littoral Zone of Arctic Seas (State of the Art and Goals)

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Abstract: The study of land-ocean interactions is one of the main Arctic geoscience problems. The dynamics of the littoral zone are an important part of this interaction. The main task for littoral zone dynamics investigations is to set up quantitative equations for the sediment balance. It has long been known that sea ice completely protects the shore and the shoreface against the hydromechanical influence of the sea in winter. In addition, American scientists believe that sea ice accomplishes much work on bottom erosion, mobilization and transportation of sediments throughout the year.

All kinds of sea ice activity in the Arctic are entirely or partially caused by hydromechanical processes, which at present are studied much less than ice activity itself. But there are serious reasons to suggest that hydromechanical removal of finegrained sediments from the shelf is one of the main causes of the continuous retreat of Arctic sea shores. Apparently frazil ice plays an extremely important part in shore retreat, favouring suspension of bottom sediments during late fall storms.

The rapid continuous retreat of Arctic sea shores cannot be explained by means of classical sea shore evolution science. The main causes of continuous retreat are high ice and silt content in sediments of the coast and shelf, shallowness of seas, meteorological tides and frazil ice activity during storms.

Zusammenfassung: Eine der wichtigsten Fragestellungen arktischer Geowissenschaften ist die Beziehung zwischen Land und Ozean und die Dynamik der Schelfzone. Die Erstellung der Sedimentbilanz der Küstenzone ist dabei das Hauptziel der Untersuchungen. Seit langem ist bekannt, daß das Meereis im Winter die Küstenzone gegen hydromechanische Einflüsse schützt. Von amerikanischer Seite wird angenommen, daß das Meereis ganzjährig einen wichtigen Beitrag zur Erosion am Meeresboden, zur Mobilisierung und Transport von Sediment leistet.

Die hydromechanischen Prozesse, die mehr oder weniger die Meereisdynamik in der Arktis steuern, sind bislang weniger erforscht als das Meereis selbst. Es spricht einiges dafür, daß die hydromechanische Erosion von Feinsediment auf dem Schelf die Hauptursache für den kontinuierlichen Küstenabbau in der Arktis ist. Offensichtlich spielt die Bildung von frazil ice eine besonders wichtige Rolle, da es das durch die Herbststürme aufgewirbelte Sediment in Suspension hält.

Der rasche Rückgang der arktischen Küsten kann nicht erklärt werden mit klassischen Mustern der Küstenentwicklung. Die wesentlichen Ursachen für den kontinuierlichen Küstenabbau liegen im hohen Eis- und Silt-Gehalt der Küsten- und Schelfsedimente, den geringen Wassertiefen, in den starken Gezeiten und der Bildung von frazil ice während Stürmen.

INTRODUCTION

It is recognised that one of the grand challenges of modern Arctic science is to predict global changes. Land-ocean interactions play an important part in the development of global changes. Littoral zone dynamics are a division of geoscience dealing with land-ocean interaction.

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Manuscript received 29 January 1996; accepted 23 May 1996.

The littoral zone is the nearshore part of the sea, where waves are able to move sandy bed material (ZENKOVICH 1962). So its outer boundary position depends on sea depth and wave parameters. In shallow seas this boundary may be situated some hundreds of kilometers from the shore.

The dynamics of the littoral zone are an intricate complex of hydromechanical and lithodynamical processes. The main processes of lithodynamics, as applied to Arctic Seas, are (i) destruction of the shore and shoreface caused by thermoabrasion, thermodenudation and thaw settlement of perennially frozen sediments; (ii) movement of sediments (along and across the shore) supplied to the sea by shore destruction, rivers and winds and (iii) accretion of sediments in relief forms, created by sea waves, currents, drift ice, as well as in deltas, dunes and even layers on the bottom (ZENKOVICH 1962, LONGINOV 1963, ARE 1988).

Thermoabrasion is the process of erosion of coasts made up of frozen sediments or ice, under the combined action of mechanical and thermal energy of sea water. It leads to shoreline retreat. Thermodenudation is the destruction of thermoabrasional shore scarps under the thermal action of air and solar radiation. This process does not lead to shore retreat but to the decrease of scarp inclinaton (ARE 1988).

The moving forces of littoral zone dynamics are
- waves and currents,
- thermal energy of sea, air, and solar radiation,
- astronomical and meteorological tides,
- drift ice,
- winds,
- glaciations and changes of sea level caused by glaciations; vertical crustal movements.

A comprehensive study of littoral zone dynamics in Arctic Seas has not been undertaken in Russia. Only uncoordinated investigations of separate processes were carried out. Considerable results were obtained in the study of thermoabrasion (GRIGORJEV 1962, ARE 1983, 1988) and of permafrost evolution in the littoral zone (GRIGORJEV 1966, 1987, ARE 1976, 1978, NEIZVESTNOV et al. 1983, SOLOVJEV et al. 1987, FARTYSHEV 1993). Processes of sediment movement, however, are very poorly understood. Reliable, quantitative evaluations of sediment balance are absent.

