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Influence of meteorological conditions on aeolian processes along the Polish cliff coast

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Abstract This article presents aeolian landforms and meteorological parameters affecting aeolian processes on the south Baltic coastal cliffs of Poland. The analysis was conducted for two weather stations at different locations. The bluffs in the vicinity of the stations have similar geological structure, but differ in height. Velocity and direction of the wind, as well as precipitation, are of dominating importance. Dispelling the cliff starts at wind speeds of two–three ms^{-1}. At this speed, the distance at which the material is transported is short and is only a few meters, while for the transport of fine sand and dust on the top of the bluff the wind speed must be over 10 ms^{-1}. It was observed that such speeds of the wind or gust is characteristic of days with an average wind velocity of at least six ms^{-1}. The number of days with potential deflation on the bluff is four times higher in the area of Ustka than in the Świnoujście region. On average, the bluff in Ustka can be dispersed by wind throughout 33 days in a year, while the one on Wolin Island in less than eight days. Erosive and accumulative eolian forms are small, their sizes are generally less than one meter, only with rhythmic swelling to the size of several meters.

Keywords *• aeolian landform • coastal cliff • wind speed • deflation • Wolin Island • Ustka*

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INTRODUCTION

Coastal cliffs along the southern Baltic Sea, including Uznam Island in north-eastern Germany and the Polish coast, are subject to the processes of marine erosion along most of their length. Early Holocene sea level rise (SL) resulted mainly from the glacio-isostatic uplift of Scandinavia. Since the beginning the Atlantic Period the eustatic sea level change became probably the main factor (Rotnicki, Rotnicka 2010). Coastal erosion results in establishing of sandy and muddy surfaces devoid of flora on the slope of a bluff, whereas on the beach and at the bluff base, Scandinavian erratics originate from bluff glacial formations and tree trunks occasionally topple from the bluff top.

The article presents a brief description of aeolian landforms created on the bluff slope and top. The process-based part of the study covers the analysis of meteorological conditions favourable for their creation.

STUDY AREA

A survey of aeolian processes along the Polish Baltic Sea coast and in other coastal areas is usually conducted over short distances, the length of which rarely exceeds several hundred meters or several kilometers. This refers to both dune and bluff coasts. In addition, individual researchers use various measurement methods of aeolian transport on the beach and foredunes, which complicates the comparison of the results. Typically, vertical sand traps having various sizes and shapes, and thus different efficiency, are used (Arens, van der Lee 1995; Borówka, Rotnicki 1999; Borówka 1980, 1990, 2001; Leatherman 1978; Łabuz 2005; Riabichin 1969; Rotnicka 2011a, 2011b, 2013a).

Transport of fine sand and dust (silt and clay) from the bluff slope to its crown was investigated with the use of aeolian fall catchers (Hojan 2009). Whereas the majority of the surveys has been conducted along the dune sections of the coast, the present survey focused on bluff sections of the Baltic Sea coast. Two coastal sections were selected: 1) Wolin Island (Świnoujście region) and 2) east of Ustka (Fig. 1). Linear distance between these locations is 180 km and they differ in terms of exposure to prevailing wind direction.

Fig. 1 Location of the study sites along the Baltic Sea coast of Poland.

At both sites, the bluffs are composed of glacial and fluvioglacial sediments (Subotowicz 1982). The total length of the bluff coast of Wolin Island is 12 km and is divided into two sections: the eastern section, covering a length of 7 km, and the western – 5 km (Subotowicz 1982). In the west, the bluff is higher than its eastern part, reaching a maximum height of 95 m above mean sea level (ASL). The top part of the bluff is formed by aeolian sand cover. The bluffs located to the east of Ustka can be divided into three sections: 1) ~0.5 km long Rowy Bluff; 2) Dębina Bluff with a total length of 5 km, and 3) Ustka Bluff, ~2.5 km long (Subotowicz 1982). The top part of the bluff structures includes aeolian cover sands and occasional dunes. The maximum height of the bluffs located in this part of the Baltic Sea coast is approximately 35 m. In the majority of cases they are lower than the Wolin Island bluffs. The tidal waves on the south coast of the Baltic Sea reach small values approximately 3.6 cm in the vicinity of Kołobrzeg and 3.3 cm at Władysławowo, and therefore they have no great importance in shaping coast relief. The waves generated by the wind usually does not exceed 1 m (Rotnicki, Rotnicka 2010).

RESEARCH METHODOLOGY

Field research was carried out on the basis of systematic observations of aeolian processes. Also measured wind velocity and direction on a slope of a bluff. On the top of the bluff assumed aeolian fall measurement network. Samples were collected once a month and the observed episodes of intensive aeolian processes.

Weather stations in Świnoujście and Ustka are located within the coastal zone of the Baltic Sea (see Fig. 1). These locations allow for accurate assessment of meteorological conditions responsible for the deflation on the cliff slope. A survey of aeolian processes on the bluff coast of Wolin Island was carried out between 2001 and 2005 (Hojan 2009, 2012). On the basis of these observations, selected meteorological elements affecting aeolian processes were quantified. The following conditions must be fulfilled before aeolian transport from the bluff slope to its crown occurs:

1) total precipitation in the period of five days cannot exceed 6 mm,
2) average daily air humidity must be less than 95%,
3) average daily wind velocity must exceed 6 ms^{-1}, with wind directions within the range of SW–NE (onshore and alongshore wind directions),
4) average daily air temperature must be above 0°C or below –10°C (Hojan 2009).

The formulated method was used in the present analysis, using the 2001–2010 database from weather stations in Świnoujście (53.91ºN; 14.23ºE; 5 m ASL) and Ustka (54.58ºN; 16.86ºE; 6 m ASL), included in the Institute of Meteorology and Water Management (IMGW) network. Meteorological station in Świnoujście is located on a sand dune in the distance of 120 m from the coast. In contrast, in Ustka station is located at the foot of the lighthouse in the distance of about 50 meters from the shore. In addition, on the basis of a review of the weather charts of Europe, published daily in *Codzienny Biuletyn Meteorologiczny* [Daily Meteorological Bulletin] (2001–2010) the types of air masses favourable for potential deflation on the bluff were identified.

A similar method was used by Szpikowski (2008) to assess niveo–aeolian processes in the water catchment area of the Perznica River. The author assumed other criteria affecting the occurrence of niveo–aeolian erosion, transport, and accumulation processes.

RESULTS

The research conducted on Wolin Island revealed that the aeolian processes are mainly active on the beach and, to a lesser extent on the bluff slope (due to higher wind velocities necessary to transport sand and silt up the bluff), where they generate a variety of erosional and depositional features. The analysis of meteorological data indicates that the occurrence of wind erosion of the bluffs is affected primarily by wind velocity and direction, number of days without precipitation, air temperature, and air humidity.

