RESEARCH PAPER

DYNAMICS OF DUNE MASSIFS IN VARIOUS METEOROLOGICAL CONDITIONS ON THE EXAMPLE OF THE CURONIAN SPIT (SOUTH-EASTERN BALTIC SEA COAST)

Zhanna I. Stont[1], Alexander Yu. Sergeev[2], Marina O. Ulyanova[1,3*]
[1]Shirshov Institute of Oceanology, Russian Academy of Sciences, 36, Nahimovskiy prospekt, Moscow, 117997, Russia
[2]A.P. Karpinsky Russian Geological Research Institute, 74, Sredny prospect, St. Petersburg, 199106, Russia
[3]Immanuel Kant Baltic Federal University, 14, Nevskogo str., Kaliningrad, 236016, Russia
***Corresponding author:** marioches@mail.ru
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ABSTRACT. A study of geomorphological changes in the continental dune massifs of the Curonian Spit is presented. Analysis of sand dynamics was carried out using satellite images. A relative decrease in the area of open dunes as a result of vegetation of the western slope was revealed. It was determined that the dune belt displacement of the southern part of the Curonian Spit occurs eastward at a speed of 2-5 m per year. Good correlation of the directions of the slopes of large dunes in the villages Morskoe and Rybachy with the direction of the resulting wind vector at the nearest weather station was noted. The relationship between the formation of relief microforms on the surface of the dunes and the resulting wind vector is revealed. In addition, meteorological parameters affecting aeolian processes in the southeast of the Baltic Region were investigated. The prevailing importance for the formation of aeolian relief forms of the Curonian Spit are the speed and direction of the wind in conjunction with precipitation. For the period 2006–2018 the average annual number of favorable days for the formation of the dunes of the Curonian Spit was 36±17.

KEY WORDS: aeolian transport, open dunes dynamics, effective winds, microtopography, limiting conditions

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INTRODUCTION

The main factor in the formation of huge sand bodies on a millennium scale is sea level rise in the presence of excess sand material in the coastal zone and at an optimal angle of approach of the prevailing wind to the general direction of the coastline (Badyukova and Solovieva 2015). Modern climate warming and the associated rise in the level of the World Ocean cause a global process of destabilization of existing coastal dune massifs. Coastal dunes are susceptible to radical changes in the wind regime, storm surges and vegetation. Wind-blown sand represents one of the simplest geomorphological transport systems and its understanding is necessary for study of the coastal dune systems (Ellis and Sherman 2013). The importance of wind-blown sand as an agent of landscape modification has been long recognized, especially in the context of the deleterious effects of sand encroachment on human systems.

As known, regional wind is one of the key factors in the formation (Fryberger 1979; Wasson and Hyde 1983) and orientation (Rubin and Ikeda 1990) of aeolian landforms. Sandy landforms actively interact with the wind, modifying it both in speed and direction. The processes of generating annual sand transport potential and the general direction of transportation are directly related to the processes of dune migration. By analyzing wind conditions, these processes can be associated with the morphology (relief) of the dunes. In addition to wind conditions, other meteorological parameters also affect the dynamics of the dunes: precipitation, air temperature and humidity.

Currently, many scientists are studying the dynamics of dune massifs in the Baltic Sea region (Rivis et al. 2009; Kobelyanskaya et al. 2011; Michalowska et al. 2016; Morkūnaitė 2011; Česnulevičius et al. 2017; Morkūnaitė et al. 2011; Tylkowski 2017; Łabuz et al. 2018). However, the comprehensive studies presented in this paper for the dunes of the Curonian Spit, which are one of the highest dunes in Europe, have not been carried out previously. The aim of the authors was to identify the dependences of the formation and dynamics of open dune massifs on various meteorological parameters. The object of study was the sandy massifs of the Curonian Spit (Southeastern Baltic Region), which is included in the UNESCO cultural heritage list.

MATERIALS AND METHODS
Study area

A specific feature of the geographical location of the Southeastern Baltic Region is its openness for penetration by western transit air masses. The transit of Atlantic cyclones occurs in the absence of orographic obstacles, which determines the local specificity of the wind regime. Wind roses in the southeast of the Baltic Sea are almost symmetrical relative to the axis W-E, the directivity pattern is close to circular, and the absolute values of the resulting wind speed and its stability are low. Nevertheless, the summation of small impulses leads to significant manifestations in mobile mediums (air, sea, and sand): the longer they occur, the more significant the influence is (Abramov and Stont 2004).

In classification of sandy coast sandbars of the Baltic Sea presented in Łabuz et al. (2018) Curonian Spit is a «spit barrier – separate spits, one or two or jointed barrier islands which due to lateral increase formed barrier, separating water body or swamp/wetland, jointed by channel or mouth with the proper sea basin». The Curonian open dune massifs are an «inland coastal sand bodies – shifting or stabilized large dune areas of permanent sand load in the past and accumulation as different large dunes».

The Curonian Spit is the largest coastal accumulative form on the southeastern coast of the Baltic Sea. It extends in a northeastern direction and looks like a flat arc, concave towards the sea. Its total length is 98 km; the width varies from 0.4 to 4 km. Its western (marine) edge is leveled, and the eastern (lagoon) one is indented. The average height is about 40 m, and the maximum is 68 m above the level of the Baltic Sea. The Curonian Spit is a young geological formation that arose 8–5 thousand years ago as a result of the erosion of coasts and the movement of sediments by the coastal currents of the transgressing Baltic Sea (Sergeev et al. 2017). The formation of the spit began in the Middle Holocene, when the sea level was lower than recent. Formation of relict lagoon mud formed behind the sand barrier and presently outcropping nearshore in the vicinity of Lesnoe, Russia, took place between 7.4 and 6 cal. ka BP (Zhamoida et al. 2009). Radiocarbon dating of the lagoon marl (c. 6.9–8.3 cal. ka BP) exposed in the outcrop beneath the Parnidis dune indicates that this sediment is slightly older than that sampled offshore. Dating of the oldest paleosoil of Curionian Spit is dated to c. 5.8 cal. ka BP (Dobrotin et al. 2013). Some archeological sites onshore were dated about 4.5 ka BP (Badyukova et al. 2007). In its modern form, the spit formed about 5 thousand years ago, when the sea level became more or less stable.