A large number of high level investigations of Beaufort Sea shores and shelf evolution were carried out in the USA during the last 20 years. The major focus was sea ice as an agent of sediment erosion and transportation. Results of U.S. investigations added considerably to our knowledge of Arctic Seas littoral zone dynamics. Especially important were those studies that defined the various physical mechanisms of interaction of sea ice and sediments, making up the bottom and shores, as well as the role of sea ice in the evolution of Beaufort sea shores and shelf. Therefore it is interesting to discuss the results of U.S. investigations, to compare them with Russian data and to evaluate their applicability to the Arctic Seas of Eurasia.

THERMOABRASION OF SHORES

American investigations of thermoabrasion did not bring anything new to the theory of this process, but gave additional support to some of the concepts still under discussion. For example, it is confirmed that the frozen state of sediments does not hamper the shore erosion during open water season. In many publications the importance of storm surges for shore destruction is emphasized (Reimnitz et al. 1988).

Thermoabrasion is a process that is initiated by erosion of the sea bottom in the littoral zone and depends on many factors. Therefore it cannot have good correlation with any single factor, especially with subaerial parameters such as bluff height, lithology and ice content of sediments making up the bluffs etc. (Are 1988). This was confirmed by statistical treatment of data obtained on the Canadian Beaufort Sea coast (Hequette & Barnes 1990).

The maps of Alaskan Beaufort Sea coast published by the US Geological Survey are another important achievement of U.S. scientists (Reimnitz et al. 1988, Barnes et al. 1991). The scale of the maps is 1:50,000. They cover 650 km of coast. Submerged and emerged territories and diagrams of mean shore retreat rates during last 30 years are shown on the maps. The volumes of shore and shoreface erosion up to the 2 m isobath are given in the manuals accompanying the maps.

No similar maps are compiled for Eurasian Arctic shores. It is evident that such maps are needed, not only for various practical purposes, but also for quantitative evaluations of the sediment balance of the Arctic shelf.

ICE GOUGING

The entire surface of the Alaskan Beaufort Sea shelf is either undergoing or has undergone the process of drift ice gouging to at least the 75 m isobath (Reimnitz et al. 1972). Gouging creates peculiar macrorelief features on the sea bottom in the form of trenches paralleled with flanking ridges. It creates a continuous surface sediment layer of ice-keel turbate, where stratification is absent and conditions for benthic life are destroyed. Gouging increases hydraulic roughness of the bottom and bulldozes bottom sediments in the direction of ice drift. The latter two aspects are important for the study of littoral zone dynamics. Increase of bottom roughness increases the transport of both suspended- and bedload. But no quantitative evaluation of this increase has been made till now.

Very simple experiments have shown that sediments piled into flanking ridges in the course of gouging are displaced in direction of gouging for a distance of about 2-3 times the trench width (Reimnitz et al. 1990). This allows calculation of the transport of bedload caused by ice gouging, given repetitive sonographs and echograph that allow determinations of the number and size of gouges that form each year in an area. It is important that gouging was found to occur predominantly westward along the isobaths or at a small angle to them in the on-shore direction. Thus, gouging transports sediments along the shore but not offshore.

BEACH NOURISHMENT FROM ICE TRANSPORT OF SHOREFACE SEDIMENTS.

Pile-ups of broken ice along the Beaufort Sea shores are not uncommon. The pile-ups are created by first-year drift ice movement onshore. The drift ice in the course of pile-up formation erodes the bottom to a depth of 5 m and transports sediments onshore. According to the viewpoint of U.S. scientists, this process plays a key role in barrier island evolution in Beaufort Sea (Reimnitz & Barnes 1987a, Reimnitz et al. 1990).

It is worthy of attention that the influence of pile-up formation on littoral zone dynamics in winter and in summer is opposite. The nourishment of beach in winter occurs because of bottom erosion, which deepens the littoral zone of the sea. This deepening increases the wave energy in summer and so favours the erosion of sediments supplied to the beach in winter.

LOCAL BOTTOM SCOUR CAUSED BY SEA ICE.

Local scour of the bottom occurs around grounded ice (stamuhi), in gouged areas and by the drainage of river flood waters through cracks in sea ice cover.

Depressions with depths up to 3 m and horizontal dimensions up to 100 m presumably related to grounded ice floes are observed on the sea bottom. These forms are filled with sediments after floating and departure of stamuhi during one to three seasons of open water (Reimnitz & Kempema 1982). Generally speaking this type of local scour doubtlessly favours sediment movement but appears not to influence significantly the sediment balance of the littoral zone as a whole, because the radius of stamuhi influence on bottom scour is small.

Local scour caused by gouges should play a more important role, because gouges occur over the majority of the Beaufort Sea shelf, occupy up to 75 % of the bottom area and are recreated every year. That is why macro-roughness of the bottom caused by gouging influences movement of bed- and suspended load continuously and ubiquitously. This influence results in a decrease of critical velocity and consequently in sediment transport increase within and out of the entire littoral zone up to the 65 m isobath.

