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Clusters of Cyclones and Their Effect on Coast Abrasion in Kaliningrad Region

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Abstract: The shores of the Kaliningrad Region (the Russian part of the South-Eastern Baltic Sea) are regularly exposed to extreme storms, which leads to intensive abrasion and flooding of the land. Based on archival data, meteorological monitoring, forecast and synoptic maps, an analysis of extreme storms observed in the autumn–winter periods of the early 21st century was done. The cyclone type was determined using the HYSPLIT (Hybrid Single Particle Lagrangian Integrated Trajectory Model), which makes it possible to reconstruct the trajectory of the approach of the atmospheric vortex to the coast. The seasons with clusters of storms were identified, when deep cyclones affected the coasts of the Kaliningrad Region in a relatively short time. Regardless of the type of trajectory, storms cause destruction of both natural and infrastructure objects. But the shores of the northern exposure are most susceptible to destruction by "diving" cyclones, the wave regime of which has a high potential energy. Earlier it was noted that the frequency of cyclones with northerly winds increases. Clusters of northern cyclones are especially dangerous, as was in January 2022, when 4 atmospheric eddies affected the coast with an interval of several hours to 2–3 days. When the water level was high, the waves crashed on the coast, causing catastrophic damage. The coastal monitoring revealed numerous destruction of the banks, breakthroughs of the foredune, both flooding and collapse of forests, critical damage to engineering and coastal protection structures and infrastructure facilities. Dozens of hectares of coastal territories have been lost. There are environmental problems associated with numerous emissions into the marine environment of a huge amount of anthropogenic mega-, macro-, meso-, micro-debris with a predominance of plastic after extreme storms.

Keywords: cyclone clusters, storm activity, storm coast erosion, level, autumn–winter season, Kaliningrad Region, South-Eastern Baltic Sea, coastal protection structures

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Introduction

Autumn–winter cyclones, carrying storm energy to the coasts under conditions of intense anthropogenic activity, damage natural shores and infrastructure. The formation of coastal dynamics and the development of the coastal zone of the inland Baltic Sea occur under the increasing influence of extreme storm conditions, especially in the case of the passage of a series of cyclonic eddies, which are the result of modern climate change.

The maximum destruction of the coast of the Kaliningrad Region occurs during the period of storms. During the year, according to long-term hydrometeorological data, the coast of the South-Eastern Baltic Sea is affected by more than 60 storms of various intensity. Once every 10 years, the coast is affected by a wind force of 8–9 points on the Beaufort scale, which forms wind waves with a height of more than 5 m. An extreme storm is observed every 20–30 years, when the height of the open sea waves reaches 8 m [*Zhindarev et al.*, 1998].

At the beginning of the 21st century the sea storm activity has increased, more than 25 extreme cyclones have already been observed, which caused severe damage on the sea coast of the Kaliningrad Region and led to deformations of coastal protection structures. Moreover, most often extreme storms are characterized not only by an increase in wave height (up to 6 m), but also by a reduction in "windows of good weather" and an increase in the duration of the period of a unidirectional storm up to 3–4 days. Such a long storm period causes strong surge phenomena, a sea level rise of 1.5–2 m which is comparable to the height of the beaches on the Baltic coast, and leads to erosion of the sea slopes of foredunes, with a breakthrough of through blowing basins [*Boldyrev*, 1981, 2009].

In the southeastern part of the Baltic Sea, there is an increase in storm activity and periods of extreme impact on the coastal zone, caused by observed changes in climatic characteristics, regardless of their cause. This is relevant with an increase in the frequency of northerly winds, especially associated with the entry of "diving" cyclones into the water area of the southern part of the Baltic Sea, which has been observed before [*Bobykina and Stont*, 2015; *Bobykina et al.*, 2021].

The purpose of the study is to assess the impact of extreme storms on the coast of the Kaliningrad Region in the autumn–winter seasons of the first quarter of the 21st century, characterized by the passage of a system of cyclone clusters.

Materials and methods

Characteristics (direction, speed, duration) of storms for the period 2006–2022 were considered based on hourly data obtained from the automatic meteostation installed on the oil platform D6 located 22 km from the coast of the Curonian Spit (Figure 1). Wind speed is based on a standard measurement height of 10 m.

The synoptic situation was assessed using maps of surface atmospheric pressure for 00 UTC at the Bracknell meteorological center (https://www.metoffice.gov.uk/). The trajectories of extreme cyclones were reconstructed using the HYSPLIT trajectory calculation model (https://www.ready.noaa.gov/hypub-bin/trajtype.pl?runtype=archive). Information on sea level (cm, BS) was obtained from historical data given on the Unified State System of Information on the Situation in the World Ocean (ESIMO, http://www.esimo.ru) and with the help of an automatic tide recorder installed in the city of Svetlogorsk (Figure 1). Wave height and direction were estimated using forecast maps (WAM model) of the Warsaw Center (http://www.meteo.pl/).

Data on the dynamics of the sea coast of the Sambia Peninsula and partly of the Curonian and Vistula spits and photographs were obtained from the materials of ground-based monitoring by E. E. Esiukova in the period 2011–2022.

Main characteristics of storm clusters, their trajectories, destruction over the period 2006–2022

Characteristics of storms in autumn–winter seasons

It is known that the maximum number of cyclones in the Baltic Sea is observed in winter and early spring [*Lehmann et al.*, 2011]. When storms impact coasts and coastal infrastructure, this is the season when the maximum damage occurs [*Danchenkov and Belov*, 2019; *Ryabchuk et al.*, 2020], especially during the formation of cyclone clusters. A cluster of cyclones means a set of deep cyclones that have passed through a certain area in a short period [*Nesterov*, 2018]. From this point of view, the autumn–winter seasons for the period 2006–2022 are considered, which are distinguished by their storm regime with extreme cyclones with a wind speed of ≥ 20 m/s and a duration of ≥ 6 h (Table 1).

For the southeastern part of the Baltic Sea, such clusters were identified based on the results of meteorological monitoring (2006–2022). Significant destruction was observed in the following autumn–winter periods (October–February): 2006–2007 (23); 2011–2012 (22); 2013–2014 (14); 2016–2017 (21); 2018–2019 (16); 2021–2022 (26). These selected time periods are characterized by the passage of a series of cyclones both along the western and northern trajectories and destruction along the entire coast of the Kaliningrad Region.

