These proceedings of the Ninth International Conference on Permafrost (NICOP) extend the documented legacy of permafrost related research begun in 1963 when the first International Conference was held in West Lafayette, Indiana, USA. NICOP also marks the 25th anniversary of the Fourth International Conference on Permafrost that was convened in Fairbanks in July 1983. It is imperative that we continue this international and long-ranging dialogue of cooperation on permafrost, particularly during a period of overall global warming. At no time in the past has our overall interest level in permafrost been greater. The number of papers published in these proceedings substantiates this interest. In addition to climate change, development in regions of permafrost is contributing additional stress to this thermally sensitive environment. This recent increased growth is often associated with resource development such as oil and gas, and various mineral resources.

The papers presented in these proceedings are diverse in both time and space; they cover results from field and laboratory studies, remote sensing, analyses and modeling – or some combination of these. Both scientific and engineering aspects of various permafrost issues are presented, and are often intertwined with each other. We hope these proceedings provide one more positive step in our understanding of the permafrost environment that intrigues us as scientists and engineers.

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Coastal Processes at the Tabular-Ground-Ice-Bearing Area, Yugorsky Peninsula, Russia

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Abstract

Observations on Yugorsky Peninsula since 1998 cover periods with changing climatic controls of coastal processes. Coastal dynamics are connected to the activation of thermal denudation, the most widespread process in the area with tabular ground ice enclosed in geological sequences. Thermodenudation comprises cryogenic landslides, slumps, and earth flows resulting from tabular ground ice thaw. Thermoabrasion is a less common mechanism of coastal retreat in the study area. The dominating mechanism allows subdivision of coasts into thermodenudation, thermoabrasion, and mixed types. Coast types are time-dependent, and alternation of types depends on climate fluctuations. For the bluffs with tabular ground ice exposures, the increase of sediment yield onto the beach is determined on the one hand, by a relative amount of tabular ice in a section, and on the other, by increase in the thaw index. Activation of thermoabrasion depends on sea ice coverage along with wind speed and direction. Activation of thermoerosion results from heavy winter precipitation followed by a bursting spring.

Keywords: climatic controls; coastal dynamics; earth flows; thermoabrasion; thermodenudation; thermoerosion.

Introduction

Observations on Yugorsky Peninsula since 1998 cover the basic climatic controls of various coastal processes in the study area (Kizyakov et al. 2006): periods with changing summer temperature, ice coverage of the Kara Sea, amount of summer and winter precipitation, wind speed and direction, and wave action.

Coastal dynamics result from the activation of thermal denudation, the most widespread process in the area with tabular ground ice enclosed in geological sequences. The importance of the massive (tabular) ground ice occurrence as a major factor in coastal retreat is recognized in the literature (Lantuit & Pollard 2003, Solomon 2003, Lantuit et al. 2005, Kizyakov et al. 2006). Thermal denudation comprises cryogenic landslide/slump/earth flow processes, resulting from tabular ground ice thaw and removal of meltwater and waste material onto the beach and into the sea by gravitation (Leibman & Kizyakov 2007). Depending on climate fluctuations, coastal dynamics result from alternating or coinciding cryogenic landslide/slump/earth flow, thermoabrasion, and thermoerosion mechanisms. According to the dominating mechanism, coasts are subdivided into thermodenudation, thermoabrasion and mixed types (Sovershaev 1992, Kizyakov et al. 2003). Coasts are affected by nivation, earth falls, and aeolian processes as well, though they play subordinate roles.

Thermodenudation assumes special features in the tabular ground ice areas. These features are the formation of specific thermodenudation landforms such as thermocirques and thermoterraces, resulting from the tabular ground ice thaw and slope mass waste. The rate of coastal retreat at the backwalls of these forms is much higher than the coastal retreat rate at the adjacent portions of the coastal bluffs (Kizyakov et al. 2006).

This paper deals with coastal dynamics at the Yugorsky Peninsula coast. Field observations and monitoring reveal the main mechanisms which determine coastal types and destruction rates.