The Curonian Spit coast features ridges of high ancient dunes, from 40 to 62–65 m high and 700 to 1200 m wide (Łabuz et al. 2018). Nearly all the dune ridges and masses are artificially forested mainly by mugo and black pines except for four areas between 17 and 75 km of the spit where chains of moving dunes have been left in their natural state.

The modern relief of the Curonian Spit is represented mainly by aeolian sand moving eastward. The speed of movement of sand in different parts of the spit between the first and second halves of the XX century decreased from 4–5 to 2–3 m per year due to anthropogenic interference (Povilanskas et al. 2006). At the beginning of the XX century as a result of deforestation, average speed of dunes migration was 10 m/year (Berendt, 1869).

To analyze the dynamics of the dunes of the Curonian Spit, two key areas on the lagoon coast of the spit were selected: south of the village Rybachy (55.122°N; 20.786°E) and south of the village Morskoe (55.217°N; 20.906°E), where open sections of dunes are developed (Fig. 1).

Satellite images. The decoding of high-resolution satellite images available through the Google Earth service was performed for the following time series: September 20, 2007, July 10, 2010, April 26, 2014, and September 13, 2016.

Sea level. The work used daily satellite altimetry data (Global ocean gridded L4 sea surface heights and derived variables reprocessed) (http://marine.copernicus.eu), which went through the process of post-processing, combining and data quality control by the data providing service. The spatial resolution of the data is 0.25° in latitude and longitude, and the temporal resolution is 1 day. The standard error of the data is 3 cm (for coastal areas). The product MSS_CNES_CLS11 (http://www.aviso.altimetry.fr/) is used as an intermediate level. Conversion, averaging, and other statistical calculations were performed using the Python programming language and Microsoft Visual FoxPro. The average level was calculated for 1993–2019.

Sediment sampling and grain size. To assess the grain size distribution of dune sediments, samples were taken by the envelope method from profiles from the surface horizon of dune massifs near the villages of Morskoe and Rybachy (Fig. 2) on April 26, 2018. The sampling frequency was determined by approximately the same distance between the points at the open dunes (without vegetation). The areas of sampling excluded relief microforms. The grain size analysis provides the data on sediment particles

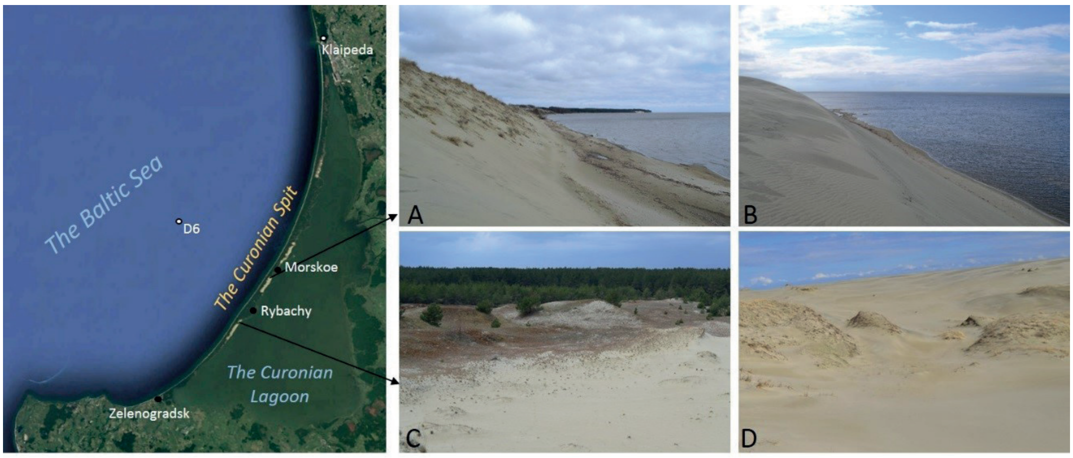

Fig. 1. Geographical location of the research area. The weather stations are located at the oil ice-resistant platform (D6) and in Klaipeda. Arrows indicate the location of the studied dunes. A and B are pictures of the lagoon steep slope of the dunes, near Rybachy and Morskoe respectively; C and D are pictures of the dune surface, partly covered by vegetation near Rybachy and open dune near Morskoe

distribution at the surface of the open dune and helps to reveal the dependence of the grain size from the western and eastern parts of the dunes.

Grain size analysis of surface sand was carried out by the sieve method, sieves mesh sizes of 10; 4; 2.8; 2.0; 1.4; 1.0; 0.71; 0.5; 0.355; 0.25; 0.18; 0.125; 0.1; 0.09; 0.063; 0.05 and less than 0.05 mm on a vibratory sieve shaker Analysette 3 Pro Fritsch (Fritsch, Germany). Classification of particle size distribution was carried out according to (Kachinsky 1965): gravel 3-1 mm; coarse sand – 1-0.5 mm; medium sand – 0.5-0.25 mm; fine sand – 0.25-0.05 mm.

Meteorological data. To analyze the influence of meteorological conditions on the recent transformation of the dunes, the following meteorological data were obtained from the oil ice fixed platform D6 (data of LUKOIL ltd.) and Klaipeda (www.rp5.ru) for 2006–2018 (Fig. 1). Relative air humidity, wind speed and direction, air temperature were obtained from the meteorological station installed on the offshore platform (22 km from the sea coast of the Curonian Spit, Fig. 1). The height of measuring the wind speed is 32 m; according to (Guide… 2008) the speed was reduced to the standard 10 m. The average hourly values of all values were averaged to the daily values, which were used for analysis.

Most of the models of coastal aeolian environments are commonly based at the moist sand surface, surface crusting, variability in the topography, wind and fetch length, and obstructing vegetation (Ellis and Sherman 2013). Since the studied dune massifs are almost completely open (there is almost no vegetation), the parameter of the vegetation cover was not taken into account. September 2016 was comparatively warm (average 16.6^{0}C), thus, at the satellite image the vegetation presents in significant amount. For comparison, the temperature in September in other years was lower (2007 – 15.0^{0}C; 2010 – 14.4^{0}C; 2014 – 15.7^{0}C) and there is almost no vegetation.