At both sections of the fluvioglacial bluff coast along the south Baltic Sea shoreline of Poland, deflation is the dominant process. The eroded sand is transported up-slope to the bluff top (Fig. 2A) and accumulates in the form of aeolian cover sands (sand sheets and dunes, Fig. 2B).

In the majority of bluffs on Wolin Island, the sand transported along and across the beach has no possibility of reaching the bluff crown. The height and steepness of the bluff is the main obstacle, along with

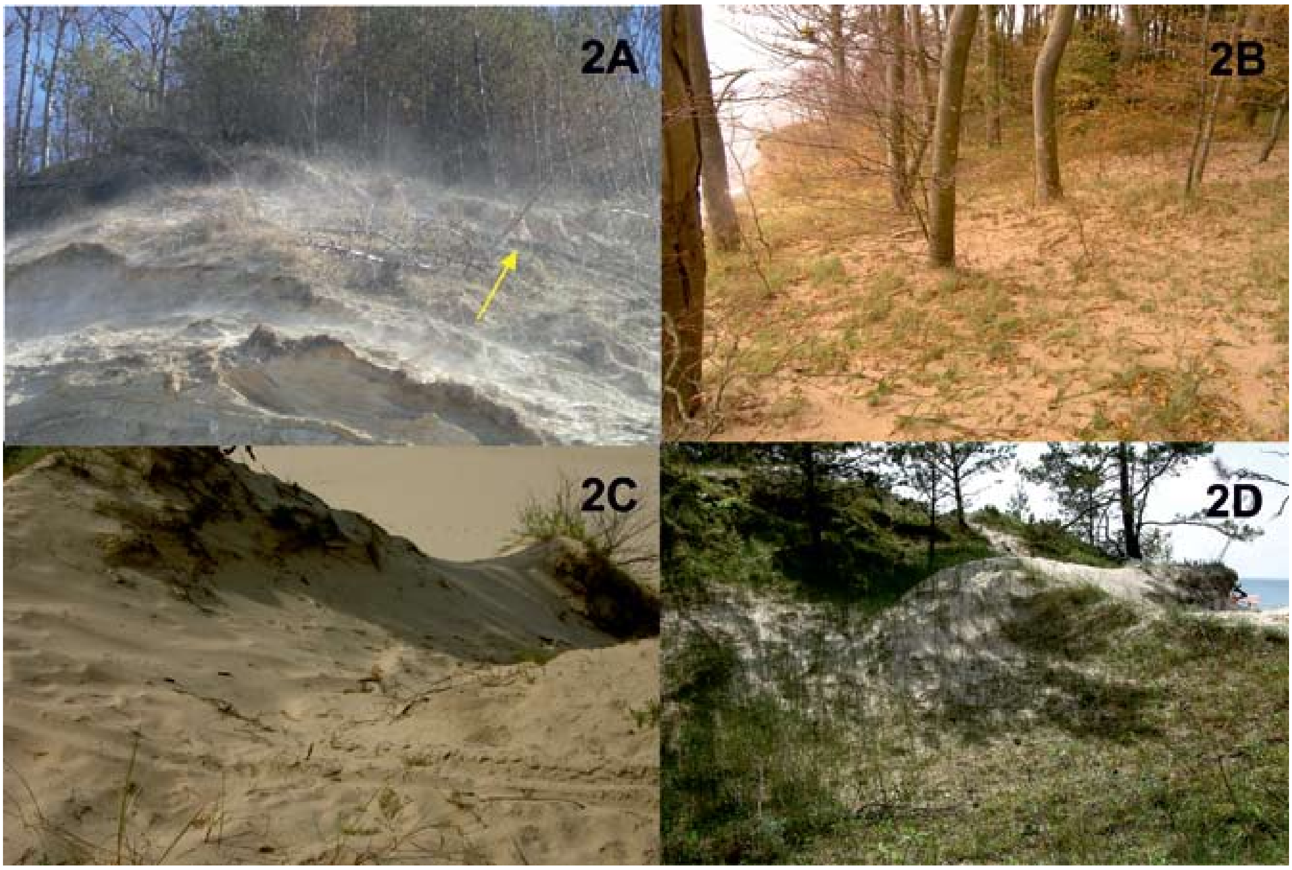

Fig. 2 Aeolian processes and landforms on the bluff. **A –** Sand transport up-slope to the bluff top, arrow indicates direction of aeolian transport (20 April 2005). **B –** Aeolian cover on the top of the bluff (29 August 2004). **C –** Small incision (gully) (17 May 2013). **D –** Small dunes on the bluff top (17 May 2013). Photos by M. Hojan.

the coarse size of the beach sand. Only in the east section of the bluff on Wolin (close to 398th km of the sea coast), the beach sand can reach the bluff crown. Here, the cliff is ~5 m high and is sand dominated, which contributes to the lower gradient compared to clay dominated or clay-sand bluffs. Transport of the beach sand up the bluff is also influenced by human activity. During the summer, tourists looking for a convenient descent to the beach may trigger the development of small incisions (gulleys) on the bluff slope (Fig. 2C). During a strong wind event (daily average >6 ms^{-1}), the sand is transported from the beach to the bluff slope and eventually up to the top. The geometry of the incisions causes additional increase in wind velocity, thereby facilitating sand transport up the bluff. Consequently, small dunes are formed on the bluff top and are quickly stabilized by vegetation (Fig. 2D). A similar pattern of sediment transport to the bluff top was presented (Saye *et al.* 2006) in their models of sand material delivery above the top edge of a bluff.

Also east of Ustka, low bluffs (up to ~20 m), a similar mechanism of sand delivery from the beach to the bluff top has been observed. This type of aeolian transport was investigated by Florek *et al.* (2007). Both in the case of the bluffs along the east section of Wolin Island and east of Ustka, sand movement from the beach up the bluff is possible when the wind blows inland. In order to constrain the directions and velocities of wind which are particularly conducive to the process, further research is necessary.

Along clay and clay-sand bluffs exceeding 20 m in height, transport of the material from the beach to the bluff crown was also observed. The process occurs much less frequently, and the scale is much smaller compared to the low sandy bluffs. During intensive rain falls the geological structure of clay bluffs results in rill erosion that generates alluvial cones at the bluff base. After drying out, the cones are subject to the process of corrasion or human trampling, which contributes a mud fraction to the upper beach. In the event of a strong wind, this fraction is advected along the beach in suspension and ultimately transported to the bluff crown. The material is entrained during modest changes in coastal regime, such as local modification of wind direction from alongshore to onshore.