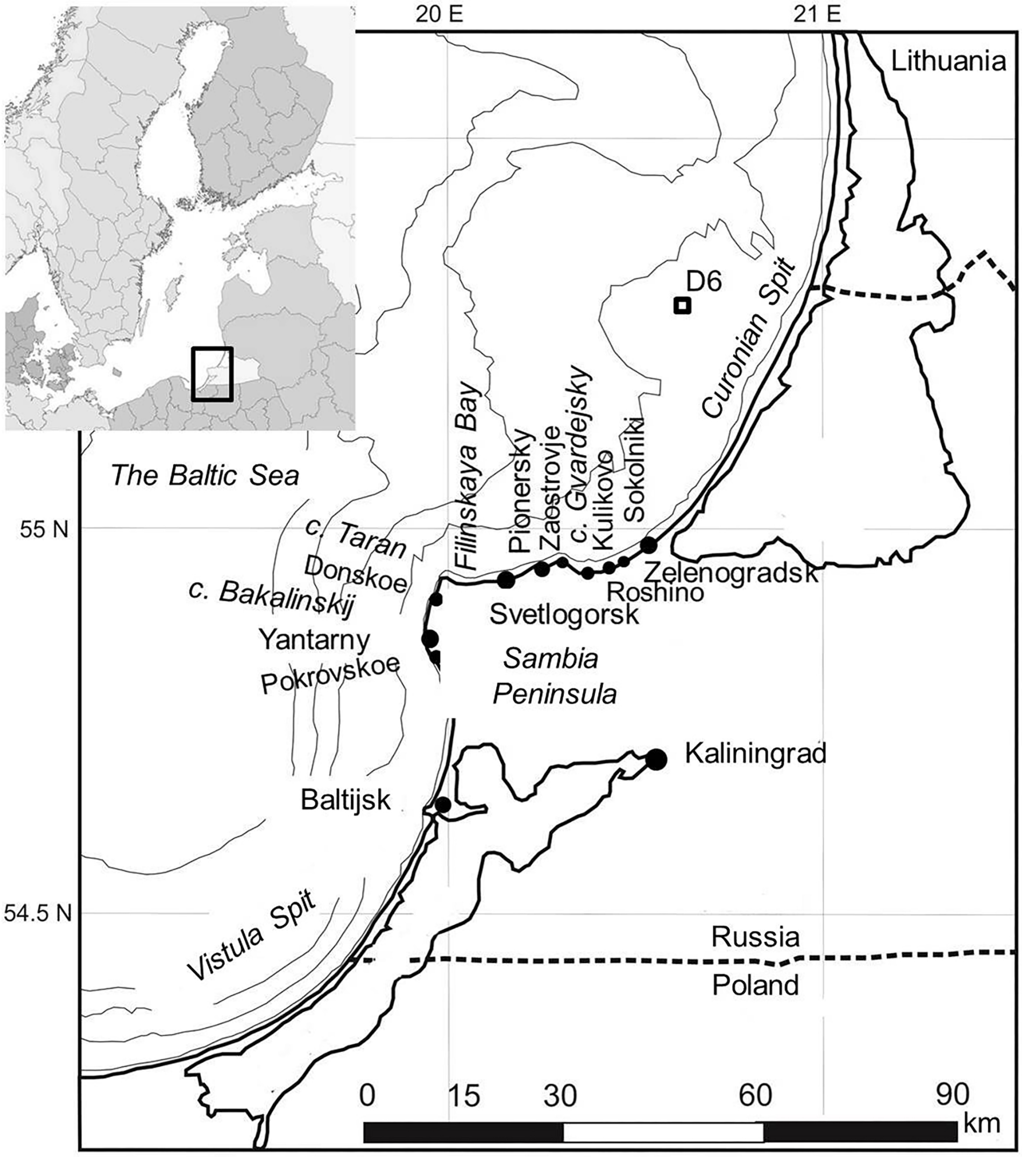

Figure 1. Study area.

In the 2006–2007 season more than 20 active Atlantic cyclones have been noted. Deep cyclonic eddies caused a sharp increase in western winds up to 20–26 m/s, in gusts the wind reached 32 m/s. The wave height from the southwest was 4–5 m [*Boldyrev et al.*, 2008]. November storm cyclone *Britty* came in from the north. The northern wind with a speed of up to 25 m/s generated wind waves with a maximum acceleration up to 5–6 m high. The level rose sharply to +105 cm BS (Pionersky) (Table 1). January 2007 turned out to be the most stormy month – 10 storms with 11-magnitude winds coming along the western trajectory. Of the January storms, two extreme eddies can be distinguished – storms *Franz* and *Kirill*. The speed of the northwest wind reached 26 m/s, in gusts 32 m/s, the duration was more than a day. The height of the wave was 4–5 m.

Thus, the number of storms and their strength increased from October 2006 to January 2007. Stormy westerly winds prevailing during the cold season caused a surge and maintained its high level throughout the entire period starting from October 2006. Water level in the Pregolya River rose to +138 cm, flooding was observed in the lower part of the river within the city. The foredune on the Curonian Spit was broken in 11 places, the area near the spit's root was the most damaged. As a result of beach erosion along the entire

Table 1. Characteristics of extreme storms (wind speed ≥ 20 m/s, duration ≥ 6 h) for South-Eastern Baltic Sea and Kaliningrad Region for 2006–2022