The following conditions must be taken into account (Hojan 2009; Hojan and Więcław 2014):

- the amount of precipitation for five days should not exceed 6 mm;
- the average daily humidity is less than 95%;
- the average daily air temperature should be above 0 0C or below –10^{0}C;
- the average daily wind speed is more than 6 m/s;
- direction of effective winds (South-West – North-East according to the orientation of the sea shore (Danchenkov et al. 2019).

The amount of precipitation was considered according to the weather station of Klaipeda (55^{0}42’N 210^{0}9’E; height 6 m; WMO ID 26509). According to the criteria given above, the obtained data were filtered.

RESULTS AND DISCUSSION

Dunes sands grain size

The surface layer of the dune in the village Morskoe is composed mainly of medium sands (0.5–0.25 mm), in some samples their share is more than 80%. Coarse and fine sands were observed in the admixture. The content of the predominant fraction and impurities is uneven and varies from east to west. Thus, the content of fine sand reaches a maximum at points M1/1 (17%), M1/5 (18%), M2/4 (22%) and M2/9 (20%). These values are minimal at points M1/8 (10%) and M2/7 (8%). Coarse sand content is negligible (a maximum of 3.5%). On average, for the massif, the content of fine sand was about 14%, medium-grained 75%, coarse-grained about 11%.

The dune deposits near the village Rybachy were also presented mainly by medium sands. The maximum content of fine sand was observed at point P2/9 (22%). The minimum content was observed at points P2/2 and P2/4 (4%). The maximum values of coarse sand were observed at the point P2/4 (41%); minimum – P1/9 (0.5%). Gravel deposits were noted on both profiles as traces. On average, for the massif, the content of fine sand was about 11%, medium-grained 77%, coarse-grained 12%.

It was supposed that the sediment type distribution along the profiles will indicate the main direction and strength of the sandy particles transport as fine sands are the most mobile in the wind-sand flow, however there was no obvious tendency towards the transport and distribution of the fine sand fraction. The possible reason of such regularity absence may be moving the fine sandy particles off the dune massive to the lagoon. The spatial distribution of sand of various size of the massif south of the village Morskoe was relatively homogeneous. The reason for this may be the openness of the massif (lack of grassy vegetation) and, consequently, the susceptibility to the constant transport of sand over the entire area of the massif. Whereas south of the village Rybachy a certain

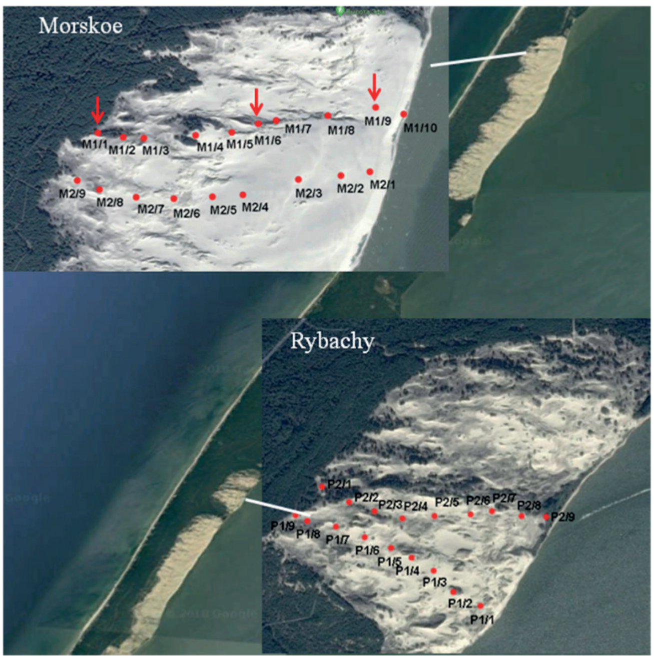

Fig. 2. Location of the samples for grain size distribution analysis (26.04.2018)

regularity was observed: at the edges of the massif (near the forest and the lagoon), the amount of coarse fraction decreased (up to 2-3%), and in the central part of the massif it increases significantly (up to 25%), and gravel appeared.

Water level and weather conditions

The lagoon is non-tidal. By satellite data analysis, the water level monthly anomalies in Curonian Lagoon varied within 0.02 and 0.26 cm (Table 1). Such values could not cause the shift of the beach by up to 4.5 m. At the dates of the passage of satellites, the weak variable winds of up to 5 m/s prevailed, excluding September 2007. On September 20, 2007, a cyclone passed with south-west winds of up to 8 m/s, September 19 – the wind of the western points with a speed of 6 m/s. When the wind subsides (without changing direction), the level quickly returns to its original value.

Aeolian forms dynamics

Results of analysis of remote sensing data are shown in Fig. 3. The zones of vegetation areas represent by dune binding plants (mainly *Lathyris maritimus Bigel, Tragopogon, Viola littoralis L., Cakile baltica Jord. ex Pobed., Anthyllis maritima Schweigg., Erignium maritinum L., Linaria loeselii Schweigg., Lamium*), which fixed sand and areas of bare sands with deflation landforms, where erosion processes lead to the formation of a surface with the removal of sand, exposure palaeosoils and sand movement towards the lagoon. The position and direction of sand ridges of the dunes and sand waves were identified; the position of the coastal line of the Curonian Lagoon was designated. Table 2 shows the numerical characteristics of the position and direction of migration of sand forms for different periods.

Table 1. Water level in the Curonian Lagoon and weather conditions during satellite imagery

Month and year	Water level monthly anomalies, cm	Wind direction and speed in a day of the satellite image
September, 2007	+0.26	20.09.2007: SWW up to 8 m/s
July, 2010	+ 0.03	10.07.2010: variable (W, S, E), weak up to 5 m/s
April, 2014	–0.02	26.04.2014: E, weak up to 5 m/s
September, 2016	+0.03	13.09.2016: E, weak up to 5 m/s

