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"DIVING" CYCLONES AND CONSEQUENCES OF THEIR IMPACT ON THE COASTS OF THE SOUTH-EASTERN BALTIC SEA

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A generalization of historical data for more than 40 years on destructive cyclones observed on the coast of the South-East Baltic Sea has been made. According to the trajectories reconstructed using the HYSPLIT calculation model, cyclones with a northern trajectory, the so-called "diving" cyclones, were identified. A register of such cyclones has been compiled, showing their increasing occurrence: since the 80s of the last century, two such cyclones have passed (1981 and 1983), and since the beginning of this century, over a 22-year period – 14. They differ in a significant acceleration length – about 1000 km from the Gulf of Bothnia to the southeastern coast of the Baltic Sea and have high potential energy. At the same time, atmospheric vortices cause wind waves up to 7–8 meters high. They are associated with significant, sometimes catastrophic, abrasion and retreat of coasts, especially the northern exposure, as well as the destruction of the coastal infrastructure of resort towns, including federal ones, historically concentrated on the northern coast of the Kaliningrad (Sambia) Peninsula of the Kaliningrad Region. The degree of destruction after the impact of each cyclone depends on the prehistory of its formation and development, the height of the surge of coastal waters, and the morphological features of the coast. There are two main scenarios for the development of seasonal storm activity. For example, in the winter season 2011–2012 and 2018–2019 after active cyclones with strong westerly winds of more than 20 m/s, which raised the sea level to +(40–60) cm, the approach of a "diving" cyclone with storm northerly winds caused an instant "splash" of the level up to +(100–120) cm above the ordinary (the marked maximum was 160 cm), which corresponds in order of magnitude to the heights of the beach. The second scenario is associated with the development of a series (cluster) of cyclones. It manifested itself especially clearly in the winter season of 2022, when four "diving" cyclones passed with short windows of good weather. The western cyclone was the final one. On the coast of the Kaliningrad Region, the level rose significantly. Both scenarios of the passage of "diving" cyclones are associated with the greatest storm damage to the coast of the Kaliningrad Region.

Keywords: storm, "diving" cyclones, coast dynamics, sandy accumulative coast, foredune, sea level, Kaliningrad Region, Baltic Sea, Curonian Spit, coast protection structures

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INTRODUCTION

In all sub-basins of the Baltic Sea, the duration of high sea levels significantly exceeds low sea levels [*Wolski and Wiśniewski*, 2020]. This asymmetry is due to the physical nature of the storm surge, which most often occurs when the Baltic Sea fills up earlier and the water rises due to the negative pressure from the movement of a deep area of low pressure (barometric effect). As a result, these factors will prevent a rapid and significant drop in sea level with negative storm surges and strong offshore winds.

According to *Majewski et al.* [1983], high sea levels on the southern coast of the Baltic Sea cause cyclones moving mainly from the North and Norwegian seas from west to east and southeast. In addition, the transitional position of the open waters of the South Baltic Sea affects the magnitude

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of extreme sea level fluctuations. Historically, the highest storm surges have been 5.7–5.8 m above mean water level, and such events can occur at either end of the elongated Baltic Sea: in the Neva Bay near St. Petersburg, Russia, and in the coastal region near Schleswig, Germany [*Post and Kõuts*, 2014]. Extremely high sea levels in the Central Baltic occur in the coastal waters of some semi-enclosed sub-basins that are open to the west, since this sector is where the strongest winds in the area blow.

Baltic polar cyclones, sometimes referred to as Baltipolar cyclones, are rare meteorological phenomena observed in the Baltic Sea `https://hypotheticalhurricanes.fandom.com/`. Due to warmer and drier conditions, polar cyclones in the region are much less common: between 1940 and 2010, only about 100 polar storms have been recorded. A newly invented mode of atmospheric variability called the Baltic-North Sea Oscillation (BANOS), which resembles an eastward-centered NAO. The BANOS index revealed a strong relationship with sea level variability in the open sea during the period 1993–2013, locally explaining up to 90% of interannual sea level variability in winter and up to 79% in summer. Both SCAND and BANOS have their northern centers in the Baltic Sea Region, which explains their strong influence on the low-frequency variability of the Baltic Sea level.

Most cyclones approaching the Baltic Sea Region come from westerly directions, but some approach from other directions as well. Skagerrak cyclones and cyclones developing downwind of the Scandinavian Mountains, often triggered by lows to the west of the mountains, are the most common in the Baltic Sea Region. About 40% of Baltic cyclones are generated in the Baltic Sea Region [*Sepp*, 2009]. Although the number of cyclones formed in the Baltic Sea Region did not change between 1948 and 2002, the cyclones became deeper.

On average, one or two polar systems form each year in the Baltic Sea, usually between November and January. They usually form in the Gulf of Bothnia, less often in the Gulf of Finland or the central part of the Baltic Sea. In the southern part of the Baltic Sea, they also form rarely, approximately once a decade [*Sepp et al.*, 2018].

The current literature on storm surges and extreme levels of the Baltic Sea caused by such surges is extensive and focuses mainly on the coasts of individual Baltic countries: Poland [*Wiśniewski and Wolski*, 2011; *Wolski and Wiśniewski*, 2020], Germany [*Jensen and Müller-Navarra*, 2008], Denmark [*Hallegatte et al.*, 2011], Sweden [*Hammarklint*, 2009], Lithuania [*Dailidiene et al.*, 2006], Estonia [*Suursaar et al.*, 2009], Finland [*Johansson et al.*, 2004]. Moreover, some studies covered part of the coast of the Baltic Sea, for example, the western and central part of the Southern Baltic Sea [*Sztobryn et al.*, 2009], the eastern coast of the Baltic Sea [*Averkiev and Klevannyy*, 2010; *Medvedev and Kulikov*, 2021; *Soomere and Pindsoo*, 2016].