A very different kind of local scouring occurs when the sea ice cover near deltas is flooded by river water in spring. This water drains through cracks and holes in floating ice. Vertical flows wash out craters and channels in the sea bottom up to 6 m deep and 25 m wide. These bottom relief forms occur at distances up to 30 km from river mouths in water depths of up to 8 m. They are filled with sediments within two to three years. These processes, called „strudel scour", may rework the bottom of prodeltas up to several meters depth during about 2300 years (REIMNITZ et al. 1974, REIMNITZ & KEMPEMA 1983, REIMNITZ & BARNES 1987b). It appears that strudel scour benefits the growth of pro-delta areas, extending the distance of river sediment transportation into the sea. For the same reason it slow delta growth. This process influences river mouth areas only and does not affect the sediment balance of the littoral zone as a whole.

MOBILIZATION AND TRANSPORTATION OF SEDIMENTS BY UNDERWATER ICE.

Strong storms with negative air temperature occur often in the fall before freeze-up in the Beaufort Sea. During such storms frazil ice in supercooled turbulent water and anchor ice „pillows" on the bottom are created. Horizontal dimensions of observed pillows average 10-40 cm, the height approximately 5-8 cm. Pillows contain a significant quantity of sediments. Turbulent water flow detaches a part of pillows with underlying frozen sediments from the bottom during storms and moves them as a bed- or suspended load. Ice cover is usually formed on the sea just after the end of the storm. Anchor ice pillows suspended during a storm float up in these new conditions and are incorporated into the growing ice cover together with their inherent sediments.

Supercooling of water is terminated under the ice cover. That is why the upper layer of bottom sediments frozen during a storm thaws under the influence of rising earth heat flow. Consequently, anchor ice pillows which were not detached from the bottom during storms and remained frozen to the bottom float up and are also incorporated into the growing ice cover. Later on sediments brought into the ice cover by anchor ice drift with the ice. Frazil ice can rise buoyantly during storms but does so primarily after storms. Accumulations of frazil on the sea surface always contain considerable amounts of fine-grained sediments which are included into the rapidly growing ice cover after a storm.

The total amount of sediment in the ice cover mobilized by underwater ice may exceed annual sediment discharge of rivers several times over. In the spring the majority of sediments contained in the ice cover settles to the bottom before the ice-break as a result of ice thawing. Thus the transportation of sediments in spring seems to be relatively minor. But in early winter, winds may break the young ice. Drifting broken ice at such times may transport contained sediments for long distances. For example, in 1982 broken new ice drifted along the shore for 430 km during 5 days (REIMNITZ & KEMPEMA 1987, REIMNITZ et al. 1987).

Field observations and laboratory experiments, carried out by U.S. scientists, give a general notion of the mechanism of sediment mobilization by underwater ice . Anchor ice (as mentioned above) is able to detach and raise bottom sediments to the sea surface through adfreezing and buoyancy forces. Frazil ice apparently does not form any durable connections with both bottom and suspended sediments (REIMNITZ et al. 1993, KEMPEMA et al. 1993). It is evident, that U.S. scientists discovered a large-scale geological and hydromechanical process, which is an important part of littoral zone dynamics of Arctic seas.

The hydraulic scheme of water flow and frazil interaction seems to be rather simple. Wave movement of water is created under the influence of wind. When near bottom velocities of water exceed the critical value, suspension of sediments occurs. By negative air temperature supercooling of water takes place and frazil formation begins. Frazil crystals in turbulent water tend to float up under the force of buoyancy. Field observations prove that floating-up does occur. Turbulent mixing of water causes single frazil crystals to stick together forming larger aggregates, all rising toward the surface. While rising they also collide with suspended particles in the water column, hamper their sedimentation and push them upward. Through these interactions, sufficiently high concentrations of frazil in a three phase suspension (water, frazil, mineral particles) can become a strong factor in raising the suspended sediment load. After reaching the sea surface, suspended sediments are included into the surface layer of frazil slush and may be held there to some extent until the ice cover is fully formed.

Of course, the processes described develop in the form of prevailing tendencies on the general background of suspension intermixing.

SEDIMENT BALANCE IN THE BEAUFORT SEA LITTORAL ZONE.

U.S. scientists have tried to evaluate quantitatively the sediment balance of the Beaufort Sea littoral zone, taking into account shore retreat, sea floor erosion, sediment discharge of rivers, hydromechanical transportation of sediments along the shore and accretion of sediments on the shelf. They found that calculated longshore transport rates are less than the sediment supply into the sea (BARNES & ROLLYSON 1991). But the surface of the inner and middle shelf of the Beaufort Sea is erosional as a whole. Holocene sediments are absent out to the 30 m isobath (REIMNITZ et al. 1982). Therefore sediments supplied to the sea from the continent are removed from the shelf.

U.S. scientists do not question the results of calculations of longshore transport and conclude that some unaccounted components of the sediment balance exist. They believe that these components are caused by the above described activity of sea ice, but admit that they cannot prove it because of a lack of reliable quantitative evaluations of all kinds of ice-related sediment transport.