Date	Wind characteristic		Sea level, cm of the BS P – Pionersky; B – Baltijsk; S – Svetlogorsk	Wave height, m
	Direction, rhumb Storm name	Speed, m/s[1]		
2006–2007 season Number of storms: Oct 3, Nov 3, Dec 5, Jan 10, Feb 2				
2006 November 2	NW→N→NE II[2] *Britty*	20 (25)	+70 B +105 P	5–6
2006 December 31	SW→W→NW I	23–25 (30)	+97 B +96 P	4–5
2007 January 14	W→NW I *Franz*	26 (32)	+81 B +77 P	4–5
2007 January 19	NW I *Kirill*	21 (25)	+95 B +96 P	4–5
2011–2012 season Number of storms: Oct 5, Nov 2, Dec 9, Jan 3, Feb 3				
2011November 28–29	SW→W→NW I *Berit*	29 (37)	+32 B +56 P	5
2011 December 9–10	SW→W I *Fridhelm*	22 (27)	+52 B	4
2011 December 17–19	SW→W→NW I *Ioahim*	20 (24)	+65 B	3
2011 December 25–27	SW→W I *Oliver*	20 (25)	+48 B	3
2012 January 12–13	NW→N II *Elfrida*	22 (28)	+99 B	5–6
2013–2014 season Number of storms: Oct 2, Nov 2, Dec 4, Jan 5, Feb 1				
2013 December 5–6	W I *Xavier*	22–25 (28)	+98 B +111 P	5–6
2014 January 10	SW→W I *Dagmar*	23 (25)	+68 B +66 P	4
2018–2019 season Number of storms: Oct 5, Nov 2, Dec 1, Jan 6, Feb 2				
2018 October 3	NW I	20	+63 B +82 P	4
2018 October 26	SW→W→NW I *Siglinda*	24	+63 B +112 P	4
2019 January 2–3	NW→N→NE II *Alfrida*	23	+68 B +92 P	7–8
2021–2022 season Number of storms: Oct 6, Nov 3, Dec 4, Jan 8, Feb 5				
2021 October 21–22	NW→W I *Hendrix*	22	+40 S	4
2021 December 2	NW I *Daniel*	22 (28)	+60 S	4
2021 December 19	N II	20	+38 S	3
2022 January 14–15	NW→N II *Elsa*	20	+44 S	3
2022 January 17	W→NW→N II *Gerhild*	25	+67 S	5–6
2022 January 20–21	NW→N II *Ida*	24	+89 S	6–7
2022 January 29	NW→N II *Mari*	20	+58 S	5
2022 January 30	W→ NW I *Nadya*	27	+93 S	7–8
2022 January 17	SW→W I *Ilenia*	22	+62 S	4
2022 February 19	SW→W I *Zejnep*	22	+85 S	5
2022 February 21	SW→W I	23	+72 S	4

[1] gusts are given in brackets;
[2] type of cyclone (I – western, II – northern, or "diving").

coast of the Kaliningrad Region lost an average of 5–7 m. Beaches were washed away on the Curonian Spit. The protective shaft of the foredune was damaged, in some places the coast decreased by 3–4 m. The wind toppled about a hundred trees, mostly those that had already reached physiological old age [*Boldyrev et al.*, 2008].

For the autumn–winter period 2011–2012 about 20 storms were recorded. At the end of November, during the passage of frontal sections associated with the Atlantic cyclone *Berit* (see Table 1), the western wind increased to a storm (29 m/s, gusts 37 m/s). The duration of the storm was ∼40 h [*Bobykina and Stont*, 2015]. The sea level in Pionersky rose sharply to +56 cm and then fluctuated around +40 cm. In December 2011 and early January 2012, several more cyclones affected the coast of the southeastern part of the Baltic.

The series of storm cyclones was completed by the Atlantic storm *Elfrida*, which hit the northern coast of the Sambia Peninsula on January 13–14, 2012, which followed a trajectory typical of "diving" cyclones. Wind northerly points (NW, N) increased to 22 m/s, gusts 28 m/s (see Table 1). The calculated probability of occurrence of such a wind from the northern points is less than 0.1% [*Gidrometeoizdat*, 1966]. The duration of the storm was 36 h. The stormy north wind, having accelerated up to 1000 km and formed a wind wave up to 5–6 m high, led to sea level rise (up to +99 cm BS, Pionersky) [*Bobykina and Stont*, 2015].

Storm *Elfrida* was devastating for the entire coast of the South-Eastern Baltic Sea, especially for the northern coast of the Sambia Peninsula. At a high level (∼100 cm), the waves, approaching along the normal coast, completely washed away the beaches from Cape Taran to the Curonian Spit. On the spit, the maximum destruction with a breakthrough of the foredune and flooding of the forest massif was noted in the root part, in the Zelenogradsk district. About 6 m of foredune disappeared. This site, like the entire northern coast of the Sambia Peninsula, has a northern exposure (see Figure 1). In the border zone of the Russian part of the spit, from 1 to 3 m of foredunes were washed away with the formation of a vertical erosion ledge 2–2.5 m high [*Bobykina and Stont*, 2015].

For the 2013–2014 storm season 14 storms were observed. In October and November, storm activity was weak: 2 storms were recorded with a maximum speed of 18 m/s. The sea level fluctuated around (+20) – (+30) cm BS. In early December 2013, the strongest hurricane *Xavier* passed through the South-Eastern Baltic Sea. In the rear of this cyclone, the wind of the western points increased to 25 m/s, in gusts of 28 m/s. A stable wind wave from the west up to 4 m high was formed. The water level rose to +111 cm BS (Pionersky), then it dropped and continued to fluctuate about 30–40 cm above the ordinary until early January. Hydrometeorological conditions associated with the formation and development of cyclone *Xavier*, analysis and assessment of threats to the coastal infrastructure of the Polish coast are considered in detail in the authors' article [*Pietrek et al.*, 2014].

In the first half of January 2014, the South-Eastern Baltic Sea was under the influence of deep Atlantic cyclones moving from Western Europe. On the southern periphery of the active cyclone *Dagmar*, the wind of the western directions increased to 23 m/s, in gusts 25 m/s. The sea level rose to +68 cm BS (Baltiysk, see Table 1).

After extreme storms in the winter of 2013–2014 (hurricane *Xavier* on December 5–7, 2013, *Dagmar* storm on January 9–10, 2014, etc.) catastrophic erosion of the entire northern section of the coast of the Sambia Peninsula occurred, with the greatest erosion near the village of Kulikovo (west of Zelenogradsk): landslides and erosion of coastal ledges reached 4–6 m. The area east of Zelenogradsk was damaged: in the root of the Curonian Spit, a sandy aeolian cushion was washed away, exposing a boulder-block beach; an erosion ledge 1.5–2.5 m high was formed; sections of ancient rocks and buried remains of building materials, tires were exposed; the coast protection structures, the foundations of power transmission line supports, the slopes to the beach, technical and utility buildings were damaged [*Esiukova and Stont*, 2015].