As the result of marine abrasion along the erosive sections of the southern Baltic Sea margin, mostly consisting of bluff coast, tree trunks and rocks are scattered along the beach (Fig. 3). The rocks are washed as colluvium and include various sizes of Scandinavian erratic clasts, up to boulder size. Wind currents that encounter trunks and boulders tend to flow around them, resulting in local changes in direction and velocity. Cavities (deflation basins) are created in front and around the obstacles. The depth and width of these features ranges from centimetres to several decimetres, depending on the obstacle size and wind velocity. These forms are modified and degraded by storm surges.

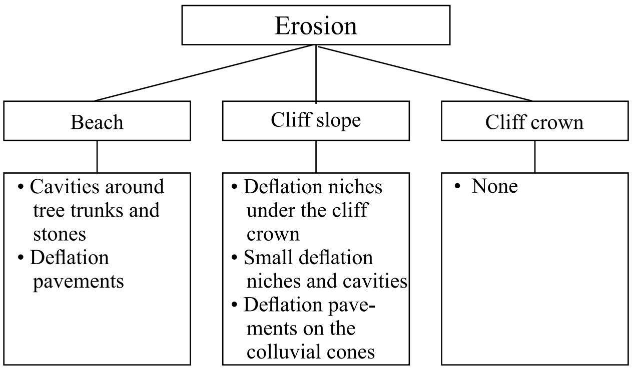

Fig. 3 Conceptual diagram of erosional aeolian features.

The aeolian pavement present on the beach can be classified as an erosive feature. It is formed by the deflation of sand (Davidson-Arnot *et al.* 1997), resulting in a coarse lag of gravel, shell fragments (McKenna *et al.* 2012), or dark heavy mineral concentrations (Buynevich 2012; Racinowski 2008). Frequently, when the beach is wet, pebbles are "suspended" on the pedestals of beach sand as the result of deflation, and characteristic wind–shadow mounds are formed behind them. These forms are ephemeral.

Wind erosion extends the bluff slope where they can be observed mainly on a sandy and sandy–clayey bluff, affecting the clayey bluffs to a much lesser extent. Erosional features include deflation niches under the bluff top (Kostrzewski, Zwoliński 1988). They can be up to several decimeters high and more than 10 m in length. Deflation niches under the bluff top are formed as a result of deflation of the dry sand and its accumulation around exposed tree roots (Fig. 4A). The resulting overhang protects the sand against pre-

Fig. 4 Erosional and depositional landforms on the bluffed coast. **A –** Deflation niches under the bluff crown (8 June 2006). **B –** Deflation cavities (15 May 2013). **C –** Rhythmic distensions developed on a wet beach (24 October 2002). Photos by M. Hojan.

cipitation, keeping it dry and more susceptible to further deflation. Deflation niches under the bluff top function until the overhang is removed, triggering the next cycle of their development that may last from several months to years.

In the event of a strong wind, deflation cavities (Fig. 4B) and niches are created on a bluff composed of fluvioglacial sands. The former features discussed above can be observed between oxidized horizons, whereas the latter forms appear under inter-beds of loam. Deflation cavities are typically small and occur on exposed sections of the bluff covering several square meters. Such cavities are between 10–20 cm deep. The widths and heights of deflation cavities, as well as the surface they are formed upon, depend on the distribution and extent of oxidized layers. They exist as long as thin oxidized horizons are exposed by deflation, typically from several days to three weeks.

Loam interbeddings in fluvioglacial sands of the bluff slope are up to 20 cm thick. As the result, deflation forms created under horizons of loam achieve greater sizes and can be classified as small deflation niches. The depth of such a niche may reach ~30–50 cm, with a height of ~20–30 cm and the width of ~100 cm. They may become wider and deeper as the result of wind activity, attaining several meters in width under extraordinary circumstances. Deflation niches under loam inter–beds exist until the section of loam is removed.

Frequently, colluvial cones located at the cliff base are blown through. Wind erosion affects the finest material, while aeolian pavement is formed on their surface. The gravel lag is gravitationally shifted to the lower part of a cone, indicating that this armor is an ephemeral form. Ripple marks are created on the colluvial cones at the cliff base. They are formed by the wind blowing from the direction along the beach. They become quickly degraded as a result of sand falling on the cliff slope and alluvial cone. Strong winds, especially those blowing along the beach, cause additional incision of the cliff-base cones. Wind parallel sediment tongues can reach several metres in length, depending on wind velocity and the volume of the sand in the colluvial cone.

The second group of forms developing as the result of aeolian processes includes accumulative forms. They can be observed mainly on the beach along the cliff coasts of Wolin Island and east of Ustka. Aeolian accumulation also occurs on the slope and crown of a bluff (Fig. 5). Sand covers (sand sheets) are formed by aeolian transport of sand transported to the beach by waves. They can be also delivered by wind from more remote parts of the coast. Ripple marks are the most prominent bed form, with their height approximately 1–2 cm and spacing approximately 5–10 cm determined by wind velocity and sediment size. They belong to ephemeral forms (Lancaster 1999).

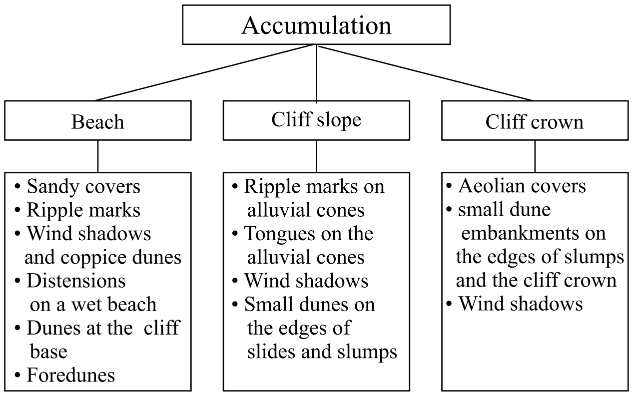

Fig. 5 Conceptual diagram of depositional aeolian features.

Another group of accumulative forms and location of accumulations on the beach includes wind-shadow dunes/mounds. Most frequently, they are observed on bluff sections of the coast where high concentrations of gravel result from bluff erosion. The scale of these features depends on the size of an obstacle existing in the path of the wind and on wind velocity. The largest observed wind-shadow mounds were up to 10 m long and one meter high. The forms exist for a relatively long time, up to two–three months, subject to gradual re–molding and fading by the wind. During storm surges, aeolian shadow structures dunes on the beach are destroyed by wave action (Rotnicka 2013b).