HYDROMECHANICAL TRANSPORT OF SOLID MATTER IN THE LITTORAL ZONE.

The outlined results of U.S. investigations testify that sea ice activity may cause the removal of sediments from the littoral zone on account of:
(1) bulldozing of bottom sediments by ice-keels,
(2) increase of sea bottom hydraulic macroroughness caused by ice-gouging,
(3) local wash-out around stamuhi,
(4) strudel scour,
(5) increase of suspended matter content in water column because of frazil and anchor ice activity,
(6) drift of sediment-bearing turbid ice.

All these kinds of ice activity are caused partially or totally by water movement. Only the first and sixth type may occur under the influence of wind without participation and even against the sea currents. All other kinds are impossible in stagnant water. So the ice transport of sediments as a whole is a secondary process, caused by hydromechanical processes.

U.S. investigations till now were concentrated on sea ice activity in land/Beaufort Sea interactions. Little attention was given to hydromechanical processes. Many investigations of solid matter hydromechanical transport in the littoral zone and on the whole shelf were carried out in Russia. The most recent summary of the results of these investigations was made by AYBULATOV (1990).

Russian investigations were carried out mainly in the Black Sea and other seas of the temperate climates. It was found that sediments move predominantly in the form of suspended load (up to 90 % of the total transport). Alongshore and cross-shelf movements are distinguished. Alongshore movement is well studied and may be calculated. The mechanism of cross-shelf movement and its part in the sediment balance of the littoral zone are poorly understood. Therefore no mathematical models of this process have been developed (AYBULATOV et al. 1989). The probability of cross-shelf directed currents is found to be an order of magnitude less than those along the shore. The measurements of current velocities were carried out mainly in surface layers of water under calm or moderately rough conditions. Velocities increase with distance from the shore, their values average 30-40 cm/s and sometimes reach 80 cm/s near the outer boundary of the Black Sea shelf.

Very little is known about near bottom currents. As a whole their velocities are lower than those of surface currents. But in individual cases high velocities were observed. For example, velocities from 30-90 cm/s were measured in December during two days in north-eastern part of the Black Sea in water depth of 60 m. Velocity of 1 m/s was measured near the Bulgarien coast at a depth of 27 m during calm weather. Velocities from 0.5-1.0 m/s were observed also in the Baltic Sea (AYBULATOV et al. 1989). These data testify that near bottom currents may suspend and transport not only loose sandy bottom sediments but also gravel and pebbles. The directions of surface and near bottom currents do not coincide and may be opposite.

AYBULATOV (1990) gave considerable attention to evaluation of cross-shelf and away-from-the-shelf sediment transport. He states that the removal of sediments from the shelf is mostly brought about by circulation vortices with a vertical axis, which are formed along the outer boundary of the shelf under the influence of longitudinal open sea currents. The diameters of the vortices range from 20-30 km. In the Black Sea vortices reach the outer boundary of the littoral zone. The vortices in Arctic seas are well marked on aerial photographs by broken ice (Fig. 1). By and large, movement of sediments along the isobaths prevails in tideless seas according to AYBULATOV (1990). Cross-shelf removal of sediments is possible only from narrow shelves. On shelves of some tens of kilometers width and greater, accumulation of sediments is taking place (AYBULATOV 1990).

The main flaw of the investigations carried out is the practically complete absence of data on currents, velocities and sediment transport during strong storms, when undoubtedly intensive flows of suspended sediments occur in the sea. The rates of these flows and their role in the littoral zone dynamics are not determined because of technichal difficulties of direct measurements during severe storms.

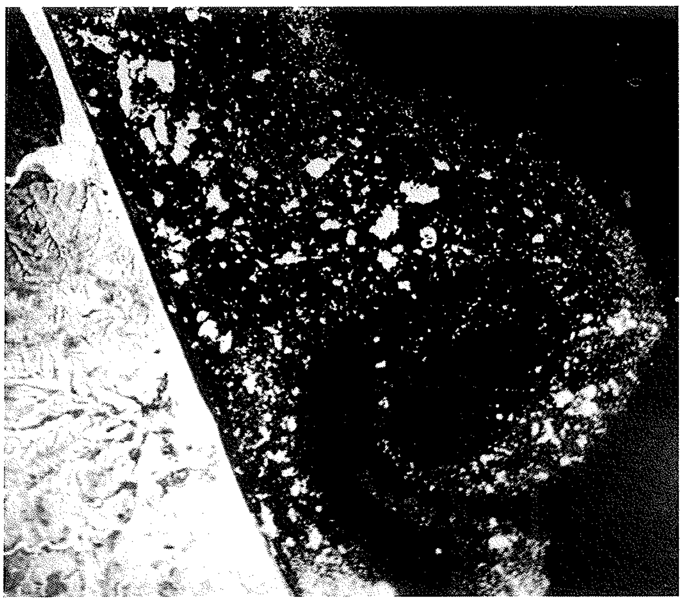

Fig. 1.: An aerial photograph of a circulation vortex with the vertical axis marked by broken ice (AYBULATOV 1990).