Study Area, Terms, and Methods

The study area, Yugorsky Peninsula at the southern coast of the Kara Sea (Fig. 1), is located on the Pai-Khoi Mountain range piedmont, a relief of rolling hills being affected by thermokarst and various slope and coastal processes. According to the records of the Amderma weather station, mean annual (summer) temperature for the period of observation ranged from -5.8 to -7.7°C (5.0–6.7°C); summer wind speed may exceed 20 m/sec, mainly in a southwestern direction; and the perennial average of annual/summer precipitation is rather low: 314/148 mm.

The area is characterized by continuous permafrost

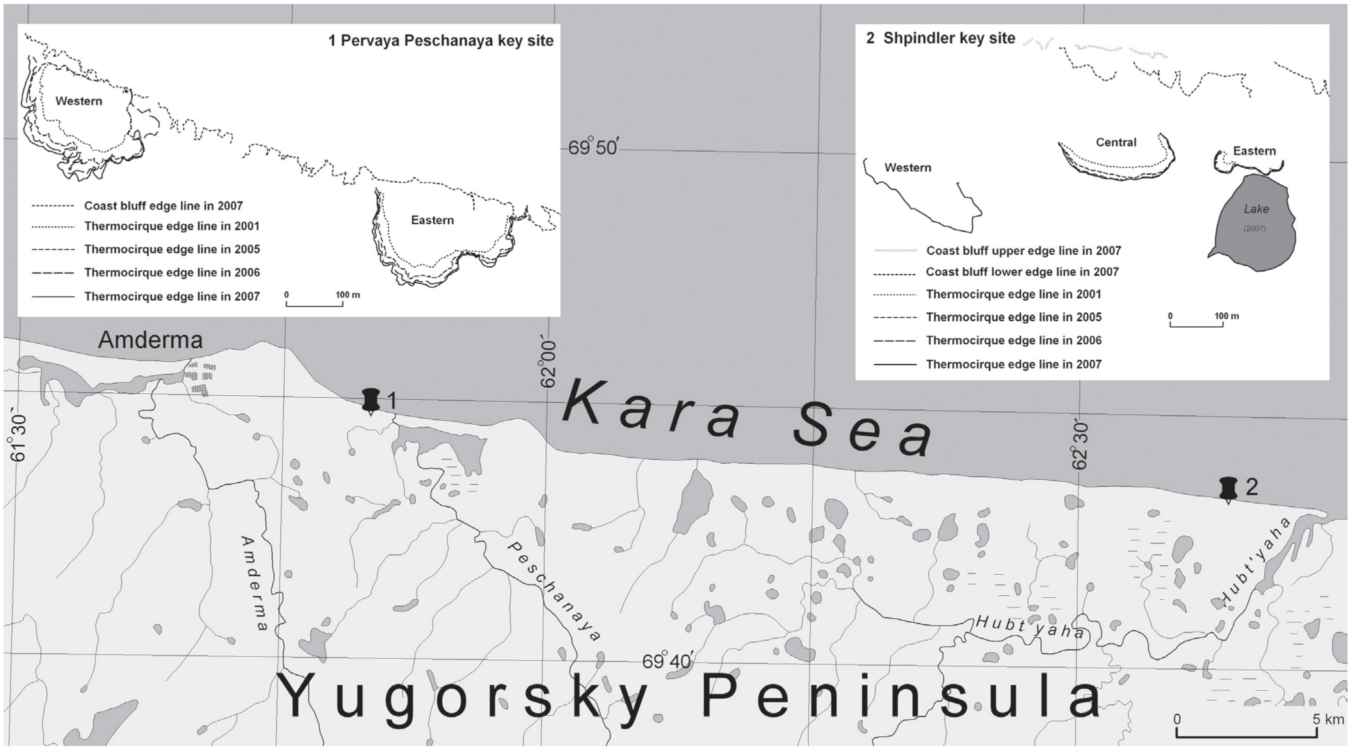

Figure 1. Yugorsky Peninsula. Pervaya Peschanaya (1, left inset map), and Shpindler (2, right inset map) key sites. Thermocirque configuration as well as annual coastlines are shown on inset maps.