Wind-shadow landforms have their derivative form in coppice dunes created in the shadow of vegetation. Along the Polish coast, they have been documented on the beach near Grodno, in central part of coast of Wolin Island. The beach is up to 50 m wide and along its upper part, mostly in the vicinity of embryonic foredunes, small fields of coppice dunes are formed. They reach a height of up to 20–30 cm and, like the aeolian shadow-dunes, are affected by wind re-molding and partial or complete destruction by storm waves.

Among the depositional forms along the beaches of cliff coasts of Wolin Island and east of Ustka, rhythmic distensions are occasionally developed on a wet beach (see Fig. 4C). Their spacing is several metres and they appear similar to large bedforms (e.g., megaripples). They are created during strong winds and constitute the largest depositional forms, typically oriented normal to the cliff base. As the beach dries out, the distensions are dispersed by the wind. The same forms was observed by Nield (2011) and Rotnicka (2013b) on the beach of the Łeba Barrier, southern Baltic Sea coast, Poland.

Medium (up to 0.5 m high) cliff–base dune embankments develop in some parts of the cliff coast of Wolin Island. Their formation requires up to a 40 m wide beach and a cliff up to 15 m in height. They are accumulated by wind blowing at a low angle toward the coastline. Vegetation growing in the upper part of the cliff is another factor affecting the development of these landforms. Dune embankments are destroyed by strong storm surges.

Small dune embankments constitute special depositional microforms. They emerge on the edges of turf slides, slumps, and cliff crown. The wind velocity at which the embankments are created is similar to that required for generating aeolian shadows on the cliff slope. Small dune embankments range from a decimeter to ~1 m long and 5–10 cm high. Their base is approximately 10 cm wide. Along the ridge, one can clearly see the edge dividing the embankment into two symmetrical sides. The emergence of small dune embankments is related to the vortex of wind streams flowing above a given edge.

On a sandy cliff slope, aeolian shadow–dunes emerge behind subsiding grass patches. They are directed toward the cliff crown and are generated by onshore winds. Their size is determined by the grass patch size and wind velocity, as well as by the volume of sand falling on the cliff slope. Fine grained sand and dust transportation to the crown of the cliff occurs with a wind velocity of ~10 ms^{-1} (Hojan 2009). The shadow–dunes observed on the Wolin cliff were approximately 50–70 cm long.

Aeolian covers (drapes) occasionally reaching a thickness of ~10 cm are deposited above the edge of the cliff. A survey conducted in Wolin Island revealed that the weighted average growth of the aeolian cover amounted to 1.7 mm during the 2001–2005 period (Hojan 2009). He also reports that under specific aerodynamic conditions, the transport of very fine sand and silt may reach 300 m. The thickness of the cover decreases with the distance from the cliff edge. Aeolian covers constitute an element of cliff naspas – type of soil in Poland systematic of soil science (Prusinkiewicz 1971) and are confined to active sections of sandy and clayey-sandy cliffs. They are degraded during the cliff top retreat, but may be regenerated once the cliff slope becomes active and sandy surfaces susceptible to deflation are exposed.

Our study demonstrates that erosional and depositional aeolian landforms are ephemeral (days–months). Minor features become degraded within several hours or days. Larger forms located on the beach main remain active until a storm surge, which causes erosion, reworking, and redeposition of the beach and cliff material. Aeolian drapes deposited beyond the top edge of the cliff persist the longest due to the range of accumulation being larger than the pace of cliff retreat.

The same aeolian features may occur on other bluff coasts composed of glacial deposits. Their dimensions will depend on the local lithological and meteorological conditions. The number of days with deflation potential was calculated on the basis of meteorological data. Our findings demonstrate considerable differences in the number of days in which sediment removal from a coastal bluff takes place. Compared to Wolin Island, the bluffs located east of Ustka are four times more exposed to deflation. On average, the bluff in Ustka can be impacted by wind during 33 days/year, whereas the one in Wolin Island in less than eight days (Fig. 6). In Ustka, the highest number of days with deflation potential was recorded in 2007 and 2004 (48 and 46, respectively).

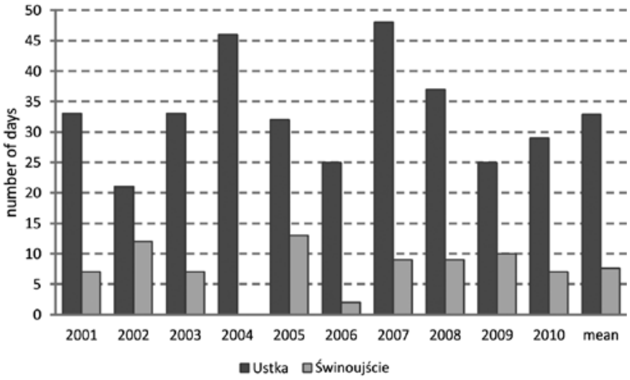

Fig. 6 Annual distribution of days with deflation potential of the bluff east of Ustka and on Wolin Island (Świnoujście region) between 2001 and 2010.

Along the bluff shore of Wolin Island, this maximum occured in different years. Twelve and thirteen days of that type were recorded in 2002 and 2005, respectively. In 2004 the highest number of days with deflation potential occurred in November and May. In 2005, 6 out of 13 days with possible deflation occurred in April. In 2007, nearly half of the days with deflation potential occurred in April and March (Table 1).

Average annual course of days with potential deflation is similar at both stations, with the highest aeolian activity observed in spring, especially in April. At Świnoujście, approximately 1/3 of the total annual number of occurrences is registered (Fig. 7). At the Ustka station, the period also includes June, and potential deflation is also increased in November

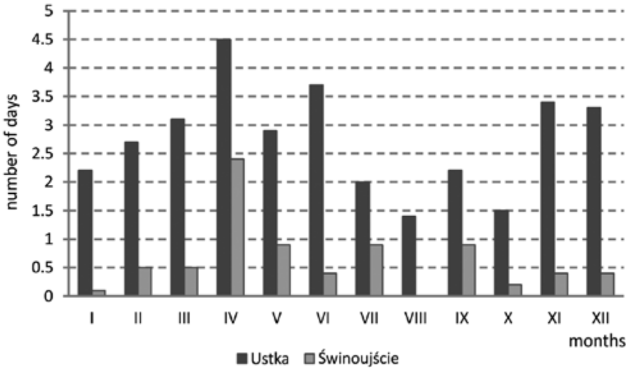

Fig. 7 Monthly distribution of days with deflation potential of the bluff east of Ustka and on Wolin Island (Świnoujście region). Average values for the period 2001–2010.

Table 1 Number of days with possible deflation of the cliff east of Ustka and on Wolin Island for individual months of the decade between 2001 and 2010.