Abb. 1: Luftbild eines durch Treibeis markierten Zirkulationswirbels (AYBULATOV 1990).

COMPARISON OF LITTORAL ZONE DYNAMICS IN LAPTEV SEA AND IN ALASKAN PART OF BEAUFORT SEA

The shores of the Arctic coastal lowlands, such as those of the Beaufort and Laptev Seas, retreated during the last decades at comparable rates that remained constant, in spite of considerable differences in a number of parameters that are important for the littoral zone (Tab. 1).

Differences in hydrology and ice regime in particular are caused by opposite prevailing directions of winter winds. Onshore winds in the Beaufort Sea drive pack ice shoreward, create large ice hummocks and many stamuhi at depths ranging to 40 m. Consequently, the sea bottom is subjected to intensive ice-gouging by ice-keels. Onshore winds cause ice-erosion of the bottom, and at the same time supply sediment to beaches through ice encroachment forming pile-ups. These winds determine the prevailing direction of ice drift and sediment transport by ice along the shore westward (REIMNITZ et al. 1994). Prevailing summer coastal currents are in the same direction (REIMNITZ et al. 1988). At Point Barrow, the head of the Barrow Submarine Canyon is situated near the shore (SHAPIRO & BARNES 1991). The bedload and a part of suspended load moving along the shore fall down into this canyon. Another part of the suspended load and sediment laden ice drift to the open sea and are included into the Beaufort Gyre. Thus, alongshore transport may remove sediments from the Beaufort Sea shelf without cross-shelf transport. But in some years unusual offshore winds occur in winter and coastal polynja (rare for the Beaufort Sea shelf) are formed. During such winters shelf sediment entrainment by suspension freezing takes place and new turbid ice drifts seaward into Beaufort Gyre. Observations carried out in 1989 showed that this type of cross-shelf transport may be a very significant component of the Beaufort Sea shelf sediment budget in some years (REIMNITZ et al. 1993).

A fundamentally different situation is observed in the Laptev Sea. The offshore winds (Fig. 2) prevent pack ice drift from approaching the shore. Favourable conditions for the presence of pack ice in the littoral zone occur only in north-western part of the sea where Taymyr drift ice accumulation is situated (KUPECKY 1970). In consequence the fast ice is formed by seasonal ice that builds northward till the middle of the winter. At this time its width reachs the maximum value, given in the Tab. 1. In such conditions the ice gouging can not be as intensive as in the Beaufort Sea on most of the shelf and probably does not influence sediment movement significantly. Offshore winds north of the fast ice outer boundary supposedly play a very significant role for sediment export from the Laptev Sea middle shelf. This role was not taken into account till recently (REIMNITZ et al. 1994). Under the action of offshore winds a well known polynya is formed approximately along the 20 m isobath. This polynya exists throughout the winter and is a powerful generator of ice, which is driven by wind to the north into deep part of the Artic Basin. In summer the polynya is an accumula-

Characteristics	Beaufort Sea	Laptev Sea
Prevailing sediment lithology of coastal lowlands	Silt, sand and gravel (REIMNITZ et al. 1988)	Silt and sand (ARE 1988)
Height of coastal bluffs	Up to 10 m (BARNES et al. 1988)	Up to 40 m (SEMJONOV 1962)
Potential thaw settlement of coastal lowlands	About 1.7 m (REIMNITZ et al. 1988)	Up to 25 m (ARE 1988)
Bottom slope inclination in depth range 0-20 m	0.001-0.005 (REIMNITZ & BARNES 1987)	0.0003-0.0005 (POPOV & SOVERSHAJEV 1979)
Width of the shelf	Up to 100 km	Up to 500 km
Maximum distance between drift ice and shores in summer	Up to 80 km (REIMNITZ & BARNES 1987)	Up to 400-700 km (SEMJONOV 1962)
Wave heigth	Up to 2.5 m (REIMNITZ & BARNES 1974)	Up to 6 m (ZATONSKY 1970)
Width and age of fast ice	Up to 40 km with pack ice inclusions (REIMNITZ et al. 1993)	Up to 500 km, seasonal ice (KUPECKY 1970)
Prevailing direction of winter winds	From sea to land (REIMNITZ et al. 1993)	From land to sea (KRUCHININ 1962; PRIK 1970)

Tab. 1: Comparison of the characteristics of Beaufort and Laptev Seas.

Tab. 1: Vergleich wichtiger Parameter in Beaufort- und Laptevsee.