Autumn–winter storm season 2018–2019 began in October 2018 with active Atlantic cyclones with northwest winds up to 25 m/s, waves up to 4 m high. A level rise was observed: the maximum +112 cm BS (Pionersky).

In early January 2019, the "diving" cyclone *Alfrida* came to the region. In the rear windy part of the cyclone moving from the Gulf of Bothnia to Belarus, there was an increase in the north wind to a storm. Waves with a height of 7–8 m from the north, having a maximum acceleration length for the Baltic Sea, had a high potential energy. Sea level reached +92 cm BS (Pionersky).

The dynamics of the sea coast of the Russian part of the Curonian Spit in the January storm of 2019 is similar to the consequences of the January storm of 2012. The greatest destruction was observed in the outlying areas: in the north (border with Lithuania), erosion was about 4.5 m, in the southern root section, a foredune breakthrough was observed, washed out up to 1 m of the sea slope. The middle part of the spit remained relatively stable (0 to −0.3 m) for about 20 km [*Bobykina and Stont*, 2015].

More details with observational data obtained from the results of studies and photographic materials on storm activity and its consequences for the coast of the South-Eastern Baltic Sea in storms of 2006–2019 can be found in the articles [*Bobykina and Stont*, 2015; *Bobykina et al.*, 2015, 2021; *Boldyrev et al.*, 2008; *Esiukova and Stont*, 2015; *Stont et al.*, 2019].

Let us consider in more detail the regime of the 2021–2022 season, for which a cluster of storm cyclones is clearly expressed.

In October–December 2021, 13 storms passed, three of them with a wind speed of more than 20 m/s: in October and December along the western trajectory and in December "diving" along the northern trajectory (see Table 1). The water level fluctuated within (+38) – (+60) cm BS (Svetlogorsk).

In early December, cyclogenesis over the North Atlantic increased sharply. The southeastern Baltic was in the zone of influence of the multicenter deep cyclone *Daniel* (980 hPa) (see Table 1), significant fluctuations in atmospheric pressure and gusty winds of western directions up to 28 m/s were observed. The wave height is up to 4 m. The water level has risen sharply to +60 cm BS (Svetlogorsk). Then, winds of offshore directions (E, SE) dominated, which led to a decrease in sea level to −22 cm BS (Figure 2).

In January–February 2022, a situation developed that can be characterized as a cluster. In January, the region was affected by 8 Atlantic cyclones, four of which can be classified as "diving". "Windows of calm weather" ranged from several hours to 2–3 days.

Since mid-January, deep "diving" (northern) cyclones have been influencing. On January 14–15, cyclone *Elza* caused an increase in the northern rhumb wind up to 20 m/s and wind waves up to 3–4 m. The level rose to +44 cm BS above the ordinary (Svetlogorsk). On January 17, the influence of the next "diving" cyclone *Gerhild* (980 hPa) spread. The speed of the NWN wind increased to 23–25 m/s. A wave up to 6 m high was formed. The level rose sharply to +67 cm BS. On January 20–21, in the rear part of the "diving" cyclone *Ida* (970 hPa), heading through the north of the Baltic Sea and the Baltic States to Belarus, an influx of cold Arctic sea air was observed with a strong and gusty northerly wind up to 24 m/s. With wind waves from the north of 6–7 m, the level increased to +89 cm above the ordinary. On January 29, another cyclone *Mari* (975 hPa) with northern winds up to 25 m/s left the Baltic countries and headed towards western Russia (see Table 1, Figure 2).

This series of cyclones ended on January 30 with the release of another deep (970 hPa) cyclone *Nadya*. With a further increase in the baric gradient and northwestern advection of cold heavy air, the wind speed in gusts reached up to 30 m/s on the coast, wind waves 7–8 m from the north. The level rose to +93 cm BS (see Figure 2).

In February, a restructuring of the atmospheric circulation took place over the Atlantic and the continent: zonal transport began to dominate. Successive Atlantic deep cyclones that formed over the Norwegian Sea and associated frontal sections caused an increase in westerly winds.

On February 17, the deep cyclone *Ilenia* (970 hPa) was accompanied by a westerly wind of up to 22 m/s and a level rise of up to +62 cm above normal. On February 19, under the influence of the next deep cyclone *Zejnep* (975 hPa), the west wind increased to 22 m/s with waves up to 5 m. The level increased by more than 20 cm (+85 cm BS). In Pregolya River, the water rose to a level close to critical (about 150 cm BS). On February 21, another western cyclone with winds up to 23 m/s and waves up to 4 m completed the second series of the storm cluster.

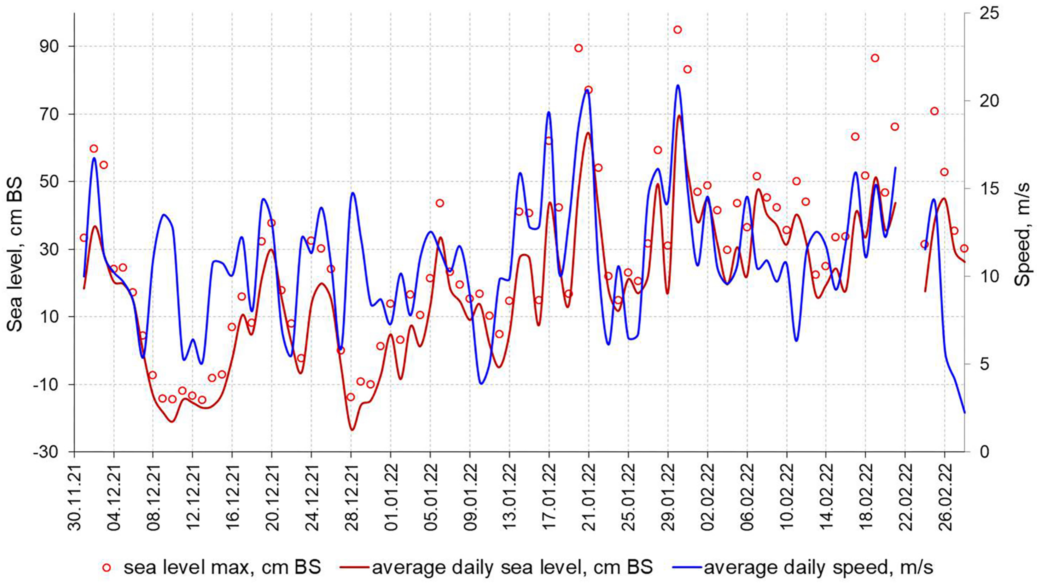

Figure 2. Seasonal dynamics of average daily sea level values (cm BS, Svetlogorsk) and wind speed (m/s), autumn–winter season 2021–2022.