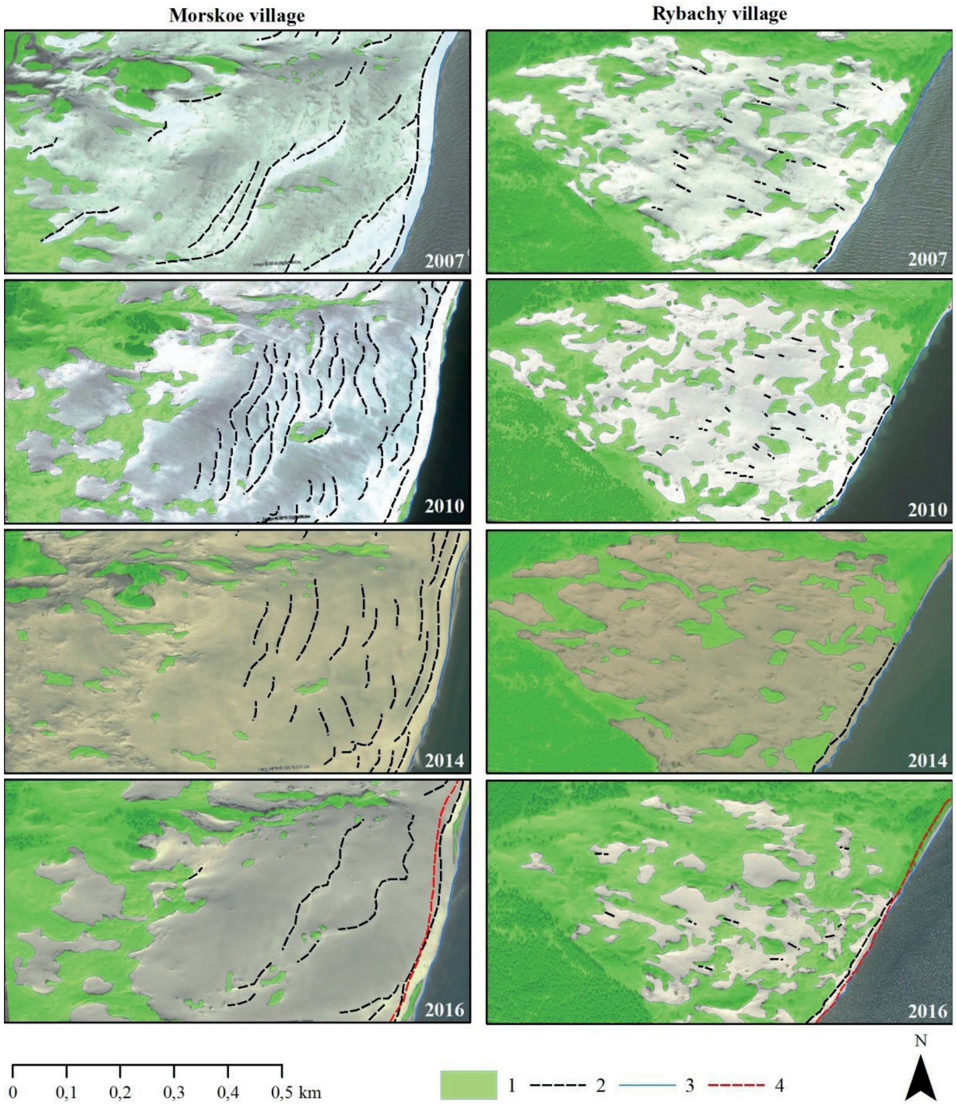

Fig. 3. The dynamics of open dunes in the area of the villages Morskoe and Rybachy according to satellite image interpretation: 1 – zones of sands fixed by vegetation; 2 – crest of a dynamic shape of the relief; 3 – position of the water edge at the date of imagery; 4 – position of the water edge in 2007. The dates of imageries are September 20, 2007, July 10, 2010, April 26, 2014, and September 13, 2016

Table 2. Characteristics of dynamic landforms

The direction of migration of dynamic landforms: «+» eastward, «-» westward					
Movement vector		2007	2010	2014	2016
Average azimuth	Morskoe	140°	170°	162°	145°
	Rybachy	113°	108°	Not detected	101°
Lagoon coastline offset					
Morskoe	edge		2007–2010	2010–2014	201–2016
	average m/year		+4.7	+2.5	+4.5
	average m/year 2007–2016		+3.9		
Rybachy	edge		2007–2010	2010–2014	2014–2016
	average m/year		+2.2	+1.0	–0.2
	average m/year 2007–2016		+1.0		
The dynamics of the vegetation zone and the weathering area					
Morskoe			2007–2010	2010–2014	2014–2016
	km^2 (%)		+0.05 (+83%)	–0.07 (–33%)	+0.1 (+133%)
	km^2		+0.026		
Rybachy			2007–2010	2010–2014	2014–2016
	km^2 (%)		+0.01 (+3%)	–0.03 (–7%)	+0.12 (+33%)
	km^2		+0.033		

When the wind speed reaches critical values, the grains of sand begin to move, and soon after that a wavy interface forms. The generated relief microforms are located along the slopes of the dunes with a long axis parallel to the extent of the slope and are almost always asymmetrical. Usually coarser or denser sand is located on the crest of the microforms. The length and height of microforms increase with strengthen wind and are directly dependent on the size of the sand. When high speeds are reached, the microforms disappear and the sand is distributed in a continuous layer (Vykhovanets 2003). According to the study of migration processes of aeolian forms in the Lithuanian part of the Curonian Spit, aeolian processes are greatly influenced by prolonged winds with an average speed of more than 6 m/s. Strong and constant winds cause rapid drying of sand and activation of deflation processes (Česnulevičius et al. 2017). In the 2007 satellite images, there is low activity of sand movement on the surface of the dunes, expressed in the presence of large rare dunes and partial growing of sand dune vegetation (Fig. 3). In 2010, there was an increased activity of sand migration, appeared in the formation of fine sand waves on the surface of the dune (5–10 m width of the sand wave bars and 25–35 m distance between sand wave bars) and the formation of shadow forms (plume) behind vegetation islands. In 2014, a decrease in the transport intensity was observed, expressed in smoothing and scattering of sand waves on the surface of the dune, as well as in the sand flooding of vegetation developed on the dunes. By 2016, the forms of sand migration take on a form close to 2007; large rare shafts again appear (15–20 m wide asymmetric shaft with an inter-shaft distance of about 100 m). The exposure of the areas of dune overgrowth is maximum for the entire observed period.