distribution with ground temperature as low as -5°C, up to 400 m thickness, with an active-layer depth maximum exceeding 1.5 m, with average around 1 m, and widespread tabular ground ice in layers of 3–12 m thick enclosed in sandy-clayey deposits of glacial (?), marine, fluvial, Aeolian, and slope-wash genesis (Manley et al. 2001, Leibman et al. 2003). Two key sites are under study: Shpindler site is located west of the Hubt'Yakha River at the easternmost end of the coastal zone under study. The westernmost end is Pervaya Peschanaya site, west of the Pervaya Peschanaya River. At both key sites several thermocirques are mapped, four of which are monitored: the western and eastern thermocirques of Pervaya Peschanaya site, and the eastern and central thermocirques of Shpindler site (Fig. 1, inset maps). The coastal zone between these two key sites was described and the thermocirque/bluff edge position measured during a foot and boat trip along the coast.

The methods applied were as follows: A network of transects perpendicular to the edge of most actively retreating thermocirques and flat coastal bluffs was established. Repeated accurate tacheometric surveys were used to create a digital model of thermocirque relief at several time slices so that coastal dynamics were characterized not only in one dimension as a shoreline retreat, but also in two and three dimensions, as area and volume losses. The area loss allows better determination of the average retreat for an edge of complicated configuration, while volumetric loss allows calculation of the volume of material transported onto the beach during the period between two survey dates (Kizyakov et al. 2006).

Retreat measurements were performed in July and August. To better understand climate controls, retreat rates and thaw index were calculated for the entire period between measurements and thus include the warm period of the preceding and following year, not of a calendar warm period.

A tacheometric survey was implemented in 2001, 2003, 2005, and 2006. In the intermediate years, a GPS survey was used to measure the shoreline position and to extend transects farther inland after stakes closer to the edge were lost through the retreat. GPS is of less accuracy compared to tacheometry, but it is still within 1 m, due to repeated measurements in a closed loop.

In Russian literature, different terms are used for coastal and lateral thermoerosion, which make coastal mechanisms easier to understand; in this paper we will use the term *thermoabrasion* for coastal thermoerosion which is the formation of wave-cut niches followed by earth falls resulting in coastal bluff retreat. The term *thermoerosion* will be used to indicate only lateral thermoerosion (linear or ravine thermoerosion produced by running water/mud flows).

A substantial portion of the coast is represented by thermocirques and thermoterraces. Mechanisms of their formation are revealed by A. Kizyakov as depending on the localization of the initial thaw. Thermocirques are formed when the tabular ground ice body gets exposed by thermodenudation inland, and waste material is transported to the shore by local streams. While thermoterraces are formed by ice exposures directly on the bluff planes facing the sea; retrogressive thaw slumps and earth flows deliver waste material directly onto the beach (Fig. 2).

Thermodenudation landforms at the coasts are step-

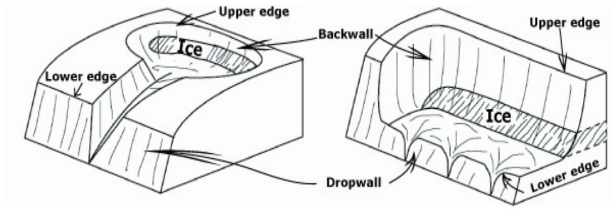

Figure 2. Thermocirque (left) and thermoterrace (right) landforms.

shaped with two retreating planes and respective edges: a thermocirque/thermoterrace backwall (retreating "upper" edge) and a dropwall to the beach (retreating "lower" edge) (Fig. 2).