Shore abrasion during the winter period 2021–2022

Extreme storms of winter 2021–2022 – especially in January and February 2022 – led to catastrophic consequences on the shores of the Kaliningrad Region. The January storms, as noted by the Baltberegozashchita enterprise (https://www.dp.ru/a/2022/02/07/Kaliningradskie_vlasti_ob), caused the destruction of coastal infrastructure facilities, about 15.5 hectares of coastal territories were lost (with soil cover and vegetation), and only according to the most conservative estimates, the coast retreated in various unprotected areas from 0.3 m to 2.7 m. In the coastal zone, an emergency mode was introduced to carry out emergency recovery work on the coast (https://www.kaliningrad.kp.ru/online/news/4620165/).

Let us note the main destruction of the infrastructure of the coastal territory and natural objects of the coastal zone of the Kaliningrad Region.

West Coast:

- on the Baltic Spit, the fortification Zapadny was critically damaged with the collapse of part of the structure; the body of the foredune is washed out and partially collapsed; due to the erosion of the foredune, parts of the old bunkers were broken and displaced, and their fragments were scattered along the beach;
- in the city of Baltiysk, the tetrapods protecting the breakwaters were torn out of the protective structures, partially broken and scattered over the breakwater by the force of the storm surf;
- in the village Pokrovskoye was broken and the slipway for boats collapsed;
- in the southern part of Yantarny, sections of the retaining wall were washed away and collapsed, and on both sides of it, the cliff bank was partially collapsed; in the protective coastal structure near the pumping station of the amber plant, the geotextile cementing shells (slabs) of BetoBOX, the girdle and the newly erected structure of shaped blocks (tetrapods) were displaced and deformed (Figure 3). In the northern part of Yantarny, in the area of the Blue Flag beach, infrastructure facilities, non-stationary buildings, and wooden flooring were damaged or completely destroyed;

- in the area of Cape Bakalinsky and the village Donskoe erosion of the bedrock coast was accompanied by powerful avalanches and landslides.

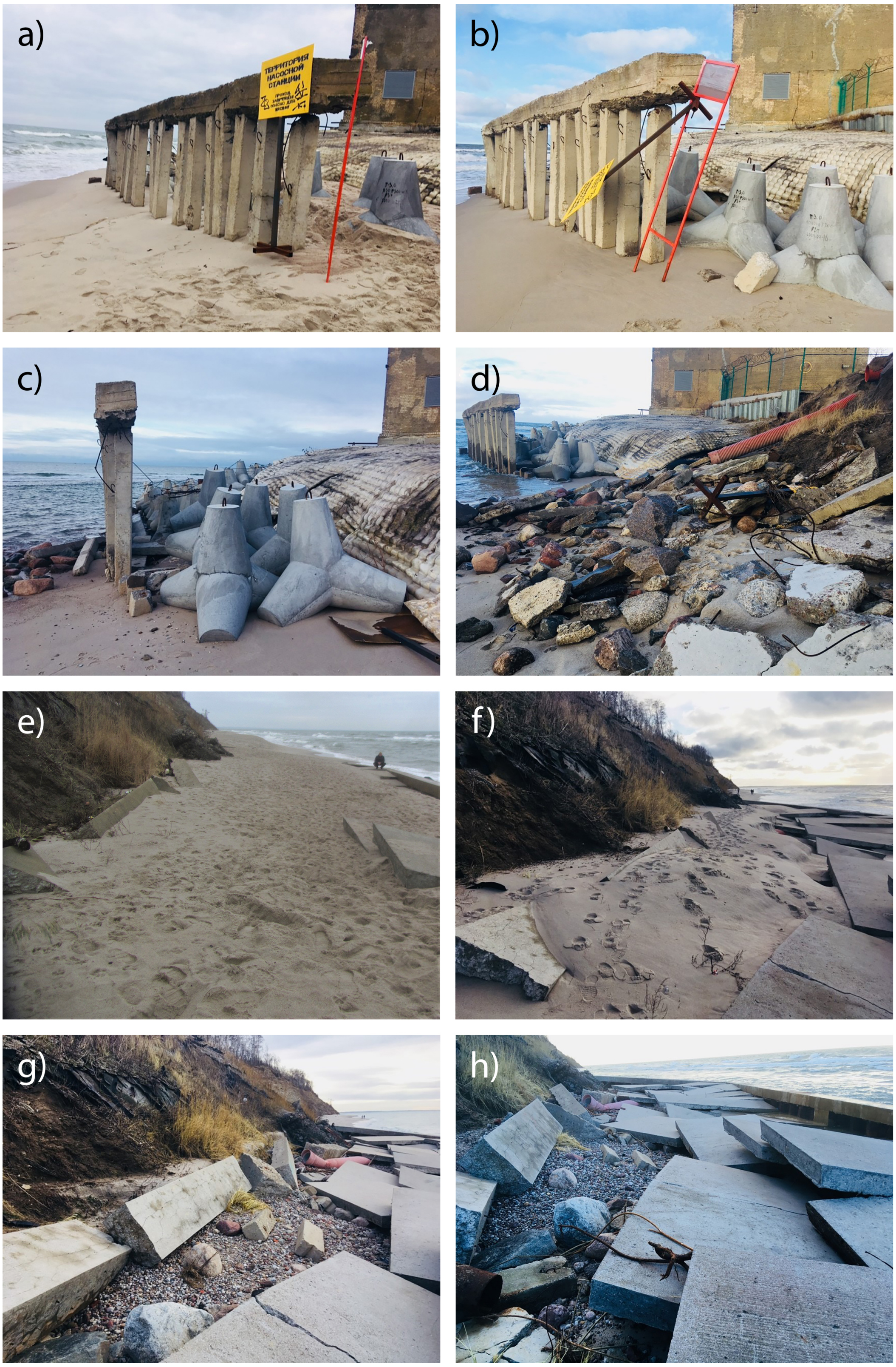

Figure 3. Dynamics of the destruction of engineering structures and the slope in the village Yantarny: (a–d) at the pumping station; (e–h) – near the bank-protective retaining wall: (a) and (e) – January 4, 2022; (b) and (f) – January 18, 2022; (c) and (g) on January 23, 2022; (d) and (h) on February 11, 2022.