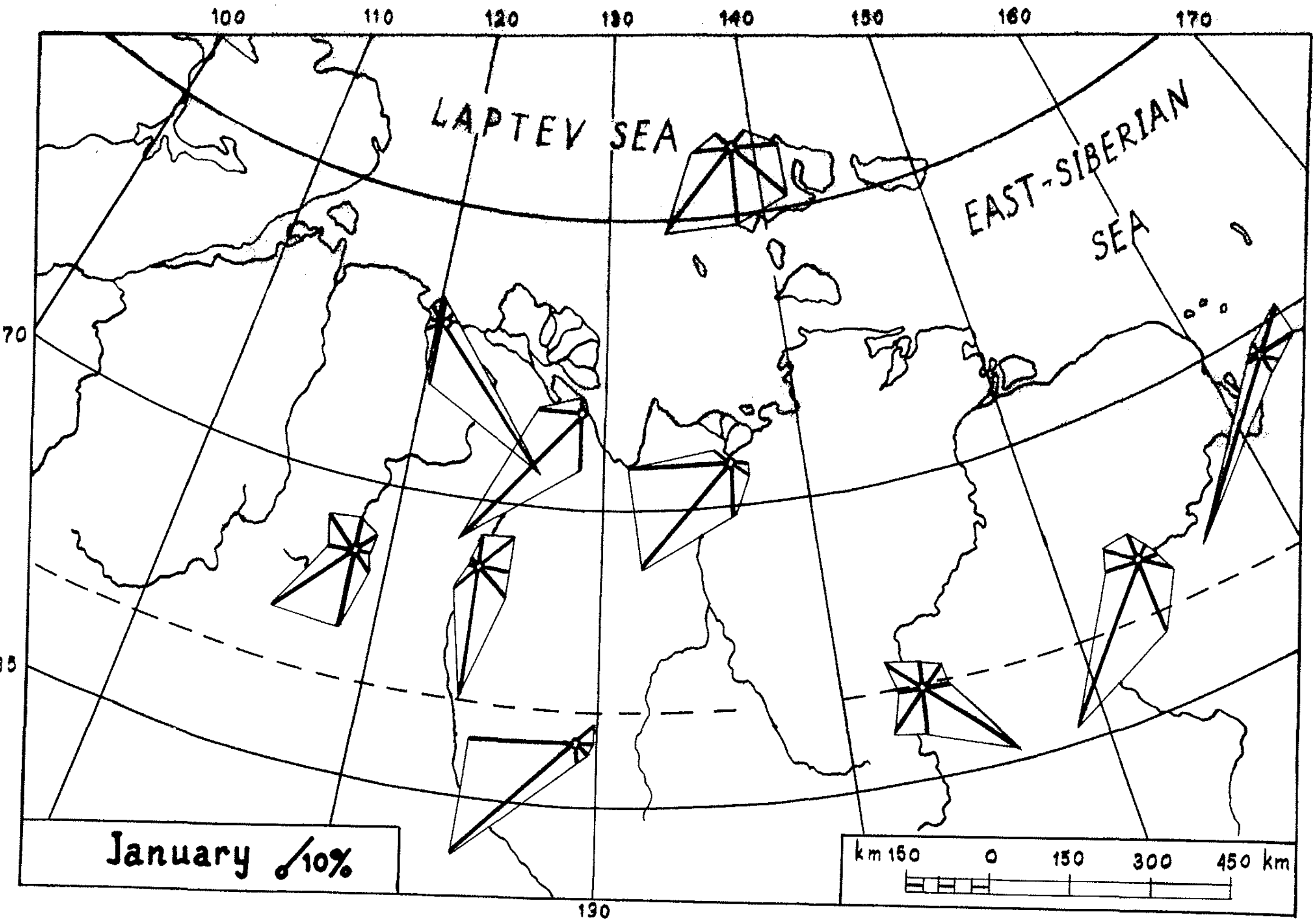

Fig. 2.: Wind roses in January on the Laptev Sea coast (KRUCHININ 1962).

Abb. 2: Windrosen der Januar-Winde im Bereich der Laptevsee (KRUCHININ 1962).

tor of atmospheric heat and strongly favours the clearing of the Laptev Sea from the ice cover (KUPECKY 1970, VETER i volny.... 1974).

A huge part of Laptev Sea is ice free by the beginning of fall storms. The fetch may reach 800 km in September (VETER i volny.... 1974). Supercooling of water and formation of frazil ice take place during freezing storms over the entire ice free area. The frazil favours sediment suspension and transportation by surface wind currents northward away of the shelf. Storms break young ice several times after freezing of the sea in October and till the middle of winter, when fast ice reaches its outer limit at the boundary of the polynya. The same processes occur through the winter in the polynya area. This sediment entrainment and export is supported by the presence of large amounts of dirty ice in the Siberian Branch of the Transpolar Drift of the Polar Basin (REIMNITZ et al. 1994).

Silt content variations in the sediments of coastal plains and sea floor are responsible for major differences in the dynamics of the Beaufort and Laptev Sea littoral zones. For example, silt content in Yana-Indigirka lowland sediments ranges from 60-80 % and exceeds these values in places (ARE 1980). Silt content of the Alaskan Beaufort Sea coastal sediments ranges from 15-60 % and only at Drew Point reaches 90 % (REIMNITZ et al. 1988). Maximum shore retreat rates of 7-15 m/y are observed precisely on this part of the coast. The particles <0.05 mm in diameter are easily suspended and transported for long distances. According to AYBULATOV (1990) such fine-grained sediments do not stay on the inner part of the shelf and are carried out to the middle and outer parts. That is why the Laptev Sea littoral zone dynamics do not follow entirely the classical laws of sea shore evolution formulated by ZENKOVICH (1962) for littoral zones composed of coarser sediments.