The occurrence of extreme sea levels resulting from storm surges along the coasts of the Baltic Sea depends on three components [*Wiśniewski and Wolski*, 2011]:

- volume of water in the Baltic (initial sea level before the occurrence of the extreme event),
- the effect of tangential winds (wind direction: towards the coast orthe sea, wind speed and duration of the wind),
- deformation of the sea surface by mesoscale baric depressions rapidly passing over the southern and central Baltic Sea, which leads to the formation of so-called baric waves and seiche-like sea level fluctuations in the Baltic Sea.

During the period of extreme storms, there is an intensive processing of the coast and the maximum resuspension of sediments on the underwater coastal slope, their redistribution by a system of alongshore and transverse currents. The coast of the Kaliningrad region (the Sambia Peninsula, the Vistula and Curonian spits) are exposed to winds of "effective" directions – 220° to 20° points, wind waves from which are most dangerous for the coast [*Bobykina and Stont*, 2015a; *Bobykina et al.*, 2021; *Danchenkov et al.*, 2019]. According to [*Wolski and Wiśniewski*, 2020], the southeastern Baltic (in particular, the coast of the Kaliningrad Region) belongs to the area for which the following indicators are typical: a) 3000–4000 h at a level of ≥ 70 cm, b) 100–400 h at a level ≥ 100 cm, c) 200–1000 h at a level ≤ -70 cm, d) 0–50 h at a level ≤ -100 cm (sea level relative to zero). The duration of periods with a high level is much longer than with a low level. This phenomenon is observed in all sub-basins of the Baltic Sea.

For "diving" cyclones coming along the northern trajectory, the winds of the northern rhumbs are characteristic. The waves generated by them have the maximum acceleration across the entire Baltic Sea (about 1000 km) and have the highest potential energy. These winds and waves approach across the strike of the northern coast of the Sambia Peninsula, and the southern root part of the Curonian Spit (stretch from west to east). Their destructive power is most manifested here. The western coast, stretched from north to south, is exposed to western winds. The length of wave acceleration caused by these winds is about 300 km. In recent years, due to climate change, storms associated with the passage of "diving" cyclones, which cause significant abrasion to the coasts of the Kaliningrad Region, have become increasingly frequent. This was especially pronounced in the winter 2022, when four "diving" cyclones passed one after another in January.

The purpose of the study is to analyze the coastal response to northern storms ("diving" cyclones) at the end of the last and the beginning of this century at the Kaliningrad coast (South-East Baltic Sea) as an example, using the method of conjugate analysis of storm conditions and quantitative characteristics of coast reshaping.

MATERIALS AND METHODS

The characteristic of storm winds was determined the period 2004–2022 according to hourly data received from an automatic weather station installed on an oil platform D-6 22 km offshore (Figure 1). Wind speed is based on a standard height of 10 m. A storm wind was a wind force of 8 or more (wind speed >15 m/s) and a duration of at least 6 hours.

The synoptic situation was estimated from surface atmospheric pressure maps for 00 UTC from the Bracknell Meteorological Center archive (https://www.metoffice.gov.uk/). Using the HYSPLIT trajectory calculation model (https://ready.arl.noaa.gov/HYSPLIT_traj.php), extreme cyclone trajectories were reconstructed and the type of cyclone was determined.

Sea level data were taken from the Unified State System of Information on the Situation in the World Ocean (http://portal.esimo.ru/). Level data in 2021–2022 were obtained using an automatic level gauge Valeport Tide Master (United Kingdom) installed in the water intake shaft in Svetlogorsk city (see Figure 1). The wave height was given using forecast maps of the Interdisciplinary Centre for Mathematical and Computa-

Figure 1: Study area. Location of weather station (D6) and level gauge (Svetlogorsk) is shown with asterisks. Alphanumeric designations show the position of stationary coastal cross sections.

tional Modelling, University of Warsaw (`https://www.meteo.pl`).

Quantitative data on the storm processing of the sea coast of the Curonian Spit and the Sambia Peninsula were obtained from the materials of coast monitoring of stationary coastal cross-sections tied to benchmarks (see Figure 1). The choice of places for laying benchmarks was carried out according to the principle of uniform coverage of the most characteristic morphodynamic areas. As part of the coastal monitoring, annual trigonometric leveling is carried out using a tacheometer. To obtain a quantitative characteristic of the dynamics, the difference in the distance (horizontal distance) from the benchmark to the marker is taken – the edge of the ledge of the abrasion or the sea slope of the foredune. Sometimes this is a well-defined bend in the upper part of the foredune slope [*Bobykina*, 2018].

“Diving” cyclones: characteristics and impact for the coastal zone for the period 1981–2022

“Diving” cyclones 80s of the 20th century

The main role in the cyclogenesis of the Northern Atlantic belongs to the North Atlantic Oscillation (NAO) [*Cheng et al.*, 2011]. It is known that the correlation coefficient between the monthly NAO index and wind speeds in the Gulf Stream area is +0.71. With a positive NAO phase, western transport increases, the frequency and depth of cyclones increase, and their trajectories shift northward [*Nesterov*, 2018]. However, the effect of large-scale atmospheric circulation, represented by the NAO index, on the Baltic Sea level is not stationary in time [*Andersson*, 2002]. The NAO has a strong influence on winter sea level variability at central and northern mareographic stations, with a much smaller influence in the southern part of the Baltic Sea [*Hünicke and Zorita*, 2008]. Mean sea level is anticorrelated with NAO in the short term, while in the long term they positively correlate for most stations [*Bastos et al.*, 2013].

An increase in cyclonic activity and the frequency of occurrence of westerly winds over the Baltic Sea, as well as a trend towards an increase in cyclogenesis, were noted throughout the 20th century [*Eremina*, 2016]. In the second half of the 20th century, the maximum circulation activity of the atmosphere was observed [*Pietrek et al.*, 2014], associated with the positive phase of the NAO index and characterized by strong westerly winds and an increase in storm conditions in the Baltic Sea. Then, from the mid-1990s, there was a trend of negative index values, which led to a weakening of western air flows.

Tn the second half of the 20th century in the southeastern part of the Baltic Sea, at least 6 extreme storms were noted [*Kirlis*, 1990]: February 1962, October 1967, November–December 1971, January 1975, November 1981, and January 1983. The proportion of deep cyclones has increased in recent years, but the total number of cyclones has not changed [*Sepp*, 2009; *The BACC II Author Team*, 2015].