North Coast:

- from Cape Taran, the entire northern coast of the Sambia Peninsula was marked by sea erosion of coastal cliffs, erosion of the native coast with landslides and tree collapse (Figure 4);
- in the area of the village Otradnoye, active erosion of the coastal cliff was accompanied by the collapse of extended sections of the piled concrete belt. In the city of Svetlogorsk, in the western part of the beach, along a stretch of several tens of meters, gabion structures (built as supports for crumbling cliffs) collapsed along with slope erosion and landslides (Figure 4a). In the cities of Svetlogorsk and Pionersky, promenades were damaged (staircases, sections of fences and handrails, embankment coverings, retaining walls made of gabions, a technical road made of concrete slabs) (Figure 4b, c);
- in the section from Pionersky to Cape Gvardeisky, the slope receded by 1–4 m with the destruction of part of the pine forest (Figure 4d). In the village Zaostrovye the gabion retaining wall at the base of the slope (built in 2016) did not save the cliff behind it from collapse (which had already been partially damaged during the *Alfrida* storm in 2019). The slope receded from the base of the gabion by more than 8–10 m, completely exposing the side and rear parts (by 6–8 m) of the already moving and

Figure 4. Erosion of the shores of the northern coast of the Sambia Peninsula: (a) Svetlogorsk city on February 15, 2022; (b) Svetlogorsk city on January 31, 2022; (c) Pionersky city on February 25, 2022; (d) village Zaostrovye February 12, 2022, (e) village Zaostrovye February 7, 2022, (g) Kulikovo February 1, 2022, (h–k) village Roshchino February 1, 2022, (l–m) village Sokolniki May 2, 2022, (n) the western beach of Zelenogradsk February 2, 2022, (o–p) the root of the Curonian Spit September 3, 2022.

lopsided protective structure (Figure 4e). At the stairway above the gabion, the *Ida* storm swept away several lower flights of stairs and twisted the concrete base;

- in the village Kulikovo, in the back part of the constructed bank-protective piled concrete belt with stone boulder fill (construction in 2020), the formed slope subsided with the exposure of the geotextile substrate. At the new slipway for boats, the soil was washed away and the boulder riprap was destroyed. A significant part of the pine forest was destroyed with the collapse of dozens of trees onto the beach; in some places the slope receded by 3–5 m. Inside the remaining narrow forest belt, there was a pile of uprooted and broken pines (Figure 4f);
- east of the village Kulikovo (village Roshchino) two coastal protection structures were damaged. On both sides of the bank-protective retaining wall made of gabions (in the design of 2018, box-shaped and mattress gabions), erosion of the slope was formed to a depth of more than 2–3 m, exposing the base, side and rear parts of the structure (Figure 4g, h). The second bank protection structure (~200 m east of the first structure), built in 2018, which has a complex multi-layer structure (geotextiles, geomats, geogrids, big bags, metal meshes, gabions), was severely destroyed along the line of contact with the collapsed slope, survived only gabion wall, behind which deep dips of 2–3 m were formed (Figure 4i). Buried concrete slabs with protruding metal rebar and heaps of woven Big Bags (or FIBC Big Bags) were exposed in front of this bank protection facility. Throughout the entire area, a system of cracks formed parallel to the cliff, followed by soil slippage and the formation of landslide ledges up to 2–4 m (Figure 4g–k);
- at the village Sokolniki, the toe of the slope washed away, followed by the collapse of the low cliff. Pointwise, the slope receded to 2–5 m (Figure 4l, m), the edge of the foredune was eroded, and a 1.5–2 m high erosion ledge was formed;
- in the western part of Zelenogradsk, the slopes of the foredune reinforced with geosynthetic materials were damaged (Figure 4n). The central part of the promenade, flights of stairs, the construction site of the cafe, as well as the wooden promenade and wooden slopes to the sea (opposite the city park) were damaged, the edge of the foredune was washed away with the formation of a washout ledge of more than 3 m (the edge of the foredune receded by 1–2 m), and a new slipway and infrastructure elements were damaged near the cemetery. There was a breakthrough of the foredune in the root part of the Curonian Spit, both the old bank protection structures and the newly built ones were damaged (with collapse in the rear part of the structures) (Figure 4o, p). In the village of Lesnoye on the Curonian Spit, the slope of the foredune receded by 2–5 m. The wooden promenade and coastal infrastructure facilities were damaged.

Discussion and results

During the period of extreme storms, intensive processing of the coast and the maximum development of alongshore sand drifts are observed. The coast of the Kaliningrad Region (the Sambia Peninsula, the Vistula and Curonian Spits) are subject to the influence of winds of "effective" directions: 220°–20° points [*Danchenkov et al.*, 2019; *Danchenkov and Belov*, 2019]. Based on the configuration features of the Baltic Sea, northerly winds and associated waves have a maximum acceleration (about 1000 km) and have the highest potential energy. These winds open the northern coast of the Sambia Peninsula of the Kaliningrad Region, which extends from west to east [*Bobykina and Stont*, 2015; *Bobykina et al.*, 2021].

The western coast, stretching from north to south, is exposed to western winds. Strong storms coming to the Kaliningrad Region from the western points generate wind waves that have a relatively short acceleration length – about 300 km. At the same time, the coast, which has a northern exposure, is in the zone of wind and wave shadow.