Ustka										
	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
I	2	1	4	0	6	1	3	3	2	0
II	4	3	0	3	2	3	0	12	0	0
III	0	6	2	2	2	2	8	0	1	8
IV	3	1	4	0	7	1	14	3	5	7
V	5	0	0	9	0	1	4	2	4	4
VI	2	2	4	7	9	3	1	4	4	1
VII	3	3	1	1	1	3	1	3	1	3
VIII	1	0	6	0	0	0	4	2	1	0
IX	0	1	4	4	0	0	4	1	6	2
X	4	0	0	1	3	0	3	2	1	1
XI	6	3	2	13	0	0	4	3	0	3
XII	3	1	6	6	2	11	2	2	0	0

Świnoujście										
	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
I	0	0	0	0	0	0	1	0	0	0
II	3	0	0	0	1	0	0	1	0	0
III	0	3	1	0	0	1	0	0	0	0
IV	1	3	5	0	6	0	4	1	3	1
V	1	0	0	0	0	0	1	3	2	2
VI	0	0	0	0	0	0	0	0	4	0
VII	1	3	0	0	1	1	0	3	0	0
VIII	0	0	0	0	0	0	0	0	0	0
IX	0	2	0	0	2	0	1	1	0	3
X	0	0	0	0	1	0	1	0	0	0
XI	1	1	0	0	1	0	0	0	0	1
XII	0	0	1	0	1	0	1	0	1	0

– values exceeding 250% of a monthly average in multiannual period

and December. At both stations, the lowest number of days in which bluff deterioration takes place is in August.

DISCUSSION

The analysis of meteorological conditions allows us to understand causes of diversification of days with deflation potential in the area of research. Our results indicate that the occurrence of days with potential deflation is mostly influenced by wind and rainfall, but minor importance is attributed to temperature and relative humidity of air. Annual air temperature is similar at both stations, yet some differences can be noticed in spring and early summer when it is lower in Ustka (Fig. 8). The location of the town in the exposed central part of the Polish coast resulted in a distinctive cooling influence of the Baltic Sea in that period. Also, the average annual number of days with a subzero daily air temperature, but higher than –10°C, is similar for both stations. It is 42 days in Świnoujście and 41 days in Ustka (Table 2), which represents as little as 11% of total days at each station. The occurrence of the aforementioned days usually excludes the possibility of cliff erosion between December and March.

Comparison of the annual trends in relative humidity indicates more significant differences between the stations (Fig. 8). In Ustka, the values are lower in the cooler half-year and higher in the warmer half-year, which suggests a stronger influence of the Baltic Sea. Days with high relative air humidity, which is unfavourable to deflation (≥ 95%) are rare, especially in Ustka, where their average annual number is only 24 (Table 3), equalling less than a 7% of annual total. In Świnoujście, this number is higher and reaches 40 days/year on average. In the annual distribution, those days are slightly more common in the period between November and February, occasionally occurring in the summer.

The analysis of the annual trends in individual meteorological elements, suggests that the most distinctive differences between the stations occur in terms of wind velocity, which is ~2 ms^{-1} higher in

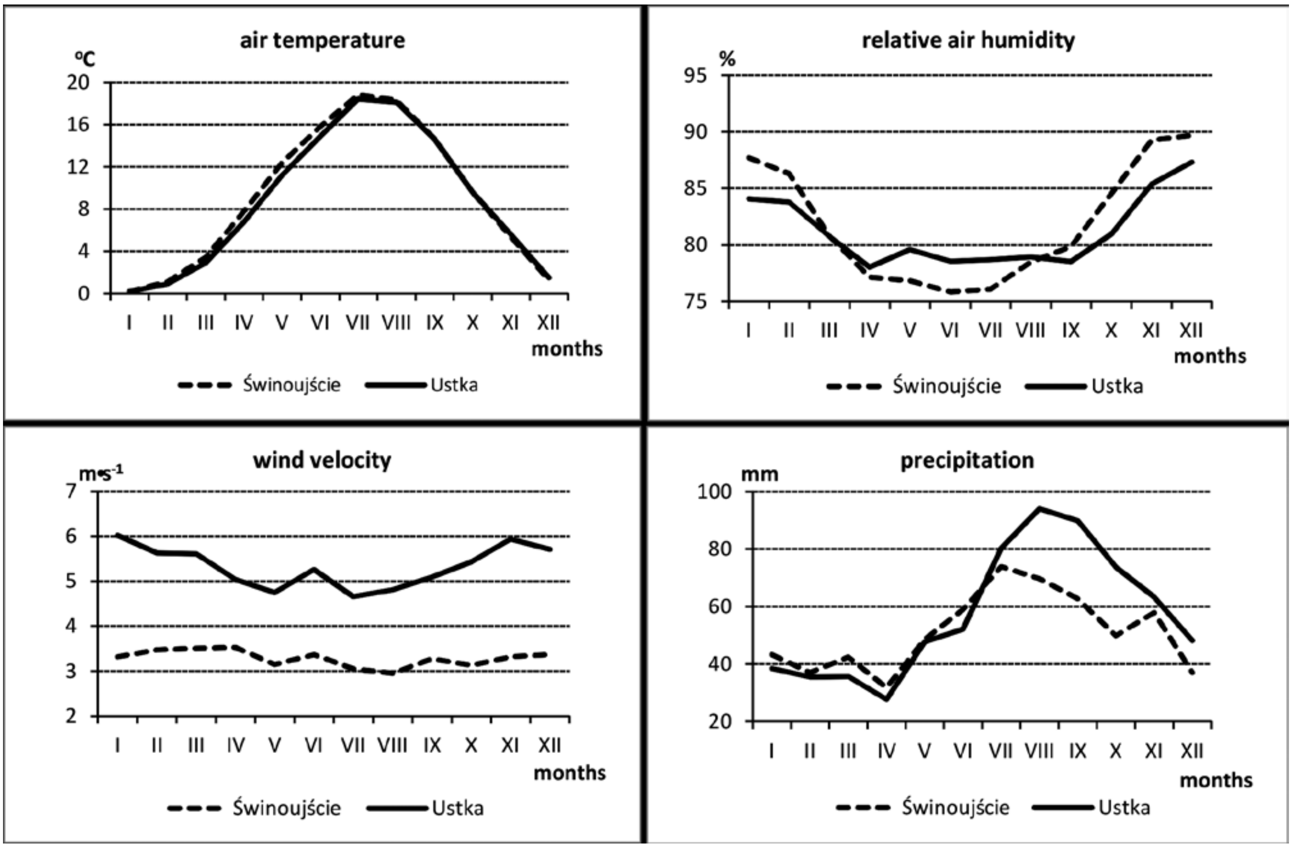

Fig. 8 Annual distribution of air temperature, relative humidity, precipitation, and wind velocity in Ustka and Świnoujście region. Average values for the period 2001–2010.