Let us consider the generalized Calendar of the main “diving” cyclones observed in the southeastern part of the Baltic Sea and the consequences of the wave-wind impact of storms on the Kaliningrad coast (Table 1).

In historical terms, the archives preserved documents about the devastating storms of the 80s of the 20th century. The reconstructed trajectories (Figure 2) made it possible to attribute the storms that came to the Southeast Baltic Sea in November 1981 and January 1983 to the category of “diving” cyclones.

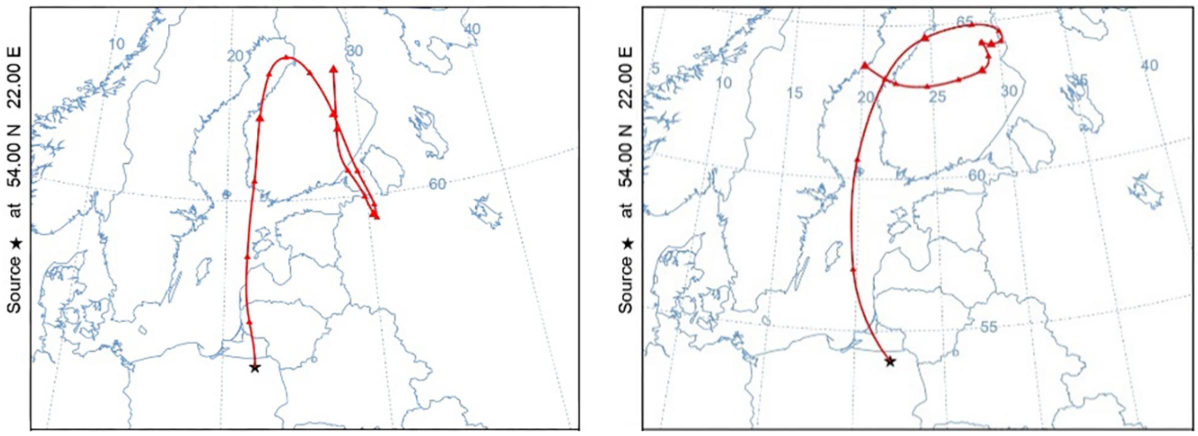

Figure 2: Reconstructed trajectories of “diving” cyclones: left – November 2, 1981; right – January 18–19, 1983.

Table 1: Calendar of the main "diving" cyclones and their characteristics for the Southeastern Baltic Sea and the Kaliningrad Region for 1981–2022

Date	Wind characteristics		Sea level (cm of the BS)	Wave height (m)
	rhumb	speed (m/s)*		
1981 November 2	NW→N	35 (40)	Baltiysk +73 Pionersky +107	No data
1983 January 18–19	W→ NW→N	25 (45–50)	Baltiysk +117 Pionersky +135	7–8 (> 11)**
2006 November 2	NW→N→NE *Britti*	20–25	Baltiysk +70 Pionersky +105	5–6
2007 January 19	NW *Kirill*	21 (25)	Baltiysk +95 Pionersky +96	4–5
2012 January 12–13	NW→N *Elfriede*	up to 22 (28)	Baltiysk +99	5–6
2016 November 27–28	NW→N→NE	22	Baltiysk +60 Pionersky +77	4
2017 January 4	N→NE *Axel*	24	Baltiysk +69 Pionersky +82	5
2018 October 24	NW→N *Siglinde*	24	Baltiysk +63 Pionersky +112	4
2019 January 2–3	N→NE *Alfriede*	23	Baltiysk +68 Pionersky +92	7–8
2021 December 19	N	20	Svetlogorsk +38	3
2022 January 14–15	NW→N *Elsa*	20	Svetlogorsk +44	3
2022 January 17	W→NW→N *Gerhild*	25	Svetlogorsk +67	5–6
2022 January 20–21	NW→N *Ida*	24	Svetlogorsk +89	6–7
2022 January 28–29	NW→N *Mari*	23	Svetlogorsk +58	5
2022 January 31	W→NW *Nadya*	27	Svetlogorsk +93	7–8

Notes: * – gusts are given in brackets; ** – [*Kirlis*, 1990].

In the autumn of 1981 (November 2–3), a "diving" cyclone entered the southeastern part of the Baltic Sea. The speed of the northwest wind was 35, in gusts 40 m/s [*Kirlis*, 1990]. According to the strength of the impact on the coastal zone, it was classified as recurrence 1 time in 25 years. The storm caused the sea level rise up to 1.07 m (see Table 1).

The northern coast of the Sambia Peninsula was especially affected. Coast protection structures in resort towns were destroyed to varying degrees. On the promenades, the stairs to the beach were destroyed, the railings were broken. In some places, the debris floating on the sea surface was thrown on the beach up to a mark of +2.8 m. Northern beaches decreased by almost 2 times – from 45–50 to 25–30 m, in some places they were completely washed away. In abrasion areas with a steep coastal slope, the base of the slopes was washed away; the coast receded by 2–6 m. On the Curonian Spit, the base of the dune (4–5 m) was washed away almost everywhere. Particularly catastrophic erosion was noted in the root part of the Curonian Spit for 25 km from the city of Zelenogradsk. In many places, the road was flooded and the sea water stood in the lowlands of the spit for more than a year. Near the city of Baltiysk, a strip of coastal dunes was washed away for 6 km [*Boldyrev et al.*, 1990; *Kirlis*, 1990].

Throughout January 1983, windy weather was observed in the South-Eastern Baltic Sea. The peak of storm activity occurred on January 18–19, when a hurricane of exceptional strength (recurrence of 1 time in 100 years) hit the Kaliningrad coast, coinciding with a period of increased storm activity in the sea [*Rybak et al.*, 1979]. The speed of the northwest wind, which gradually set to the northern rhumbs, reached 25–30, and in gusts 45–50 m/s. According to visual estimates, the wave height was up to 7–8 m [*Boldyrev et al.*, 1990]. The hurricane caused sea waves up to 9 points (according to World Meteorological Organization sea state code) and a surge sea level rise near the coast of the Curonian Spit from 3 to 4 m [*Kirlis*, 1990]. According to the trajectory, the cyclone can be attributed to "diving" ones (see Figure 2). The storm period dragged on for 10 days (until February 2), while usually the duration of strong storms is 1–1.5 days.