Results

Table 1 shows the retreat rate in relation to air temperature fluctuations. As instrumental measurements of coastal retreat were performed in mid-summer, long before the coastal processes "winter sleep," we applied a special procedure to make interannual data comparable: thaw index is calculated as a sum of positive temperatures of the preceding year, starting immediately after the date of measurement, plus a sum of positive temperatures of the next year up to the date of measurement. If a period between measurements was more than a year, both total sum and annual average are calculated. The length of the period with positive temperatures is highly variable and depends, along with climate fluctuations, on field logistics. For this reason, we are using a diurnal "thaw index" as a measure of air temperature impact on retreat rate.

Calculations indicate that maximum retreat rate depends directly on degree-days. Each period of measurements is characterized by about 0.8–0.9 cm of retreat per one degree-day of summer temperature.

According to our observations, in 1998–2005, the lower edge retreat was minimal. A boat trip along the coastline did not show any niches or failures, except for several thermocirques. This was most likely related to rather high sea ice coverage till late summer in 1998–1999, and moderate wind speed in 1998–2005. A summer 2003 trip indicated an increase in the number and size of thermocirques and thermoterraces, mainly due to a warm summer (Kizyakov et al. 2003, 2004). But climatic events of spring–summer 2006 changed the rate of the process, especially in the dropwall along the entire 43 km of shoreline observed. That year was marked by extreme wind speed with direction toward the coast, with northern winds prevailing in frequency and speed (Leibman et al. 2006).

In 2007, winter was snowier and spring was cooler than usual. Snow patches covered a significant portion of coastal bluffs preventing wave action. At the same time, snow patches provided active thermoerosion by meltwater. This was made possible by a bursting spring with June–July diurnal temperature some days as high as 24°C. That high temperature stayed only for a few days; the rest of the days the air temperature was below 10°C, thus most snow patches were preserved, but meltwater was abundant. Thermoerosion activated retrogressive thaw slumps and earth flows with mud streams running over snow patches directly onto the beach. Thus processes of coastal destruction proceeded by the alternation of thermodenudation in 2000–2005, thermoabrasion in 2006, and joint thermoerosion and thermodenudation in 2007.

Table 2 presents the average annual retreat at all 4 key thermocirques for various periods of measurement.

Analysis of Table 2 indicates that the maximum annual retreat rate of the backwall was observed in 2005–2006 when the thaw index was maximum. Thermocirques at Pervaya Peschanaya site show a higher retreat rate compared to Shpindler site. Though the thaw index reduces in 2006–2007, retreat at Pervaya Peschanaya site is rather essential (almost 4 m average). Extremes of 2005–2006 were not only due to the high summer temperature (see Table 1, thaw index per day), but also because of strong wave uprush (Leibman et al. 2006). The lower edge started retreating fast, niches were formed, earth falls occurred, and ice exposures appeared at formerly stable slopes (Fig. 3).

Table 1. Shpindler monitoring key site, Yugorsky Peninsula, Russia. Central thermocirque backwall retreat in relation to thaw index.

Period	Average* backwall retreat, m	Days between measurement	Warm period**	Thaw index total/ diurnal degree-days
16.09.2001 10.08.2002	1.6	328	77	398.4/5.2
11.08.2002 22.08.2003	4.2	377	122	755.2/6.2
23.08.2003 05.08.2005	7.65 (3.83)	714	252	1401.9/5.6
06.08.2005 28.07.2006	3.74	358	120	839.3/7
29.07.2006 15.07.2007	1.25	353	93	502.4/5.4

*Calculated as average from retreat measured along the fixed transects, in parentheses annual value if period exceeds 1 year.
**Calculated for the period between measurements including preceding and following year's warm period.

Table 2. Retreat rate of the thermocirque's upper edge at key sites "Shpindler" and "Pervaya Peschanaya," Yugorsky Peninsula in 2001–2007.

Thermocirque	Average linear retreat, m*		
	2001–2005/annual		2006–2007
Shpindler, Central	14/3.5	4	1.25
Shpindler, Eastern	4/1	1	0.48
Pervaya Peschanaya, Eastern	14/3.5	5	3.00
Pervaya Peschanaya, Western	18/4.5	10	3.83

*Calculated as retreat area divided by a bluff edge length in 2001

Figure 3. The wave uprush in 2006 caused thermoabrasion and exposed tabular ground ice at the base of the coastal bluff, Yugorsky Peninsula, Kara Sea coast.