Table 2 Number of days with mean temperature above 0°C, between 0°C and -10°C, or below -10°C. Average values for the period 2001–2010.

Ustka													
	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	Year
$t_{mean} > 0°C$	18.0	16.8	23.6	29.8	31.0	30.0	31.0	31.0	30.0	31.0	28.7	21.9	322.8
$-10°C \leq t_{mean} \leq 0°C$	11.7	11.2	7.4	0.2	–	–	–	–	–	–	1.3	8.8	40.6
$t_{mean} < -10°C$	1.3	–	–	–	–	–	–	–	–	–	–	0.3	1.6
Świnoujście													
	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	Year
$t_{mean} > 0°C$	16.7	16.6	24.8	30.0	31.0	30.0	31.0	31.0	30.0	31.0	28,4	21.1	321.6
$-10°C \leq t_{mean} \leq 0°C$	13.4	11.4	6.2	–	–	–	–	–	–	–	1.6	9.5	42.1
$t_{mean} < -10°C$	0.9	–	–	–	–	–	–	–	–	–	–	0.4	1.3

Table 3 Days with mean relative humidity ≥ 95% and < 95%. Means for the period 2001–2010.

	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	Year
Ustka													
RH ≥ 95%	3.6	2.9	2.1	3.0	2.1	0.5	0.4	0.7	0.6	0.7	3.0	4.6	24.2
RH < 95%	27.4	25.1	28.9	27	28.9	29.5	30.6	30.3	29.4	30.3	27	26.4	340.8
Świnoujście													
RH ≥ 95%	7.1	5.0	2.5	1.9	1.3	0.4	0.1	0.8	1.2	2.7	8.0	9.3	40.3
RH < 95%	23.9	23	28.5	28.1	29.7	29.6	30.9	30.2	28.8	28.3	22	21.7	324.7

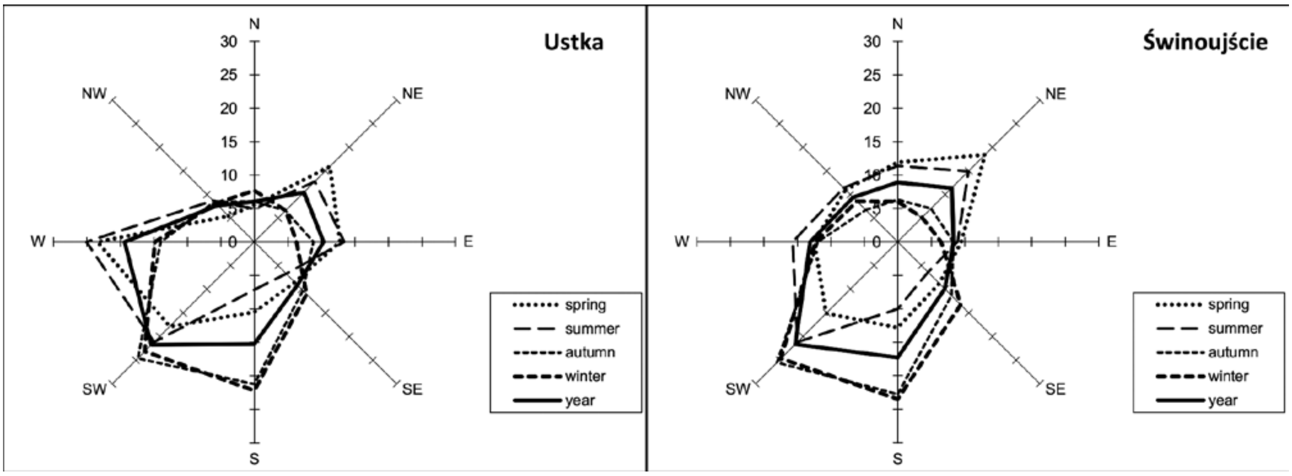

Fig. 9 The frequency (%) of wind directions in Ustka and Świnoujście region for the period 2001–2010.

Table 4 Number of days with mean wind speed > 6 m/s^{-1}. Means for the period 2001–2010.

	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	Year
all days with mean wind speed >6 m/s^{-1}													
Ustka	13.2	10.4	11.2	7.6	6.5	9.3	6.0	5.5	7.6	9.5	12.6	12.1	111.5
Świnoujście	1.2	3.0	3.3	3.9	1.8	2.0	1.9	1.1	2.6	2.0	2.3	2.7	27.8
days with mean wind speed >6 m/s^{-1}, when the wind blows of favourable direction (SW–NE)													
Ustka	11.1	8.25	8.95	6.2	5.9	7.95	5.6	5.6	6.75	7.75	11.3	10.05	95.4
Świnoujście	1.1	2.4	3.2	3.5	1.4	1.65	1.25	1.2	2.05	1.9	1.65	2.05	23.35

Ustka (Fig. 8). Such a considerable difference can be chiefly attributed to the characteristics of the station locations: Świnoujście is located in the area of Pomeranian Bay, sheltered against strong winds from the west and south-west, whereas Ustka is exposed to strong winds from the western sector. The frequency of wind direction (Fig. 9) shows that the westerly winds prevail. As the difference in distance of both measuring stations from the sea is small (70 m), it has no significant impact on the wind speed.

Annual distribution of wind velocity in Ustka is more diversified, with the highest values recorded in January, as supported by high horizontal gradients of atmospheric pressure within Poland. In Świnoujście, the highest wind velocity values are recorded in April, when there is an increased frequency of the north-east and north wind from the open sea. The lowest velocities at both stations occur in the summer season (July and August) when horizontal pressure gradients over Poland are low. Differences in average wind velocity between the stations are critical for explaining the large discrepancy between the number of days with aeolian impact on the cliff. This is further evidenced by the number of days on which the wind velocity exceeds 6 ms^{-1} (Table 4). Most days with an average wind speed of > 6 ms^{-1} is characterized by onshore wind direction from SW to NE, which is favourable for aeolian processes. In Ustka, the number of days is nearly four times higher compared to Świnoujście. Wind velocity is influenced by its direction. Spring is the time when the situation is favourable in this context. During this period, the increasing frequency of northerly wind is most relevant, especially due to the location of the Świnoujście station.