On the northern coast of the Sambia Peninsula (Pionersky), the surge level rise was 1.35 m, in Baltiysk (western coast) 1.17 m (see Table 1). At the root of the Curonian Spit, the level rise was 1.8–1.9 m. Here, for 700 m, the remains of the foredune were completely destroyed, which led to the overflow of sea water onto the lower sections of the spit and its flooding. Sea waters 3 times connected with the waters of the Curonian Lagoon. A breakthrough occurred on the northern edge of the village Lesnoy, there was a threat of flooding the village. Erosion was noted for 27 km northward from the root of the spit. On the remaining part of the spit, areas of erosion, accumulation, and stable ones alternated. The foot of the foredune receded by 5–20 m. A steep ledge from 10 to 25 m high was formed along the entire perimeter of the Sambia Peninsula, the coast receded by 11–30 m. The beaches on the Sambia Peninsula and the root part of the Curonian Spit were washed away, exposing the underlying rocks. Coastal protection and coastal infrastructure of resort towns were damaged. Dips formed on the promenade due to sediment subsidence (Figure 3).

After 1983, winter storms of varying intensity were observed every year, but due to their strength they were not included in the list of storms that had a northern trajectory and led to catastrophic destruction. In the autumn-winter storm periods, an intense impact of the surf on the coast protection structures, cutting the base of the coastal ledges was noted. In the second half of the 1990s there was an increase in the number of cyclones and a decrease in the first half of 2000, which coincided with an increase in the NAO [*Nesterov*, 2018].

Comparison of data on the rate of coastal retreat after extreme storms with average annual ones showed an increase by 5–10 times, and in problem areas by 20–60 times [*Boldyrev et al.*, 1990].

"Diving" cyclones in the first quarter of the 21st century

In the autumn-winter period of 2006–2007 (October–January), a total of 22 storms were observed, predominantly moving along a western trajectory. But the storm season began with a "diving" cyclone that came from the north. The storm of 2006 (November 2) was named *Britty*. The northern wind with a speed of up to 25 m/s generated waves with a maximum acceleration up to 5–6 m high. For 20 hours, under the influence of the northwestern, turning into the northern wind, the sea level rose sharply from zero post to +105 cm BS (Pionersky) (see Table 1).

Subsequent storms of the autumn-winter period are of the western type. The January storms came in a series of short "windows of good weather". The wind speed of the western rhumbs reached 20 m/s and more, in gusts – 23–25 m/s. The maximum duration of the *Kirill* storm (January 19, 2007) was 29 hours. The waves reached 5–6 points [*Boldyrev et al.*, 2008], the wave height was 4–5 m [*Bobykina and Stont*, 2014]. The level rose to +96 cm, according to other sources up to +150 cm [*Boldyrev et al.*, 2008]. Due to the strength of the impact on the coast and the damage caused, this storm can be characterized as a storm of 2% probability that is as a storm with a frequency of 50 years. It caused erosion of the entire coast of the Kaliningrad Region. *Kirill*, like many other severe European winter storms, was embedded in a pre-

Figure 3: Consequences of the hurricane on January 18–19, 1983. Flashes on the promenade (Zelenogradsk). Photo: `https://vk.com/zlk_overhear`.

existing anomalously wide north-south mean sea level pressure (MSLP) gradient field. In addition to a number of gusts that would be expected from a synoptic-scale pressure field, mesoscale features associated with convective overturning at a cold front are proposed as likely causes of the extremely destructive peak gusts observed at many lowland stations during the passage of the *Kirill* cold front. Compared to other storms, *Kirill* was far from the most intense system in terms of main pressure and circulation anomaly. However, the system moved into a pre-existing strong MSLP gradient over Central Europe that extended into Eastern Europe [*Fink et al.*, 2009]. This fact is considered to be decisive for the abnormally large area affected by the *Kirill*.

On the Russian part of the Curonian Spit, the coast was washed away along the entire perimeter (with the exception of the area bordering Lithuania), with the formation of a 2–3 m high erosion ledge on the sea slope. For 27 km from the city of Zelenogradsk, 5–6 m of foredunes were washed away, the maximum (–13 m) was recorded on the outskirts of the city. On the beam of dune Mount Efa, more than 10 m of the coast was washed away. At the same time, accumulation was observed on the eastern segment, the young foredune advanced by 1.7 m.

On the northern coast of the Sambia Peninsula, the edge of the erosion ledge receded from –0.1 m (Filino area) to –3.0 m (Kulikovo settlement). On the western coast of the peninsula, erosion was observed from Cape Taran to the city of Baltiysk, where it reached more than 12 m near Cape Okunevsky, in the area of Baltiysk 0.5–3 m. On the Baltic Spit, its northern tip was subjected to maximum destruction. To the west of the Baltic Strait, 4–13 m of the foredune was washed away.

For the autumn-winter period 2011–2012 over 20 storms have been recorded. At the end of November, deep Atlantic cyclones and the frontal sections associated with them, moving through the South-Eastern Baltic Sea, caused the western wind to increase to a storm (29 m/s, gusts 37 m/s). The duration of the storm was ~40 hours [*Bobykina and Stont*, 2015a]. The probability of measuring this speed in November is about 0.1% [*Gidrometeoizdat*, 1966] The level in Pionersky rose sharply to +56 cm and then fluctuated around +40 cm. In December, storm activity intensified, nine North Atlantic cyclones were noted with wind speeds up to 20 m/s (4 of them with a speed of more than 20 m/s) from the western rhumbs with a duration of up to 2 days. At the beginning of January 2012, several more storms determined the weather in the South-Eastern Baltic Sea.