Figure 4. Snow patches in 2007 protect coastal bluffs from thermoabrasion at Yugorsky Peninsula, Kara Sea coast.

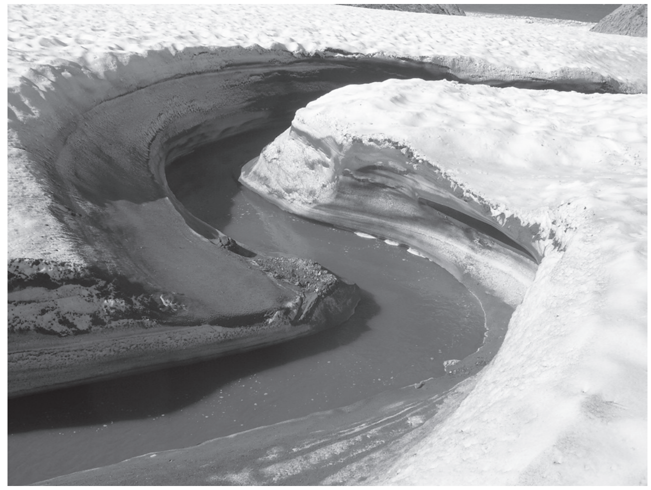

Figure 5. Snow patches filling coastal thermocirque bottoms in 2007 cut through by the meltwater streams bearing and transporting sediment load towards the beach at Yugorsky Peninsula, Kara Sea coast.

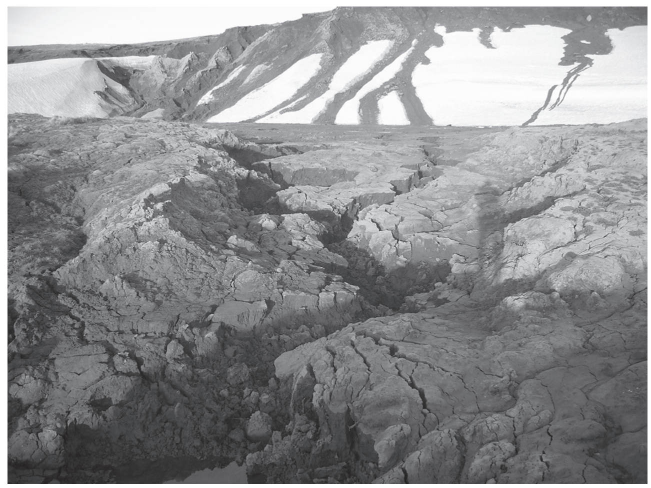

Figure 6. Snow patches in 2007 provide domination of mudflows and thermoerosion in destruction of coastal bluffs at Yugorsky Peninsula, Kara Sea coast.

Summer of 2007 was very different compared to 2001–2006. Snow patches covered most of the coastal bluffs (about 50% of the shoreline) protecting them from thermoabrasion (Fig. 4).

The high retreat rate at Pervaya Peschanaya in summer 2006–2007 is explained by both extreme wave action of fall 2006 and the increased effect of thermoerosion through the meltwater from snow patches in spring 2007 (Fig. 5). Also, nivation promotes retrogressive thaw slump/earth flow activity. Earth flows cut the surface of snow patches (Fig. 6) or run over the snow surface onto the beach. Thus, in 2007 landslides/slumps/earth flows and thermoerosion canals, promoted by snowmelt and nivation, dominate in coastal destruction mechanisms. Calculations show that a 2-week snowmelt period due to thermoerosion, transports as much sediment downslope as earth flow/slump activity during the entire warm period of any previous year.

While thermoerosion provides more intensive sediment transport compared to earth flows and retrogressive thaw slumps, thermoabrasion is quite a sparse and sporadic process at Yugorsky coast, though with an extensive mass waste due to earth falls (Fig. 7).