Thus, it was obtained that for the period 2007–2014 the speed of the shift of the lagoon coastline to the east amounted to +3.5 m/year in the area of the village Morskoe. According to the data presented in (Povilanskas et al. 2009), the speed of the Skilvit Dunes (southward the village Morskoe) shift to the east varies from 1 to 4.4 m/year for the period of 1909–1990, which is consistent with the data obtained. The data on sea level changes in the months of imagery revealed insignificant anomalies so tides or changes in river inflow quantity cannot be considered as a reason for lagoon shoreline shifting.

The direction of the dunes migration in the village Morskoe during the study period was different (Fig. 4). It can be seen that in 2007 and 2016 the azimuth was 140 and 145°, and in 2010 and 2017 170° and 160° respectively. At the same time, an analysis of the calculated resulting wind vectors for each year showed that in 2007 and 2016 the resulting transfer occurred from southwest to northeast, and in 2010 and 2014 from south to north. Thus, in 2010 and 2014 the difference between the direction of the resulting wind vector and the direction of migration of the dunes was about 180°, and in 2007 and 2016 about 65-80°.

Remote sensing analysis of satellite images of 2007 and 2016 revealed low activity of sand movement on the dunes surface, expressed in the development of large rare dune bars. In 2010 and 2014, on the contrary, sand migration activity was indicated, expressed in the formation of fine sand waves on the surface of the dune array (Fig. 4).

Morphometric analysis of the dunes showed a tendency to fix the western slope of the dunes, denudate the top of the dunes and partially flatten the eastern slope of the dune with its extension to the lagoon. A comparison of the slope directions with the denudation zones shows the prevalence of blowing from the western and north-western slopes, an increase for the opposite slopes – the eastern and south-eastern directions. It can be assumed that the most active sand transport is observed under the winds of the western and northwestern rhombuses (Badiukova et al. 2007, 2009; Povilanskas 2009; Povilanskas et al. 2009; Sergeev 2015).

Studied areas of open dunes differ significantly. Dunes in the area of the village Morskoe is characterized by larger area of open sand then dunes near the village Rybachy. As

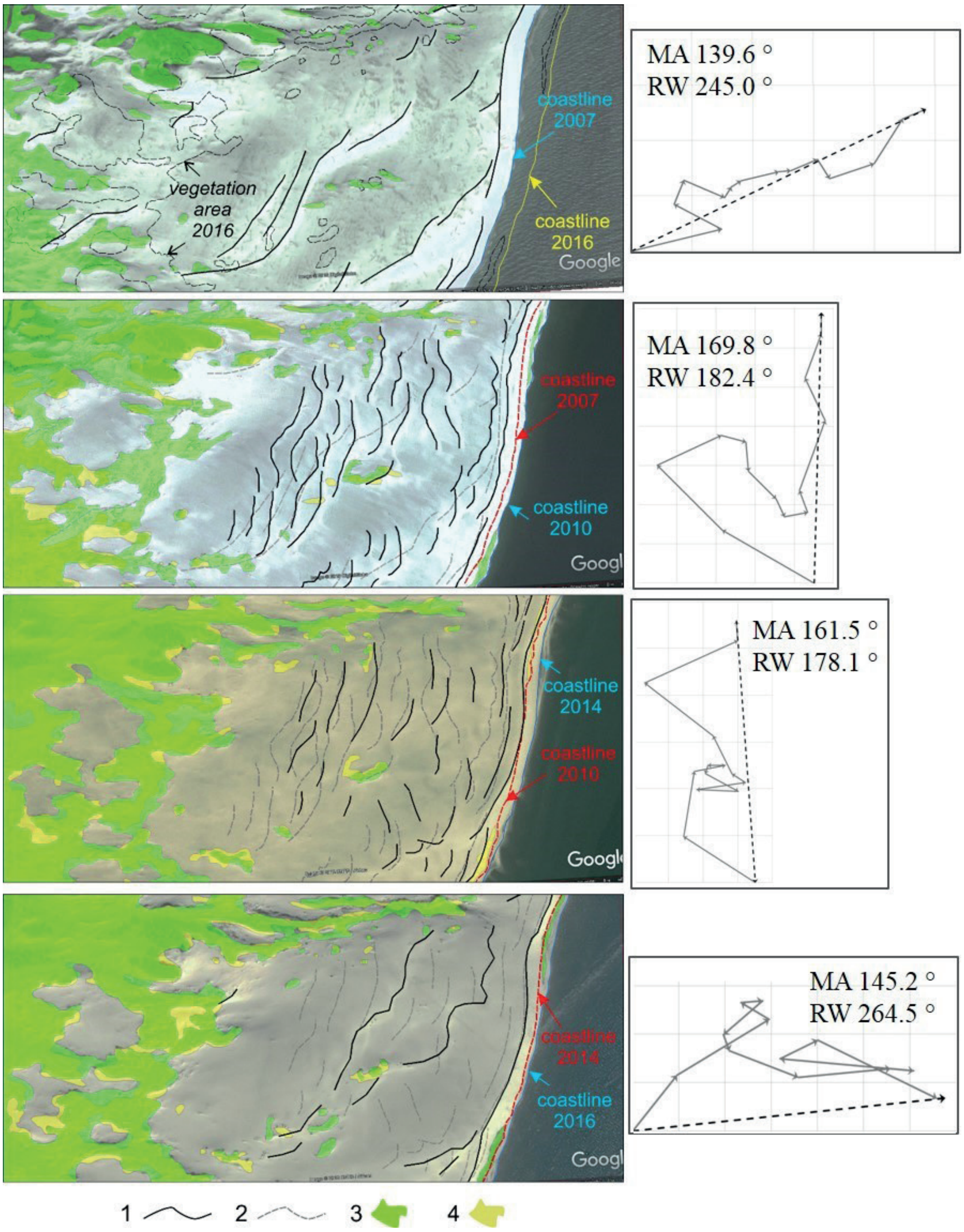

Fig. 4. Satellite images with the contours of vegetation in the village Morskoe (left panels) and average azimuth (MA) resultant wind (RW) (right panels) in 2007, 2010, 2014, and 2016. Legend: 1 – sand wave crests; 2 – sand wave crests from previous satellite image; 3 – vegetation area; 4 – vegetation area from previous satellite image

a result of blowing and transport, the rate of advancement of the dunes towards the lagoon is different.