The storm of 2012 (January 12–14), called *Elfrida*, hit the northern coast of the Sambia Peninsula, caused significant damage on the coasts with a northern exposure. This "diving" cyclone was distinguished by its peculiarities both in its formation and in its consequences [*Bobykina and Stont*, 2015a]. By the time the "diving" cyclone *Elfrida* entered the South-Eastern Baltic Sea, the sea level fluctuated around +50 cm BS.

On January 12–13, 2012, the Atlantic cyclone, centered over the Leningrad Region, began to move along the trajectory characteristic of "diving" cyclones – along the eastern coast of the Baltic Sea and through the Baltic states reached Belarus and further to Ukraine (Figure 4 left).

In the back part of cyclone *Elfrida*, the northerly wind increased to a storm. The maximum speed was 22 m/s, gusts 28 m/s. The calculated probability of occurrence of such a wind from the northern points is less than 0.1% [*Gidrometeoizdat*, 1966]. Surge north wind raised the sea level to +99 cm BS (Baltiysk). The duration of the storm was 36 hours; the storm north wind, having an acceleration of up to 1000 km, raised a wave up to 5–6 m high (code

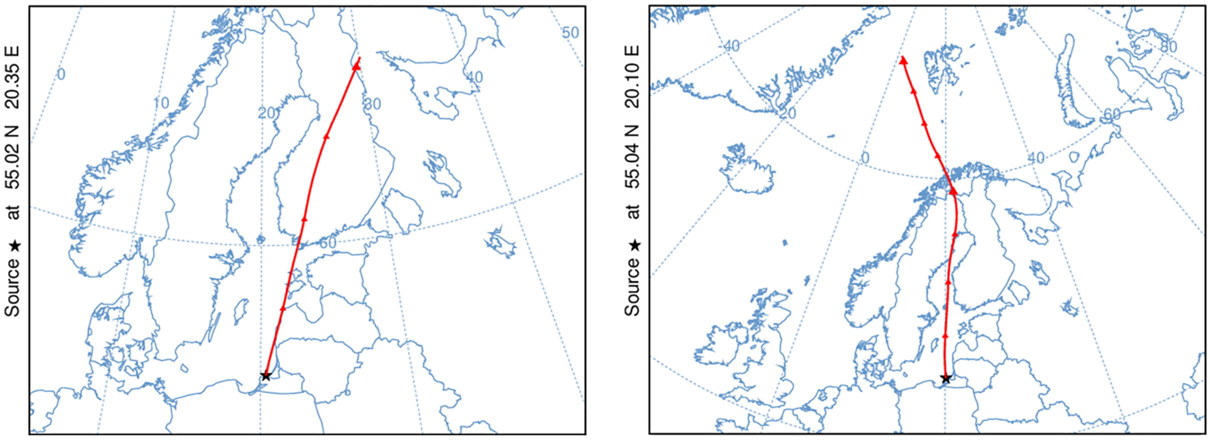

Figure 4: Reconstructed trajectories of "diving" cyclones: left – January 14, 2012 *Elfrida*; right – January 2, 2019 *Alfrida*.

VI – strong). At a high standing sea level (about 100 cm), comparable to the height of the beach, the waves, approaching the northern slope of the Sambia Peninsula along the normal, caused active destruction of the coast and completely washed away the beaches from Cape Taran to the Curonian Spit.

The storm on January 14, 2012 was devastating for the entire coast of the South-Eastern Baltic Sea. In addition to the northern coast of the Sambia Peninsula, the maximum damage with the foredune breakthrough and flooding of the forest massif was noted in the root of the Curonian Spit and the Zelenogradsk area [*Bobykina and Stont*, 2015b]. About 6 m of foredune was washed away. This site, like the entire northern coast of the Sambia Peninsula, has a northern exposure (Figure 1), then the coastline extends in a smooth arc to the northeast. The middle section of the Russian part of the spit remained stable; only the beach was reworked by the storm. In the northern part, 1–3 m foredunes were washed away with the formation of a vertical erosion ledge 2–2.5 m high.

On the Sambia Peninsula, the entire northern coast was subjected to catastrophic erosion. The promenades were destroyed and the beaches of all resort towns were washed away. Coastal erosion ledges receded to the west of the city of Svetlogorsk by an average of 0.3 m, and to the east by 1.5–2 m. The maximum was recorded in the Kulikovo area – about 6 m. On the western coast of the peninsula, south of Cape Taran, the shore receded by 0.5–1.0 m. In the area of Cape Okunevsky, about 10 m of the leaning accumulative terrace was washed away. In Parashutnaya Bay, on the contrary, accumulation proceeded; further south, up to the Baltic Strait, the coast remained relatively stable.

On the Baltic Spit, the largest erosion values were recorded at its northern tip, adjacent to the Baltic Strait, ranging from 7 to 10 m. The rest of the coast to the south experienced selective erosion. It was significant in the southern section, which is more open to northern winds, from 0.6 to 4.5 m. At the same time, the coast remained stable in the middle part.

In the autumn-winter period of 2016–2017 from October 2016 to February 2017, 22 storms were noted, of which 2 were classified as "diving". At the end of November, a storm cyclone with wind direction (up to 22 m/s) and waves (up to 5 m) from the northern rhumbs raised the sea level above the ordinary to +60 to +77 cm BS (Baltiysk and Pionersky) (see Table 1). In early January 2017, in the rear part of the next "diving" cyclone *Axel* (980 hPa), the northeast wind increased to 24 m/s. Wind waves from the north up to 5 m high hit the coast. The sea level rose to +82 cm BS (Pionersky) (see Table 1).

On the northern coast of the Sambia Peninsula, the widespread erosion ranged from 0.2 to 0.8 m, averaging 0.3–0.4 m; near Kulikovo was a maximum of more than 2 m. Everywhere there were traces of significant aeolian transport. On the Curonian Spit, the part bordering Lithuania was subjected to the greatest erosion. At the 43rd km, the foredune edge receded by 1.4 m. At the maximum at the 35th km, where more than 10 m of the foredune was washed away, and deflation turned its back slope into a sandy desert. In the root part of the spit, on the outskirts of the city of Zelenogradsk, about 0.8 m of foredune was washed away. Steadily stable coast was in the middle part.