The amount of thaw settlement of the Beaufort and Laptev Sea coastal lowland sediments is also rather different. But these differences are not radical because the value of total potential settlement does not exceed the height of the bluffs of both seas with rare exception. Therefore, the main differences in littoral zone dynamics of Beaufort and Laptev Seas are caused by the prevailing winds being obliquely onshore in the former area and offshore in the latter. The westward alongshore transport forced by prevailing winds in the Beaufort Sea drives sediment transport toward the Chukchi Sea where a large part is funneled to the Canada Basin via a submarine canyon. In the Laptev Sea cross-shelf transport prevails which removes suspended sediments from the shelf northward. Mechanical effects of drift ice on sea bottom in the littoral zone is much less in comparison to the Beaufort Sea.

The comparison of Beaufort and Laptev Sea shows that results of littoral zone investigations carried out on a single Arctic sea cannot be applied to other seas unconditionally.

THE CAUSES OF CONTINUOUS RETREAT OF ARCTIC SEA SHORES.

The continuous coastal retreat observed in the Laptev and Beaufort Seas is also typical for other Arctic seas. This does not correspond with classical views of sea shore evolution which proclaim, that coastal retreat with a constant sea level has a limit determined by a minimal submarine slope inclination of 0.005 (ZENKOVICH 1962). At such an inclination wave energy is dissipated entirely on the submarine slope and shores are not destroyed. The bottom inclination of the Laptev Sea averages 0.0003-0.0005, one order of magnitude lower (POPOV & SOVERSHAEV 1979). Nevertheless the shores of the Laptev Sea retreat at a mean rate of about 2 m/y (ARE 1983).

Some factors which may prevent stabilisation of Arctic shores were considered above, such as ice, the silt content of sediments, different kinds of sea ice activity on bottom erosion and the mobilisation and transportation of sediments. Besides these factors, hydromechanical transport of sediments deserves serious attention. This kind of transport develops very peculiarly in Arctic seas and is poorly studied.

Potential for hydromechanical sediment transport may be evaluated indirectly by means of wave parameters. According to reference sources the maximum height of waves in Laptev Sea is observed in the fall and reaches 5.8 m with length of 104 m and a period of 8.3 s. The frequency of waves >5 m high is 4.5 %, and 3-5 m is 8 % in September (VETER i volny... 1974). Similar values can be calculated by the procedures of Construction Norms and Rules (SNiP) 2.06.04.-82 for a water depth of 20 m, a bottom inclination of <0.001, and a fetch of >500 km (Table 2). During strong storms (wind speed >20 m/s) even the mean wave height approaches 3 m and occasionally reaches 6 m.

Maximum near-bottom water velocities in Tab. 2 are calculated by the following equation for shallow water waves (ZENKOVICH 1962) using wave parameters given in the same Table.

$$V_{max} = \frac{\pi h}{\sqrt{\frac{\pi h}{g}\, sh\, \frac{4\pi d}{\lambda}}}$$

where h is the wave height, d the sea depth, g the acceleration of gravity, and l the wave length. Near bottom velocities of 1.4 m/s, which arise from a wind velocity of 20 m/s and a corresponding mean wave height of 2.1 m put in motion sedimentary particles up to 3 cm in diameter, according to data of AYBULATOV (1990) and other investigators. Water flow velocities of 3 m/s may move cobblestones.

The orbital currents caused by waves are transformed into linear reciprocating currents near the bottom. The fact that the velocities of these currents are superimposed on unidirectional currents has to be considered. When the direction of both currents coincides, the velocities are accordingly higher. The calculations therefore show, that intense hydromechanical transport of sediments is taking place in the Laptev Sea during storms. This is supported by sailor descriptions of sand being thrown on decks of vessels during storms even at water depths of 50 m (KLENOVA 1948).

Quantitative evaluation of sediment hydromechanical transport is obviously necessary for littoral zone dynamics study. But the determination of sediment transport for the land-shelf system is a task for future, even for the seas of the temperate climate zone, because the necessary field measurements are either lacking or sparse. During severe storms measurements were not carried out at all. Reliable mathematical models do not exist (AYBULATOV et al. 1989, ANCIFEROV & KOSJAN 1986).

Wind velocity	Height			Period	Length	Maximum near bottom velocity, V_{max}		
	Mean value	Frequency				Mean value	Frequency	
		5 %	1 %				5 %	1 %
m/s	m	m	m	s	m	m/s	m/s	m/s
20	2.1	4.4	4.8	6.1	60	1.4	2.0	2.1
30	2.7	5.6	6.0	6.7	71	2.2	3.1	3.2
40	2.9	5.9	6.4	6.5	66	2.0	2.8	3.0

Tab. 2: Calculated parameters for waves in the Laptev Sea at 20 m depth and corresponding velocities of near-bottom reciprocating water movement

Tab. 2: Zusammenhang von Wind, Wellenhöhe und Strömungsgeschwindigkeit in Bodennähe für Wassertiefen von 20 m in der Laptevsee.