The sea coast of the Curonian Spit throughout (from the state border to the city of Zelenogradsk) is subject to steady erosion. All storms, regardless of direction, cause damage to the root section of the Curonian Spit [*Danchenkov and Belov*, 2019; *Ryabchuk et al.*, 2020]. The most significant of them, with the destruction or breakthrough of the foredune, are associated with northern winds and a rise in sea level to the level of the height of the beach.

Previously [*Bobykina and Stont*, 2015; *Bobykina et al.*, 2021] noted that there is a trend towards an increase in the number of northern winds, a repeat of the emergency on January 2, 2019 is possible.

After the passage of *clusters* of strong storms in the autumn–winter period on the shores of the Kaliningrad Region, erosion of the bases of cliffs and foredunes is observed everywhere, followed by the strongest collapse of slopes, landslides, the formation of erosion ledges up to 2–3 m, slope retreat up to 1–5 m, damage or destruction of coastal protection structures and objects of coastal infrastructure. All deformed coastal protection structures turn out to be a source of emission and pollution of beaches with geosynthetic materials that were part of their structures (geocells, geomats, bags and big-bag containers, geotextiles, fragments of plastic-coated metal meshes from broken gabions, fragments of BetoBOX shells, waterproofing film, fragments technical interlayers made of expanded polystyrene, etc.) [*Esiukova et al.*, 2018]. It should be noted that in the inter- and post-storm period, all the beaches were covered with a huge amount of grass from eroded slopes, branches and uprooted bushes, algae, wood chips and fragments of wooden piles, and tree trunks. But all these biological ingredients of post-storm erosion of slopes were mixed with mega-, macro-, meso-, micro-debris with a predominance of the anthropogenic component – plastic (Figure 5), which leads to new environmental problems [*Chubarenko et al.*, 2022, 2018; *Esiukova*, 2017; *Esiukova et al.*, 2018].

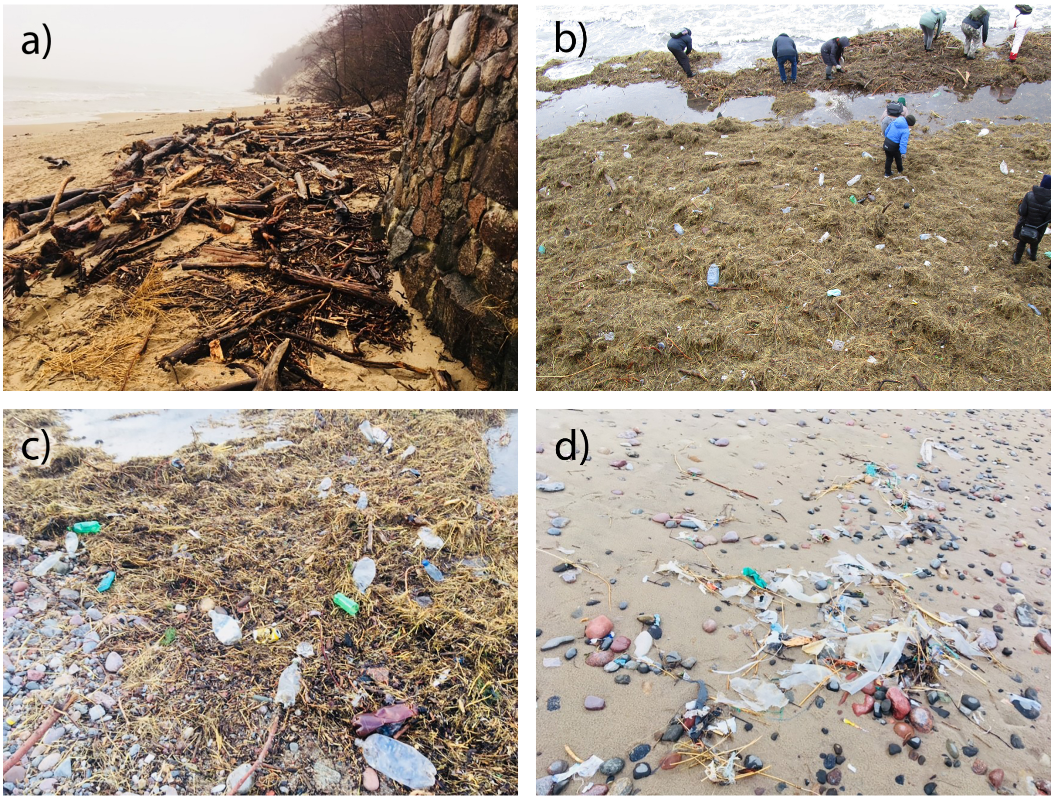

Figure 5. Storm discharges onto beaches containing plastic debris: (a) village Otradnoe January 27, 2022, (b) Zelenogradsk (city beach) February 2, 2022, (c, d) village Sokolniki May 5, 2022.

Under the probable scenario of the continued arrival of storm clusters in the autumn–winter period, further destruction of coastal infrastructure facilities can be predicted, storm waves will erode the bases of cliffs and foredunes, leading to slope collapse. Therefore, measures are needed for the systematic and regular reconstruction of coastal protection structures and shore protection.

It is also necessary to ensure regulatory restrictions in thoughtless development of coastal areas, accompanied by the destruction and tearing of foredunes, improper strengthening of cliff slopes during the construction of technical structures. It is necessary to provide for the construction of slopes to the beach in order to avoid the formation of "wild paths" and passages/driveways (the reason for the formation of new ravines and hollows of blowing). Constant control is needed at coastal points with tourism potential (especially the Curonian and Vistula Spits, the coast from Zelenogradsk to the village of Kulikovo, from Cape Bakalinsky to Baltiysk) by representatives of the police, the Ministry of Natural Resources and other departments to limit violations in the field of parking and the passage of vehicles means (cars, motorcycles, quad bikes) in the water protection zone of the sea; identification of violators who arrange parking in the forest and pave a convenient descent to the beach, cutting down the roots of trees, and burn fires in the middle of the forest and leave piles of rubbish (that is, clear violations of the laws of the "Water Code of the Russian Federation").

Conclusion

It is known that the frequency of clusters of storms over Western Europe is higher than, for example, in the North Atlantic. Deep cyclones often form clusters than ordinary cyclones. In the case of the passage of a cluster of extreme cyclones, material damage and insurance risks for coastal territories increase significantly. Dozens of hectares of coastal territories of the Kaliningrad Region have already been irretrievably lost during periods of such extreme storms.