On the Baltic Spit, erosion of the coast of the village Kosa to the west of the Baltic Strait. At 1st km from it, as a result of washing, a part of the fortification structure (Fort Zapadniy) protruding above the slope of the foredune was refracted and collapsed onto the beach.

Autumn-winter period 2018–2019 began in September, when the South-Eastern Baltic Sea was under the influence of an active Atlantic cyclone with a wind speed of up to 20 m/s. In October, 5 cyclones determined stormy weather, one of them, with a west–northwest wind speed of up to 25 m/s, caused waves up to 4 m and a level rise to +112 cm BS (Pionersky town) (see Table 1). In November–December, the storm situation was calm, the level fluctuated slightly above the ordinary, rising to +20 cm with increasing wind.

On January 2–3, 2019, the "diving" cyclone *Alfrida* came to the region (Figure 4 right). In the rear windy part of the northern cyclone, moving from the Gulf of Bothnia to Belarus, an increase in the north wind (350°–10°) to a storm wind of 23 m/s was observed. Waves 7–8 m high came from the north, had the maximum fetch length for the Baltic Sea and, accordingly, had high potential energy. The sea level rose by almost 1 m and reached +92 cm BS (Pionersky) (see Table 1).

This storm was preceded by Atlantic cyclones coming to the Kaliningrad Region from the southwest and west, which generate wind waves with a relatively short acceleration length (about 300 km). At the same time, the coast of a northern exposure, was in the zone of wind and wave shadow. Therefore, October storms with winds of greater strength and duration did not cause such destruction as the northern cyclone in early January 2019.

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 [*Bobykina and Stont*, 2015a]. On the Curonian Spit, the greatest damage was observed in the outlying areas: in the north (border with Lithuania), the erosion was about 4.5 m, in the southern root part up to 1 m of its sea slope was washed away, a breakthrough of the foredune with flooding of the forest was observed. The middle part of the spit remained relatively stable for about 20 km (0 to −0.3 m).

Autumn-winter season 2021–2022 differs from previous years in increased storm activity. In total, in October–February, the southeastern part of the Baltic Sea was affected by 26 storm cyclones, 8 of them in January, when cyclogenesis sharply increased.

Since mid-January, a series of storm cyclones has been observed, which, according to E. S. Nesterov's definition [*Nesterov*, 2018], can be attributed to a cluster. A cluster of cyclones is a collection of deep cyclones that have passed through a certain area in a short period of time. It is during the formation of the cluster that the maximum destruction of the coast and coastal infrastructure is observed. The series of deep Atlantic cyclones included four of the "diving" category.

On January 15, the arrival of cyclone *Elsa* caused an increase in the northern north wind to 20 m/s, the wave height was 3 m. The level rose by +44 cm BS above the ordinary (Svetlogorsk) (see Table 1).

On January 16–17, in the back part of the "diving" cyclone *Gerhild* (960 hPa), the wind of the northern directions was up to 25 m/s. Accelerating northern waves reached 6.0 m. A rapid rise in the level above the ordinary up to +67 cm BS was noted (see Table 1).

On January 20–21, in the back part of cyclone *Ida* (980 hPa), formed over southern Norway and heading south along the eastern coast of the Baltic Sea and the Baltic states, the gusty northerly wind reached 23 m/s. Wind action generated a wave up to 6–7 m high. The level reached +89 cm BS (Figure 5).

On January 28–29, the next "diving" cyclone *Mari* (975 hPa) with northern winds up to 23 m/s left the Baltic countries and headed towards Belarus, the level increased to +60 cm above the ordinary (see Figure 5).

On the night of January 30, the next very deep (970 hPa) cyclone named *Nadia*, which came along a western trajectory, after overcoming the Scandinavian mountains and descending over central Sweden and the central Baltic, caused an increase in the northwest wind to 27 m/s. The level rose to +93 cm BS (see Figure 5).

The greatest destruction of the coast was recorded in the root part of the Curonian Spit, where the foredune was completely destroyed for more than 1 km, storm waves penetrated into the adjacent forest area. The highway and the forest on both sides of it were flooded for a long distance. The beach in the village Lesnoy was completely washed away, the promenade was destroyed to a metal frame, and the fixed slope of the ledge receded by more than 0.5 m. The edge of the foredune slope from the city of Zelenogradsk to the village Rybachy receded from 0.5 to 7.0 m (23 km) with the formation of a vertical ledge up to 3.5 m high. The northern segment of the spit from the village Morskoe to the Lithuanian border has remained relatively stable. In areas of erosion,