Precipitation has a large impact on deflation processes on the cliff as well. The annual average number of days with a daily precipitation level equal or higher than 6 mm is 34 days/year in Ustka and 30 in Świnoujście (Table 5). Still, days with a precipitation ≥1 mm are common (approximately 120 days at each station per year) and may exceed six mm during the five subsequent days. In accordance with the criteria adopted earlier, these conditions prevent deflation. April typically has the lowest monthly amount of precipitation at both stations. In the same month it can be observed the smallest number of days with precipitation in individual height divisions. In conjunction with the velocity and direction of wind, as well as air temperature and humidity, such conditions dictate the highest number of days conducive to cliff deflation.

Based on the review of weather charts of Europe from the hour of 00 UTC, published in *Daily Meteorological Bulletin* of IMGW (2001–2010), there are identified the types of air masses present during the days with deflation potential. The analysis revealed that in April, when cliff deflation is most frequent, the advections of Arctic air are likely responsible for aeolian activity. During this month, Arctic air was present in 65% of days with deflation potential in Ustka, whereas it exceed 90% in Świnoujście (Fig. 10).

Table 5 Number of days with precipitation ≥ 0.1, ≥ 1.0 and ≥ 6.0 mm. Means for the period 2001–2010.

Ustka													
	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	Year
≥ 0.1 mm	15.3	14.3	14.5	10.0	11.9	11.9	14.0	14.9	13.7	15.4	17.6	16.5	170.0
≥ 1.0 mm	9.3	9.3	8.8	6.0	8.5	8.8	11.1	11.2	10.5	12.2	12.8	11.4	119.9
≥ 6.0 mm	1.9	1.3	1.7	1.2	2.6	2.5	4.2	4.9	3.8	4.0	3.7	2.4	34.2
Świnoujście													
	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	Year
≥ 0.1 mm	15.6	14.3	15.2	10.3	13.3	12.9	13.0	12.7	12.4	15.9	17.9	16.5	170.0
≥ 1.0 mm	9.6	8.5	9.8	6.5	9.5	9.7	10.0	9.7	9.1	11.7	11.0	10.7	115.8
≥ 6.0 mm	2.3	1.7	2.3	1.1	2.4	2.9	3.7	4.2	3.0	1.9	3.0	1.4	29.9

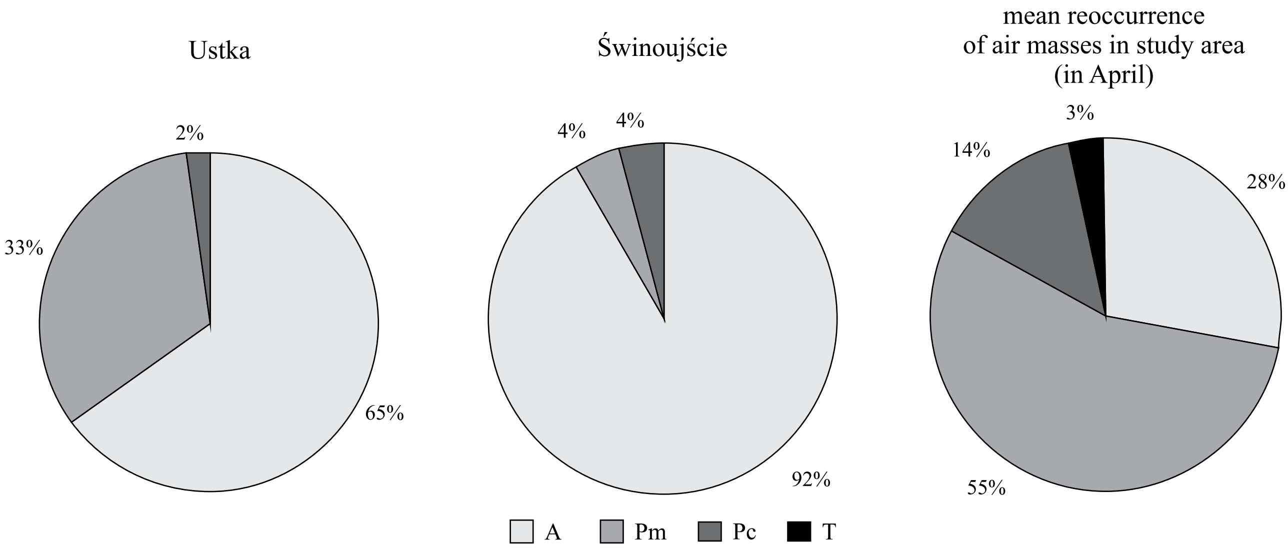

Fig. 10 Relative contribution of air masses on days with potential aeolian activity on the cliff in April in Ustka and Świnoujście region. Average values for the period 2001–2010. Legend: A – arctic air mass; Pm – polar maritime air mass; Pc – polar continental air mass; T – tropical air mass.

Inflow of that type of air in April is often accompanied by considerable horizontal gradients of pressure and high velocity of northerly winds, which are favourable for deflation, along with low air humidity, the absence or low amount of precipitation, and the average above-zero daily air temperature despite of frost.

CONCLUSIONS

Erosional and depositional aeolian features are created on the south Baltic coastal bluffs of Poland. They are usually small in size, not exceeding one meter. Larger aeolian features are several meters long. Erosional and depositional aeolian features created on the beach, slope, and the bluff top usually belong to efemeral forms. On the beach are degraded by strong winds and storm surges. On the slope of the bluff are degraded by the slope processes. Larger features are modified and degraded by storm surges.

The formation of aeolian features on the south Baltic coastal cliffs of Poland depends largely on meteorological conditions. Velocity and onshore direction of the wind, as well as precipitation, are of dominating importance. Minor importance is attributed to temperature and relative humidity of air. However, the importance of those meteorological elements increases in winter.

The number of days with deflation potential is four times higher on the cliffs located east of Ustka than in the Świnoujście region. On average, the cliff in Ustka can be impacted by wind during 33 days/year, whereas the one on Wolin Island less than eight days. The difference can be chiefly attributed to the characteristics of the station locations: Świnoujście is located in the area of Pomeranian Bay, sheltered against strong winds from the west.

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References

Arens, S. M., van der Lee, G. E. M., 1995. Saltation sand traps for the measurement of aeolian transport in to the foredunes. *Soil Technology 8*, 61–74. http://dx.doi.org/10.1016/0933-3630(95)00007-5

Borówka, M., Rotnicki, K., 1999. Main directions of aeolian sand transport and its budget on barrier sandy beach (Łeba Barrier case study). In R. K. Borówka, Z. Młynarczyk, A. Wojciechowski (eds), Ewolucja geosystemów nadmorskich południowego Bałtyku [Evolution of coastal geosystems in the south Baltic Sea]. Bogucki Wydawnictwo Naukowe, Poznań–Szczecin, 7–24. [In Polish].