Taking into account the current trends in the wind-wave regime, such as an increase in wind speed, an increase in the frequency of northerly winds, at which the maximum accelerating wind waves are observed that affect the infrastructure of the coast of the Sambia Peninsula, it is necessary to systematically with serious scientific justifications for all projects and, mainly, comprehensively carry out anti-landslide work, measures for the formation of wide wave-damping beaches, the construction of hydraulic and coastal protection structures using high-quality materials, and, finally, begin to recreate coastal forest belts along the coast and stop cutting down forest areas (a dangerous trend on the Kaliningrad coast when construction of various civil engineering facilities).

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References

Bobykina, V. P., and Z. I. Stont (2015), Winter storm activity in 2011–2012 and its consequences for the southeastern Baltic coast, *Water Resources*, *42*(3), 371–377, https://doi.org/10.1134/s0097807815030021.

Bobykina, V. P., Z. I. Stont, and K. V. Karmanov (2015), Peculiarities of dynamics of the sea coast of the Curonian Spit in the winter period of 2013–2014, in *Problems of explore and conservation natural and cultural heritage of the national park "Curonian Spit"*, 11, pp. 69–78, IK BFU, Kaliningrad (in Russian).

Bobykina, V. P., Z. I. Stont, and A. V. Kileso (2021), Deformations of the marinve coastline of the Curonian spit (South-Eastern Baltic Sea) during autumn-winter season of 2018-2019, *IKBFU's Vestnik: Natural and medical sciences*, (2), 73–83 (in Russian).

Boldyrev, V. L. (1981), On coastal processes in the Baltic, *Water Resources*, (5), 71–76 (in Russian).

Boldyrev, V. L. (2009), Emergency situation on the Kaliningrad coast of the Baltic Sea, *GeoRisk*, (1), 32–34 (in Russian).

Boldyrev, V. L., V. P. Bobykina, and E. M. Burnashov (2008), State of the Curonian Spit coast after the winter storm period, in *Problems of explore and conservation natural and cultural heritage of the national park «Curonian Spit»*, 6, pp. 105–114, IK BFU, Kaliningrad (in Russian).

Chubarenko, B., A. Kileso, E. Esiukova, V. Pinchuk, and F.-G. Simon (2022), Dataset on geosynthetic material debris contamination of the South-East Baltic shore, *Data in Brief*, *40*, 107,778, https://doi.org/10.1016/j.dib.2021.107778.

Chubarenko, I. P., E. E. Esiukova, A. V. Bagaev, M. A. Bagaeva, and A. N. Grave (2018), Three-dimensional distribution of anthropogenic microparticles in the body of sandy beaches, *Science of The Total Environment*, *628–629*, 1340–1351, https://doi.org/10.1016/j.scitotenv.2018.02.167.

Danchenkov, A., N. Belov, and Z. Stont (2019), Using the terrestrial laser scanning technique for aeolian sediment transport assessment in the coastal zone in seasonal scale, *Estuarine*, *Coastal and Shelf Science*, *223*, 105–114, https://doi.org/10.1016/j.ecss.2019.04.044.

Danchenkov, A. R., and N. S. Belov (2019), Morphological changes in the beach-foredune system caused by a series of storms. Terrestrial laser scanning evaluation, *Russian Journal of Earth Sciences*, *19*(4), 1–14, https://doi.org/10.2205/2019ES000665.

Esiukova, E. (2017), Plastic pollution on the Baltic beaches of Kaliningrad region, Russia, *Marine Pollution Bulletin*, *114*(2), 1072–1080, https://doi.org/10.1016/j.marpolbul.2016.10.001.

Esiukova, E. E., and Z. I. Stont (2015), On extreme storm erosion of the coast at the root section of the Curonian Spit in the winter period of 2014–2015, in *Problems of explore and conservation natural and cultural heritage of the national park «Curonian Spit»*, 11, pp. 78–91, IK BFU, Kaliningrad (in Russian).

Esiukova, E. E., B. V. Chubarenko, and E. M. Burnashov (2018), Geosynthetic materials as a source of pollution of the marine environment by plastic debris, *Regional Ecology*, *53*(3), 15, https://doi.org/10.30694/1026-5600-2018-3-15-28 (in Russian).

Gidrometeoizdat (1966), *Reference book on the climate of the USSR. Issue 6. Lithuanian SSR and Kaliningrad region. RSFSR. Part III. Wind*, 90 pp., Leningrad (in Russian).

Lehmann, A., K. Getzlaff, and J. Harlaß (2011), Detailed assessment of climate variability in the Baltic Sea area for the period 1958 to 2009, *Climate Research*, *46*(2), 185–196, https://doi.org/10.3354/cr00876.

Nesterov, E. S. (2018), *Extreme cyclones in the Atlantic-European region*, 104 pp., Hydrometeorological Scientific Research Centre of the Russian Federation, Moscow (in Russian).

Pietrek, S. A., J. M. Jasinski, and I. A. Winnicki (2014), Analysis of a storm situation over the southern Baltic Sea using direct hydrometeorological and remote sensing measurements results, *Scientific Journals. Maritime University of Szczecin*, *38*(110), 81–88.

Ryabchuk, D., A. Sergeev, E. Burnashev, V. Khorikov, I. Neevin, O. Kovaleva, L. Budanov, V. Zhamoida, and A. Danchenkov (2020), Coastal processes in the Russian Baltic (eastern Gulf of Finland and Kaliningrad area), *Quarterly Journal of Engineering Geology and Hydrogeology*, *54*(1), https://doi.org/10.1144/qjegh2020-036.

Stont, Z. I., M. O. Ulyanova, E. V. Krek, D. A. Churin, and D. E. Gubareva (2019), Stormactivity during autumn-winter period of 2018–2019 in the South-Eastern Baltic sea, *Scientific journal "KSTU News"*, (53), 61–72 (in Russian).

Zhindarev, L. A., A. S. Khabidov, and A. K. Trizno (1998), *Dynamics of sandy shores of seas and inland waters /*, 271 pp., Nauka Publishers, Novosibirsk (in Russian).