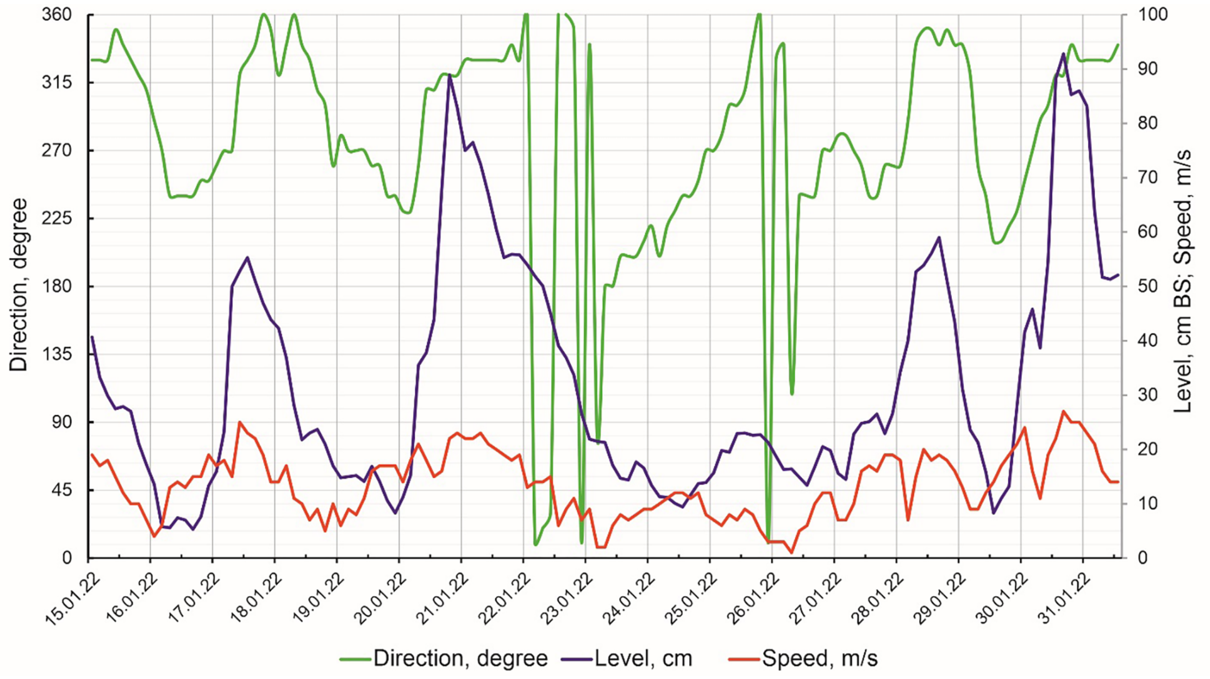

Figure 5: Dynamics of the sea level, direction and speed of the wind during the passage of a series of "diving" cyclones (January 15–31, 2022).

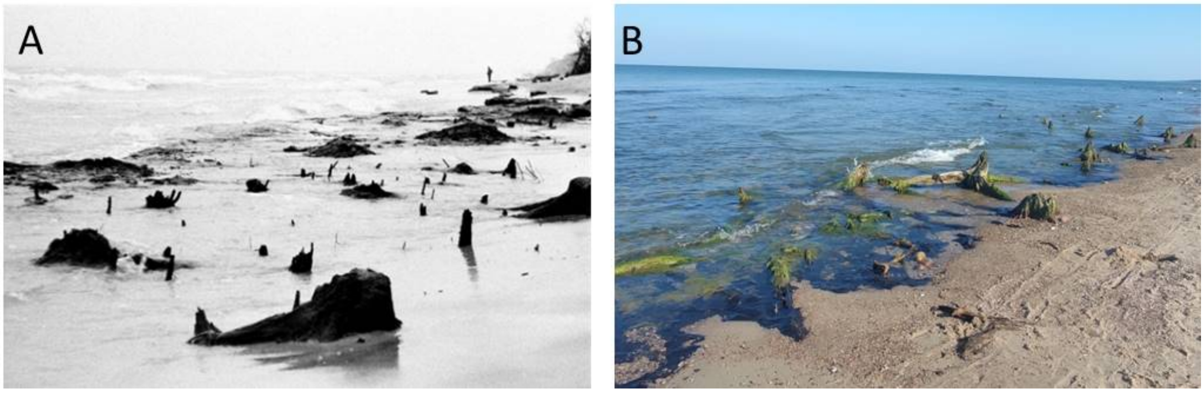

Figure 6: Outcrop of a relict forest on the beach in Zelenogradsk after the cyclones in January: A – 1983 (photo: O. Ryabkova); B – 2022 (photo: M. Ulyanova).

sand deposits has been washed away. Near Zelenogradsk and at 25–27 km, the underlying peat strata were exposed. And in the waterfront strip, the remains of a sunken forest were exposed (Figure 6).

The coastal infrastructure of the resort towns located on the northern coast of the Sambia Peninsula (Svetlogorsk, Pionersky, Zelenogradsk) was destroyed to varying degrees, as well as unprotected sections of the coast in the village of Kulikovo and the Baltic Spit. Here, too, sands were washed off the beaches, exposing a boulder-pebble base.

The erosion of the coast, the destruction of the coastal infrastructure of resort towns and villages (the village of Lesnoy at the Curonian Spit) was presented in more detail as the impact of the storm wind and strong waves of the northern points accompanying the "diving" cyclones that passed in January 2022 (Figure 7).

A consistent surge of waters near the coast was observed: from +44 cm BS (01/15/2022) to +89 cm BS (01/20–21/2022), which is comparable to the height (about 1 m) of the beach in the village Lesnoy (see Figure 7a). The beach was washed out and separate structures of the promenade were destroyed (Figure 7b). On January 30–31, the wind from the north-west increased again to 27 m/s, on the coast in gusts up to 30 m/s. A new storm cyclone began to influence. The sea level rose to +93 cm BS (Svetlogorsk).

In early February 2022 (after the *Nadia* storm) the promenade was completely destroyed, eolian accumulations between the promenade and the coastal slope were washed away and removed, and the slope itself was washed away. The base of the coastal slope was not affected. An erosion ledge 4.5 m high was formed (see Figure 7c, 7d).

Previous storms have washed away the beach's sandy sediment layer, exposing boulders or ancient peatland. Only after the sea level raised above the standard by 0.9 m, the process of intensive erosion of the coastal slope and the destruction of coastal infrastructure began. It should be noted that it is possible that the critical surge height, which causes coastal erosion, is different for different morphodynamic areas depending on the height of the beach.

Conclusion

For the coast of the southeastern part of the Baltic Sea, the most typical are the cyclones of the western rhumbs. However, recently, cyclones coming along the northern trajectory, the so-called "diving" cyclones, have become more frequent. In the rear windy part of such a cyclone, northerly winds (NW-N-NE) with a speed of more than 20 m/s are observed. The wind-wave impact of these cyclones has significant potential energy, since the wave acceleration from the Gulf of Bothnia to the coast of the South-Eastern Baltic Sea is more than 1000 km. The waves that affect the northern shores of the region have destructive energy and lead to catastrophic consequences, especially at high level standing.

Regardless of the rhumb, all storms cause destruction on the root part of the spit. The most significant of them, with the destruction or breakthrough of the foredune, are associated with northern winds and a rise in sea level of more than 1 m (the maximum noted was 1.6 m), which in order of magnitude corresponds to the heights of the beach.