Borówka, R. K., 1980. Present day dune processes and dune morphology on the Łeba Barrier, Polish coast of the Baltic. *Geografiska Annaler 62A*, 75–82. http://dx.doi.org/10.2307/520454

Borówka, R. K., 1990. The Holocene development and present morphology of the Łeba Dunes, Baltic coast of Poland. In K. F. Nordstrom, N. Psuty, B. Carter (eds), Coastal Dunes. Form and Processes. John Wiley & Sons, Chichester, 289–314.

Borówka, R. K. 2001. Intensification of aeolian transport and its conditions within the coastal dunes area in Łebsko Spit. In K. Rotnicki (Ed.), Przemiany środowiska geograficznego nizin nadmorskich południowego Bałtyku w vistulianie i holocenie [Changes of the geographical environment of coastal lowlands in the south Baltic Sea in the Vistulian and Holocene]. Bogucki Wydawnictwo Naukowe, Poznań, 95–100. [In Polish].

Codzienny Biuletyn Meteorologiczny [Daily Meteorological Bulletin] (2001–2010). Instytut Meteorologii i Gospodarki Wodnej [Institute of Meteorology and Water Management], Warszawa. [In Polish].

Buynevich I. V., 2012. Morphologically induced density lag formation on bedforms and biogenic structures in aeolian sands. *Aeolian research 7*, 11–15.

Davidson-Arnot R. G. D., White D. C., Ollerhead J., 1997. The effect of artificial pebble concentrations on eolian sand transport on a beach. *Canadian Journal Earth Sciences 34*, 1499–1508. http://dx.doi.org/10.1139/e17-122

Florek, W., Kaczmarzyk, J., Majewski, M. 2007. Factors conditioning velocity and character of development of cliffs near Ustka. In E. Smolska, D. Giriat (eds), Rekonstrukcja dynamiki procesów geomorfologicznych – formy rzeźby i osady [Reconstruction of morphological processes dynamics – landforms and deposits]. Warszawa, 151–164.

Hojan, M., 2009. Aeolian processes on the cliffs of Wolin Island. *Quaestiones Geographicae 28A/2*, 39–46.

Hojan, M. 2012. Characteristic of aeolian processes on the cliffed coast of Wolin Island. In M. Więcław (Ed.), Środowisko przyrodnicze w badaniach geografii fizycznej [Natural environment in physical geography research]. *Promotio Geographica Bydgostiensia 9*, 141–151.

Kostrzewski, A., Zwoliński, Zb., 1988. Morphodynamics of the cliffed coast, Wolin Island. *Geographia Polonica 55*, 69–81.

Lancaster, N., 2009. Aeolian features and processes. In R. Young and L. Norby, Geological Monitoring. Boulder, Colorado, Geological Society of America, 1–25.

Leatherman, S. P., 1978. A new eolian sand trap design. *Sedimentology 25*, 303–306. http://dx.doi.org/10.1111/j.1365-3091.1978.tb00315.x

Łabuz, T.A., 2005. Coastal dune development under natural and human influence on Świna Gate Barrier in the light of own complex monitoring method. In A. Kostrzewski and R. Kolander (eds), Zintegrowany monitoring środowiska Przyrodniczego. Funkcjonowanie geosystemów Polski w warunkach zmian klimatu i różnokierunkowej antropopresji [Integrated monitoring of natural environment. Functioning of Polish geosystems in the conditions of climate change and multidirectional human pressure]. Biblioteka Monitoringu Środowiska, Bogucki Wydawnictwo Naukowe, Poznań, 299 –311. [In Polish].

McKenna, N. C., Li. B., Nash, D., 2012. Micro-topographic analysis of shell pavements formed by aeolian transport in wind tunel simulation. *Journal Geophysical Research 117*. doi:10.1029/2012JF002381. http://dx.doi.org/10.1029/2012JF002381

Nield, J. M., 2011. Aeolian sand strip mobility and protodune development on a drying beach: examining surface moisture and surface roughness patterns measured by terrestrial laser scanning. *Earth Surface Processes and Landforms 36 (4)*, 513 –522. http://dx.doi.org/10.1002/esp.2071

Prusinkiewicz, Z., 1971. Cliff naspas – new type of the coastal soil. Zeszyty Naukowe UMK w Toruniu, *Geografia 26 (8)*, 133 –157. [In Polish].

Racinowski, R. 2008. Significance of heavy minerals analysis in the studies of the Quaternary deposits in Poland. *Annales UMCS Sectio B, vol. LXIII (1)*, 7–44. [In Polish].

Riabichin, E. L., 1969. An outline of the work with sand traps in field conditions. *Problemy Osvoyenya Pustyn 3*, 33 –37. [In Russian].

Rotnicka, J., 2011a. Impact of beach surface type on the rate of sand transport by wind. *Journal of Coastal Research, SI 64* (*Proceedings of the 11th International Coastal Symposium*), 2058–2062.

Rotnicka, J., 2011b. Factors controlling the development of foredunes along the Łeba Barrier on the south Baltic coast of Poland. *Journal of Coastal Research, SI 64* (*Proceedings of the 11th International Coastal Symposium*), 308 –313.

Rotnicka, J. 2013a. Aeolian vertical mass flux profiles above dry and moist sandy beach surfaces. *Geomorphology 187*, 27–37. http://dx.doi.org/10.1016/j.geomorph.2012.12.032

Rotnicka, J. 2013b. Aeolian sand transport on a tideless beach: rate, controlling factors and influence on foredune formation (Łeba Barrier case, Poland). *Studia i Prace z Geografii i Geologii, Bogucki Wydawnictwo Naukowe*, 1 –159. [In Polish].

Rotnicki, K., Rotnicka, J., 2010. Poland. In E. C. F. Bird (Ed.), *Encyclopedia of World`s Coastal Landforms*, 627–638. doi 10.1007/978-1-4020-8639-7_8.8. Springer Science + Bussines Media.

Saye, S. E., Pye, K., Clemmensen, L. B., 2006. Developments of a cliff–top dune indicated by particle size and geochemical characteristics: Rubjerg Knude. Denmark. *Sedimentology 53*, 1–21. http://dx.doi.org/10.1111/j.1365-3091.2005.00749.x

Subotowicz, W., 1982. Litodynamika brzegów klifowych wybrzeża polskiego [Litho-dynamics of Polish coast cliff edges]. Wydawnictwo Naukowe PAN, Wrocław, 1–152. [In Polish].

Szpikowski, J., 2008. Role of niveo-aeolian processes in formation of young glacial area landforms (water catchment area of Perznica river, Drawsko Lake District). *Landform Analysis 9*, 198–201. [In Polish].