The rates of coastal retreat for thermocirque edges may be 2–5 times higher than thermoabrasion retreat rates. Sediment transport through a narrow (10–30 m) exit from thermocirque onto a beach is equal to the sediment yield from 500–1000 m portion of a flat-bluff coast (Kizyakov et al. 2006).

Discussion

Observations in the key area with tabular ground ice occurrence show results close to those obtained in the Canadian Arctic by Lantuit & Pollard (2003), Lantuit et al. (2005), and Solomon (2003): tabular ground ice through thermodenudation (retrogressive thaw slumps) essentially increases the rate of coastal retreat, not only in the area of their direct occurrence, as in our study, but in the nearest vicinity (Lantuit & Pollard 2003).

The long-term retreat rate calculated from analysis of remote-sensing data at the Yugorsky coast (Kizyakov et al.

2006) was close to that obtained for various arctic areas and is around 1 m/yr for the period 1948–2001. Rather similar areas of the Canadian Arctic, as mentioned above, show a retreat rate of 1.03 m/yr in 1970–2000 (Lantuit et al. 2005). Though records averaged for a long period (53 years for Yugorsky Peninsula after Kizyakov et al. 2006, and 30 years after Lantuit et al. 2005) show a relatively low retreat rate, annual data at the coasts with tabular ground ice and respective retrogressive thaw slumps (thermal denudation in Russian terminology) display much higher rates. The highest rates are not directly connected to immediate climate warming. Lewkowizc (1987) reported retreat rates for slumpy slopes on Banks Island at 8.6–11.4 m/yr in average with a maximum 15.5 m/yr in 1983–1984. Lantuit & Pollard (2003) noted that the retreat rate was much higher in 2000–2001 (average 7.6 m) and even higher in 2001–2004 (9.6 m/yr).

These data correlate with our observations of increased retreat rates in the 2000s (up to 10 m/yr average, Table 2), exceeding a 55-year average by an order of magnitude. An order of magnitude difference between perennial average retreat rate and seasonal rates at the years of process activation shows that coastal retreat is of a cyclic character, and after several years of thermodenudation activity (12–15 years as in Lewkowicz 1987), a period of recession follows, compensating high rates of coastal destruction on the long-term scale.

High retreat rates result from tabular ground ice representing an essential part of the geological section. At Yugorsky Peninsula this part may be as high as 30–35% of the section as at the Central thermocirque of Shpindler site (Leibman et al. 2003).

As retreat rates appear to depend essentially on the tabular ground ice amount, it is critical to subdivide coastal types based on the existing exposures. At the coast under study, there are one or two ice layers depending on the marine terrace origin, age, and height. At the high terraces (35 to 45 m above sea level) two ice layers are exposed, the upper being 8–12 m thick at depths 15–25 m from the hilltop surface.

The lower ice layer dips westward, with the lower limit from 5–10 m above sea level at the Shpindler key site, and to below sea level at the Pervaya Peschanaya key site. The lower ice layer is found at practically all the terraces, both low and high ones. Flat coastal bluffs separating areas with tabular ground ice exposures may contain ground ice as well, only well insulated by thick scree deposits separating the ice surface from seasonal thaw even in warm years. But of course it should be taken into consideration that these areas are potential resources for activation of coastal destruction in a case of considerable climate warming. One more way to trigger the ice thaw is active thermoabrasion at the now stable flat bluffs.

A two-layer ice distribution pattern produces a specific shape of the coastal profile. The sea-facing macro-slope may consist of several steps with hanging thermocirque/thermoterrace bottoms formed by the thawed upper ice layer, and lower steps based on the toe of the lower ice layer. Only in the case of ice occurrence below sea level, as at Pervaya Peschanaya key site no steps are formed, but rather a thermokarst depression (Leibman et al. 2003, Leibman & Kizyakov 2007).

Figure 7. Intensive mass waste due to thermoabrasion (frozen-block falls) at Yugorsky Peninsula, Kara Sea coast.