The entire coast of the Russian part of the Curonian Spit is experiencing steady erosion. On individual benchmarks, the total value of the coast dynamics over the 14-year monitoring period approximately corresponds to the total value of storm erosion.

The greatest damage to the shores of the Sambia Peninsula and the root part of the Curonian Spit is associated with the successive passage of a cluster of "diving" cyclones. As a rule, these storms are rarely repeated in strength (mainly 1 in 25, 50 years). They are associated with the destruc-

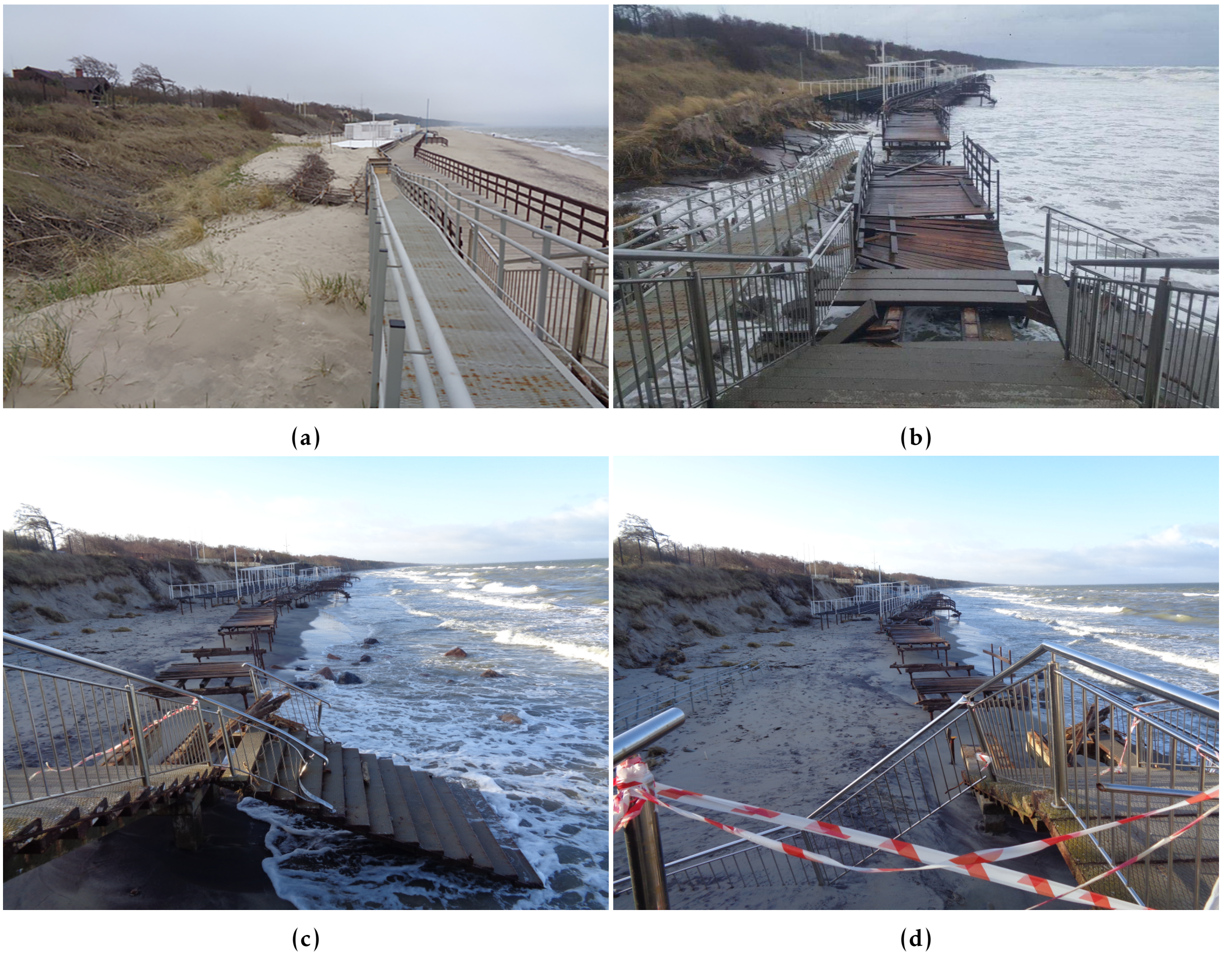
(a) (b) (c) (d)

Figure 7: The destruction of the coast in the village Lesnoy (Curonian Spit) by the cluster of January cyclones on January 15–31, 2022: (a) – village Lesnoy, promenade, before cyclones, May 30, 2021; (b) – after the storm *Ida* on January 20–21 (01/27/2022); (c) and (d) – after the storm *Nadya* on January 30 (02/11/2022). Photo: V. Bobykina.

tion of the coastal infrastructure of historical resort towns on the northern coast of the Sambia Peninsula with active abrasion of slopes composed of glacial deposits. Even on the coast slopes protected by various structures, local erosion of the base is observed with the activation of slope processes, the retreat of the edge of the coastal ledge.

On the dune shores of the Curonian Spit in the root part, only from the beginning of the 21st century after the storm of 1983 (2012, 2019, 2022), a deep breakthrough of sea waters on land was observed during the storm with flooding of a large section of the highway and adjacent forests. This part of the spit is associated with the greatest storm destruction of the foredune. In 2022, for more than 1 km from the city of Zelenogradsk was completely washed away. In the remaining part of the spit, where it changes its strike to the northeast, erosion, stability, or accumulation of the coast during a storm are selective.

An analysis of the cluster of "diving" cyclones in 2022, which consisted of four successive northern cyclones and a final western one, showed that the degree of coastal destruction depends on the number and sequence of their movement, which ultimately leads to the maximum surge rise near the coast of sea level. Sometimes the height of the standing level is equal to or exceeds the height of the beach. It is then that catastrophic erosion of the coast occurs, causing damage to both nature and infrastructure of the coast.

A similar effect was observed from the impact of one cyclone, but of a long duration (the storm of 1983, lasting 10 days), classified as a storm according to the frequency of northerly wind strength 1 time in 100 years.

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