Average, the dune near the village Morskoe shifts by almost 4 m/year, while the front of the dune near the village Rybachy, average, shifts by 1 m/year (see Table 2). Moreover, in both cases, depletion of the dunes is noted, manifested in the partial exposure of buried paleosoils and the deepening of deflation basin on the dunes. Aeolian transport of sand into the lagoon, followed by the erosion of the coastal zone and the interruption of sand supply from the sea coast, will probably soon lead to almost complete degradation of the dune.

The shift rate of the lagoon coastline, the vegetation and areas of wind erosion to the east depends on the direction of the resulting wind vector. For the period 2007–2010 and 2014–2016 southwest transport was observed. This led to a more intensive displacement of the lagoon coastline to the east (+4.7 and +4.5 m/year, respectively). The appearance of the southern component in the resulting transport caused a decrease in displacement to +2.5 m/year for 2010–2014. Thus, the average shift of the coastline to the east for 2007–2016 was 3.9 m/year.

Research of dunes dynamics in southern coast of the Baltic Sea (Poland) where the meteorological conditions are similar revealed the range of shifting dune displacement in the years 1998–2015 amounts to ca. 180 m (Michalowska et al. 2016). The Czołpinska Dune (56 m in height) is the highest dune still affected by aeolian deflation, while the Łącka Dune (c.a. 42 m in height – changing due to sand movement) is the highest shifting dune, its movement rate being estimated (from the base) at 1–2 m a year (Miszalski 1973, Borówka 2001). Thus, the results obtained by the authors are consistent with data from neighboring regions. In addition to strong effective winds, the following conditions are necessary for the occurrence of deflationary relief forms: insignificant precipitation and low air humidity; air temperature is either above 0 °C or below -10 °C (Hojan 2009). Analysis of the annual course of monthly average meteorological data for 2006–2018 (Fig. 5) allowed drawing the following conclusions:

1. January and February are unfavorable in temperature, when the monthly average temperatures are in the range from 0 to –10 °C;
2. Average monthly wind speeds of 7 months (September-March) exceed 6 m/s;
3. The average monthly relative humidity does not exceed 95% throughout the year;
4. The average monthly precipitation is minimal in February-April (about 30 mm/month). Then the amount of precipitation increases, reaching a maximum in August (more than 80 mm/month), then drops sharply in September-October and again increases in November (more than 60 mm/month).

A mild climate with prevailing cloudy weather and frequent rainfall is formed under the dominant influence of the Baltic Sea. Severe frosts are rare and short-lived. Over the past decade (2006–2018), an average of 45 days a year (12%) was observed for the Curonian Spit with average daily negative temperatures (< 0^{0}C), of which 2 days with frosts below -10^{0}C (Table 3).

On the coast of the Curonian Spit, relative air humidity is usually high (70-95%) (Handbook of the climate… 1968). Days with high humidity, which is unfavorable for deflation (≥95%), are rare, their average annual number is 19 days (Table 3), which is equivalent to a little more than 5%. In the annual distribution, these days are confined to the autumn-winter period (from November to March). In the summer, their number drops to zero (July-August).

The meteorological situation is the most important factor in the lithodynamic processes occurring on the coasts. The wind regime determines the along shore transport of dry sand material, the removal of sand material, as well as its dynamics along the transverse profile. The wind speed in conjunction with the duration of exposure to individual directions determines the energy transport potential.

The greatest influence on deflation processes is exerted by wind conditions. The most affecting coastal dunes are the winds of sea directions, with a speed exceeding the critical wind speed for the sands of the available particle size distribution (Bagnold 1941). Sand movements in different physical and geographical conditions begin at a wind speed of 4-5 m/s (sand transport by wind only occurs with relatively high wind speeds in most cases over 6 m/s). With an increase in speed up to 10-12 m/s, the power of the motions increases slightly, then there is a sharp increase in the speed range from 13 to 16 m/s. The most powerful sand movements occur at a wind speed exceeding 16 m/s. The daily effect of the wind at a speed of 20 m/s is comparable to the work of the wind at 5 m/s for 22 months (Safyanov 1996). The Curonian Spit is open to the impact of the prevailing throughout the year winds of the western

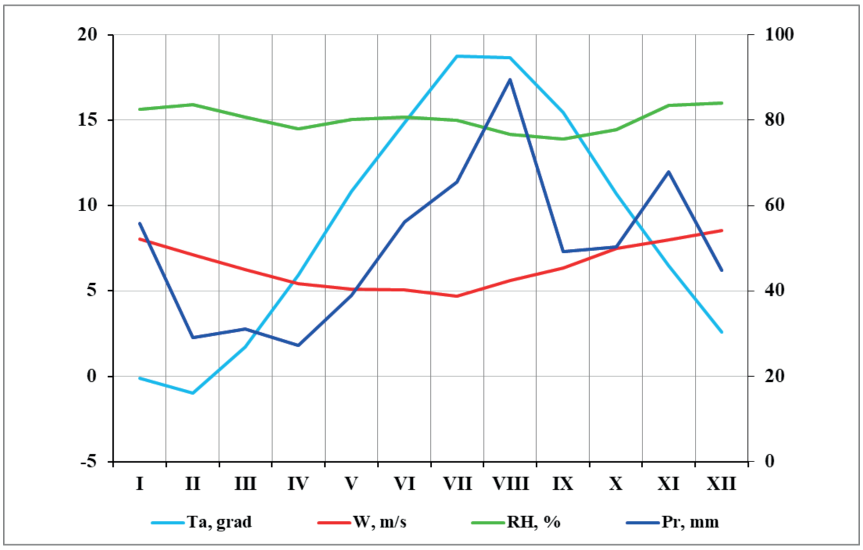

Fig. 5. Intra-annual variability of individual meteorological parameters (2006–2018) (monthly average values for 2006–2018). Ta – atmosphere temperature, W – wind, RH – relative humidity, Pr – precipitation

Table 3. Number of days with average daily meteorological conditions conducive to the development of aeolian processes (2006–2018)

Condition	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	Year
Air temperature (T °C)													
T av. > 0 °C	17	13	23	30	31	30	31	31	30	31	29	24	320
-10°C≤ Tav.≤ 0°C	13	14	8	0	–	–	–	–	–	–	1	7	43
T av. < -10°C	1	1	–	–	–	–	–	–	–	–	–	0	2
Relative humidity (f %)													
f ≥ 95%	3	4	2	2	2	2	1	0	0	1	2	1	19
f < 95%	29	25	29	28	29	29	30	31	30	30	28	30	346
Speed (W, m/s) and wind direction (rhumb)													
W ≥ 6 m/s	22	18	15	11	9	8	6	12	14	20	22	24	180
(SSW–ENE) and ≥ 6 m/s	9	9	8	6	4	5	4	9	8	13	21	24	120

rhumbs (from southwest to northwest), which have the greatest force. The resulting transport vector in the region for 2006–2018 was directed from SW to NE (230°), the value of the vector transport rate is 1.68 m/month. Compared with previous years, it has changed little, which indicates the constancy of transport (Bobykina and Stont 2015). The dunes are protected for the northern winds by forests, and are open for the eastern winds.