Upper thermocirque/thermoterrace edges are located at a distance (several dozen to several hundred meters away) from the shoreline, they are not interacting with the sea. Even low terraces with thermocirques formed due to lower ice layer thaw are not affected by wave action and develop only due to air temperature and precipitation.

An overview of the flat coastal bluffs, thermocirques/thermoterraces, and thermoabrasion coasts during 7 years at the key sites, as well as observations during a long-shore trip showed the following: There were 2 periods of active coastal destruction. The summers of 2000 and 2001 were noted for re-activation of thermodenudation and exposure of tabular ground ice at the eastern (2000) and western (2001) thermocirques of Pervaya Peschanaya key site.

The summer of 2006 changed the whole coastal type structure. Most of the stable dry slopes, as well as dropwalls of thermodenudation slopes, turned into thermoabrasion coastal types with niches, frozen block falls, and cracks at the bluff edges, which prepared continuous failures for the remaining summer months of 2006. In 2007 about 50% of the coasts turned into the thermodenudation-thermoerosion type, thermoabrasion being almost entirely suppressed because wave action was prevented by abundant sea ice and snow patches armoring the dropwalls.

Thus, a combination of coasts of various types at any given time slice constitute the Yugorsky coasts. Coasts are represented by flat to convex bluffs, retreating parallel to themselves due to slow gravitation processes (scree and slopewash) or thermoabrasion (formation of niches followed by earth falls), combined with stepped, concave coasts with thermocirques/thermoterraces and ravines developing due to thermodenudation and thermoerosion. Material transported to the beach is evacuated, depending on the wave activity, in a few days under a strong wind and open sea conditions, to a few weeks if none of the above occur.

After a year of active thermoabrasion in 2006, the lower tabular ice layer was exposed, and this started thermodenudation at the dropwall, which continued in 2007 beneath the snow patches when the melt season started.

The basic conditions for proceeding activation are: (1) presence of rather thick ice layers; and (2) removal of the material delivered from the bluff onto the beach. For the bluffs with tabular ground exposures, the increase of material yield to the beach is determined on the one hand, by a relative amount of tabular ice in a section, and on the other hand, by an increase in summer air temperature, surface-thaw rate, summer atmospheric precipitation, speed and sediment load of eroding flows, and accordingly, amount of sediment and distance of its transportation.

The dual role belongs to winter precipitation. Plentiful snow preserves slopes from thaw. However, the snow contributes to thermodenudation through the nivation process, and provides excessive meltwater flow, increasing sediment yield to the bluff toe, at the same time speeding up the sediment removal from the beach.

Air temperature acts dually as well. High summer temperature prolongs the ice-free period, and along with the intensive wind enhances wave action, promoting both thermoabrasion and removal of sediment. If the summer temperature rise is not accompanied by significant atmospheric precipitation, then sediment yield and removal are slowed down by landslide bodies in the transition zone.

The activity of cryogenic processes unequivocally amplifies only at increase of the thickness and proportion of tabular ground ice.

Conclusions

A coastal dynamics study at the Yugorsky Peninsula coast (Kara Sea) was performed in 2001–2007. Tabular ground ice in the geological sections is responsible for the essential role of thermodenudation in the coastal destruction. Two commonly subdivided types of coasts: thermoerosion and thermodenudation cannot be applied in a study devoted to time-related patterns. Any portion of the coastline in a short-term dynamic under the climate fluctuations cannot only be transformed from stable into actively retreating, but also into a different type or into a mixed type existing within one time slice. Years with a wave uprush increase the proportion of coastal bluffs with the thermoabrasion mechanism dominating. Mixed type occurs when the "upper" edge is retreating according to thermodenudation pattern, while the "lower" edge is destructed by thermoabrasion.

From climatic controls, the main forcing factor for the rate of coastal retreat is summer air temperature (thaw index). The dominating mechanism for the time-dependent coastal destruction (dynamic type of coasts) is determined by different climatic parameters such as wave uprush caused by low sea ice coverage and strong landward winds, intensive winter precipitation resulting in numerous snow patches, which in the conditions of a bursting spring cause domination of thermoerosion and earth flows.

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