Unique peculiarities of Arctic shelves, such as shallowness and resulting meteorological tides, formation of frazil ice during late fall storms increasing suspended matter content in water column, and high silt content in sediments of coastal lowlands, create extremely favourable conditions for hydromechanical transport of sediments. This suggests that hydromechanical removal of sediments from the shelf by favorable combinations of wind and hydrological conditions is one of the main causes of the continuous retreat of Arctic shorelines.

CONCLUSIONS

The study of the land-ocean interaction is one of the main problems for geosciences in the Arctic. An important part of this problem are the dynamics of the littoral zone. Investigation of the latter is necessary for the wise use of the coastal zone by humans and for a quantitative evaluation and forecast of global change. The principal challenge is to develop a quantitative equation for the sediment balance in the littoral zone. All component processes of littoral zone dynamics have to be studied for this purpose.

Among component processes, thermoabrasion is relatively well known. The main regularities, conditions and pecularities of thermoabrasion as a single geocryological process are established (ARE 1988). But quantitatively thermoabrasion of Russian Arctic shores is poorly studied. Therefore, an obvious task that is relatively easy to achieve is the preparation of maps of coastal evolution for Russian Arctic seas by means of comparisons of aerial and space photographs, taken over a 20 to 30 year interval. Such maps are needed for the wise utilization of the Arctic coastal zone by humans, and for a quantitative evaluation of sediment supply into the littoral zone.

During last 20 years the most profound and extremely important contribution to littoral zone dynamics of Arctic seas was made by the U.S. investigators E. Reimnitz, P. Barnes and their colleagues. They found that sea ice, completely protecting shores and the upper part of the submarine slope against the hydromechanical influence of sea in winter, accomplishes much work toward bottom erosion, mobilization and transportation of bottom sediments throughout the year.

Conclusions of U.S. scientists concerning the role of ice in littoral zone dynamics were made on the basis of Beaufort Sea investigations. These conclusions cannot be fully applied to other Arctic seas unconditionally, because ice activity manifests itself differently in every sea. The role of different types of ice activity and their total effect elsewhere may be very different from the Beaufort Sea situation. Therefore the investigations of ice processes in the Russian Arctic remain an important scientific task.

All types of sea ice activity in the Arctic are either entirely or partially caused by hydromechanical processes, which at present are studied much less than ice activity itself. There are serious reasons to suggest that hydromechanical removal of fine-grained sediments from the shelf is one of the main causes of the continuous retreat of Arctic sea shores. Apparently, frazil ice activity plays an extremely important part in shore retreat, favouring suspension of bottom sediments during late fall storms. This part has not been studied quantitatively.

Hydromechanical sediment transport during storms is very poorly known, even for typical ice free conditions, but is totally unknown for conditions where frazil and anchor ice are involved. Without a doubt, bed- and suspended load transport increases steeply during extremely severe storms. Therefore, direct measurements of suspended matter content in the water column, and of directions and velocities of currents during storms are especially important. Such measurements were not carried out till now because of technical difficulties. Today, possibilities of modern measurement techniques and automatisation make this task quite feasible.

Arctic seas, and especially the Laptev and East-Siberian Seas, are unique water bodies because of their vastness and very shallow depths. Coastal evolution in such seas is not entirely consistent with classical concepts, which are mainly based on investigations of relatively narrow littoral zones. For example, in the Black Sea, where a major part of Russian investigations were carried out, the width of littoral zone does not exceed tens of kilometers. In the Laptev Sea, the outer boundary of the littoral zone is situated some hundred kilometers away from the shore. During severe storms the waves are able to move loose bottom sediments on most most of this shelf area. The notion of littoral zone loses its usual meaning under such conditions, because intensive lithodynamical processes occur over huge territories.

The height of meteorological tides and their role in littoral zone dynamics increases sharply in large shallow water areas and especially for complicated shore line configurations. Coastal bluffs, locally situated several kilometers from the shore line at normal sea level, undergo destruction during high meteorological tides. Most of the unusual processes discussed above have never been or are only scarcely investigated. Therefore, the study of Arctic Sea lithodynamics represents a vast and extremely interesting field of activity for investigators of land -ocean interaction in the Arctic.

ACKNOWLEDGEMENTS

This overview was made possible thanks to Erk Reimnitz and Peter Barnes from USGS, who initiated correspondence with Russian scientists on littoral zone dynamics of Arctic seas in 1988. This paper is based largely on their publications sent to me, of which the absolute majority is unavailable in Russia. Study of these publications gave me a unique possibility to understand the importance of ice-driven processes in the coastal zone of the Arctic seas and to inform my Russian colleagues. I would like also to thank Hans Hubberten of the Alfred Wegener Institute (AWI) Research Facility at Potsdam, Germany for help in preparation of this manuscript for publication and Erk Reimnitz and Professor R. Mäusbacher from Friedrich-Schiller-University, Jena for reviews which helped to improve the manuscript.

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