The wind speed on the Curonian Spit depends on its direction. Most days with an average speed of ≥ 6 m/s are characterized by the coastal direction of the effective wind from 200 to 50° (SSW – W – ENE), which contributes to the development of aeolian processes. The spring-summer period is characterized by the minimal number of situations in this context. In the autumn-winter period, more than 2/3 days may develop aeolian relief forms (Table 3).

There is a direct relationship between wind speed and sediment particle transport. Therefore, at a wind speed of 5-6 m/s, the maximum sizes of moving grains of sand are 0.25 mm, and at a speed of 11-13 their size increases to 1.5 mm (Table 4, Ananyev et al. 1992). The critical wind speed increases not only with increasing particle size, but also with their decrease, due to susceptibility to coagulation adhesion. According to the results of particle size analysis of sand in the dune massifs of the Curonian Spit, it was revealed that the majority is 0.18-0.50 mm fraction (Table 1 of supplementary material). Consequently, even with light winds at a speed of 5-6 m/s, the transfer of most of the particles along the surface of the dune begins.

The repeatability of the directions is shown in Figure 6. The intra-annual distribution of days with daily average wind speeds of ≥6 m/s is seasonal. The greatest number of days was observed in the autumn-winter period: up to 24 days in December, which is confirmed by significant horizontal gradients of atmospheric pressure. The decrease in the number of days with winds of more than 6 m/s begins in February, reaching a minimum in the summer period, especially in July (6 days). In summer, the horizontal gradients of atmospheric pressure are the smallest. In August, an increase in the frequency of wind speeds of ≥6 m/s begins.

However, the limiting factor is the regime of precipitation. An increase in sand moisture substantially increases the critical value of the dynamic velocity and causes a noticeable decrease in the wind-sand flow. In the summer months, when the intensity of heavy rainfall increases, the number of favorable days decreases to 8 days in August (Fig. 7). The maximum monthly average number of days when the development of aeolian landforms is possible is typical for the spring period (March, April up to 17 days). It should be noted that at wind speeds of up to 15-16 m/s there is a noticeable difference between the amount of dry and wet sands transported: very wet sands (moisture content up to 25%) move in an amount 3-4 times less compared to dry (Shuisky 1986). At higher speeds, the difference is minimal. Wet sand can undergo mass transport only at a wind speed of more than 20-22 m/s. The repeatability of this wind speed is up to 1.5% (2007) of all measurements per year (standard eight-term observations).

The main factors that have the greatest impact on the formation and development of aeolian landforms are the wind regime and the amount of precipitation. In the complex of all factors, the largest number of days was observed in November – up to 12 days (Fig. 7). In November, the maximum wind speeds of the western points were observed (effective direction), air temperature rarely drops below 0 °C. The minimum number of days was observed in the summer period. This is due, firstly, to a decrease in wind speed and, secondly, to a gradual increased in the amount

Table 4. Critical wind speeds for dry particles of various sizes (Ananyev et al. 1992)

Wind speed, m/s	Particle size, mm
11-13	1.0-1.5
9-11	0.5-1.0
7-9	0.25-0.5
5-6	0.1-0.25
6-9	0.05-0.1
10-12	< 0.05

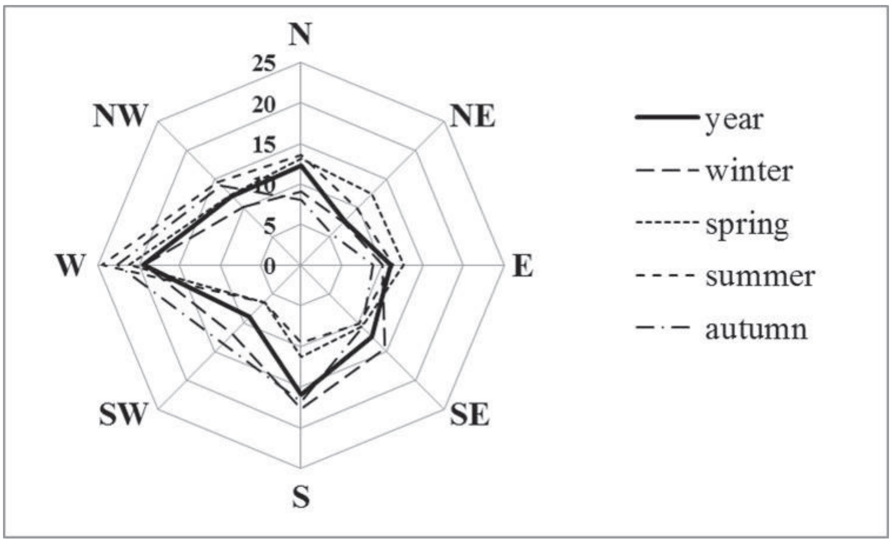

Fig. 6. Wind repeatability in directions (%) throughout the year and in seasons (average for 2006–2018)

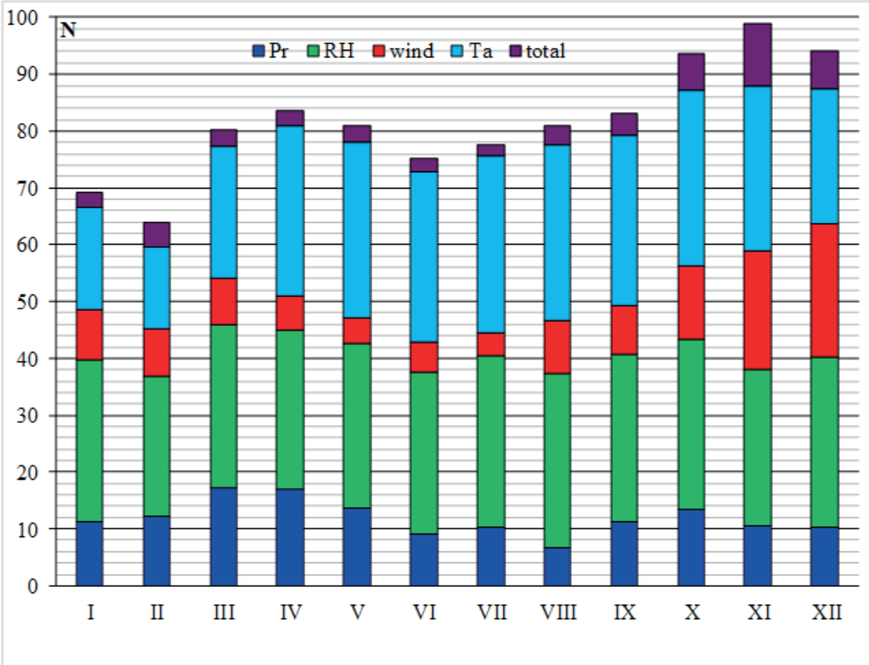

Fig. 7. The average monthly number of days for certain factors contributing to the formation of aeolian landforms (2006–2018). Pr – precipitation, RH – relative humidity, Ta – air temperature

of rainfall, especially in August, when the maximum rainfall occurred. In autumn, the wind speed increased, which is an important factor for aeolian processes (Stont et al. 2012; Bobykina and Stont 2015; Navrotskaya and Stont 2014; Stont and Demidov 2015).

Interannual variability

The analysis of the complex of meteorological conditions revealed that for the development of aeolian landforms on the Curonian Spit the best conditions were observed in 2013 when 47 days were favorable. In 2009, there were only 15 such days (Table 5). On average for the period 2006–2018 only 30±8.5 days/year the potential deflation with the formation of aeolian relief forms was possible. There is a tendency to increase days with favorable factors for the formation of aeolian landforms (the trend coefficient is positive 0.30 at R^2=0.02; the corresponding increment for the period was 4 days). However, talking about the reliability of the trend for a short period (13 years) is incorrect. The short-range of data available does not allow us to highlight the cyclical nature.

Table 5. Number of days favorable for the development of aeolian processes on the Curonian Spit (for individual meteorological elements and in total)

Parameter	Air temperature	Relative humidity	Wind speed	Wind direction	Precipitation	Total number
2006	312	**355**	**161**	236	189	35
2007	337	341	177	223	153	22
2008	**355**	349	178	**240**	146	29
2009	334	350	180	193	153	**15**
2010	**278**	343	183	182	162	26
2011	329	**330**	196	234	159	40
2012	326	350	177	221	**112**	27
2013	306	346	169	198	193	**47**
2014	330	333	189	**176**	**221**	36
2015	352	341	195	228	189	33
2016	345	350	181	208	155	31
2017	338	334	**200**	231	148	32
2018	315	336	166	181	179	21
mean	328	343	181	212	163	30
±σ	20,9	7.9	11.8	23.1	27.6	8.5
min	278	330	161	176	112	15
max	355	355	200	240	221	47

**Extremums in bold*

The temperature conditions of the Curonian Spit on average 328±21 days/year were favorable for the formation of aeolian relief forms. In 2008, air temperature did not interfere with aeolian processes throughout the year (355 days); the smallest number of days (278 days) was observed in 2010. This year was the coldest of the considered period (av. 7.2 ± 8.6 °C). Winter temperatures dropped to −15 °C (Stont and Demidov 2015; Stont and Bukanova 2019).

The coast of the Kaliningrad region belongs to the zone with prevailing western winds with a force of up to 5-6 points on the Beaufort scale (7.5-12.4 m/s). Up to half the days in a year (181±12 days), winds prevail with an average daily speed of more than 6 m/s. The spread was from 161 days in 2006 up to 200 days in 2017, the effective direction of the wind, characteristic of the orientation of the Curonian Spit, was in the range of SSW-ENE on average 212±23 days a year. In 2008, such winds accounted for 240 days, in 2014 176 days. With such wind directions, conditions are observed for the development of aeolian landforms.

Even though the southeastern part of the Baltic Sea belongs to the region with excess moisture, in 46% of all days (average 163±28 days) precipitation did not prevent the development of aeolian processes. The most favorable was 2014 (221 days), the least favorable 2012 (112 days). The average daily relative humidity of only ~20 days a year is more than 95%. The spread range was from 330 days in 2011 to 355 days in 2006.

CONCLUSION

For the Curonian Spit (southeastern part of the Baltic Sea) the following main features of the development of aeolian processes were revealed.

1. There is a relationship between the numerical characteristics of the position and direction of migration of sand forms and the resulting wind vector – with the appearance of the southern component of the transport (2010 and 2014) the small forms of the aeolian relief were developed; with the south-western transport (2007 and 2016) – large rare bars occurred on the surface of the dunes.
2. The shift to the east of the lagoon coastline, the vegetation, and the area of wind erosion also depend on the direction of the resulting wind vector. Under the dominance of the southwestern transport, a more intense shift of the coastline to the east was observed (up to +4.7 m/year). The appearance of the southern component in the resulting transport caused a decrease in displacement to +2.5 m/year.
3. An average of 30±8.5 days per year can be expected with meteorological conditions favorable for the development of aeolian processes. There is a tendency to increase days with such factors.
4. The distribution of days with wind speeds of ≥6 m/s is seasonal, the largest number of days was observed in the autumn-winter period. Most days with an average speed of ≥6 m/s were characterized by the coastal direction of the effective wind, which contributes to the development of aeolian processes. In the autumn-winter period, more than 2/3 days may develop aeolian landforms; the spring-summer period is characterized by the least number of situations in the context.
5. The limiting factor is the regime of precipitation. In the summer months, when the intensity of heavy rainfall increases, the number of favorable days decreases. The maximum monthly average number of days when the development of aeolian landforms is possible is typical for March and April.
6. The main factors that have the greatest influence on the formation and development of aeolian landforms are the wind regime and the amount of precipitation.

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