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The influence of coastal morphology on wind dynamics

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Abstract. An analysis of the dynamics of wind velocity along the Baltic coast of Lithuania is presented, based on data collected during field experiments in the summer, fall and winter of 1999–2001 and 2007–2009 at several sites (Būtingė, Šaipiai, Smiltynė, Juodkrantė, Pervalka and Nida). The locations were chosen in order to encompass a wide spectrum of beach and dune ridge morphology. The relationship between wind velocity dynamics and coastal morphology was established, based on measurements of the slope angle, height and shape of the dune crest, as well as measurements of the morphology of the area behind the foredune ridge. On the basis of a comparison of near-surface wind velocity patterns, shear velocity (U^*) and surface roughness length (z_0) were calculated. It was determined that U^* decreases from the middle of the beach towards the foredune toe, then increases towards the crest of the foredune and decreases down the lee slope. A direct correlation exists between U^* and the stoss slope inclination, and the relative height of the foredune. Surface roughness length also increases from the beach towards the foredune crest.

Key words: Lithuania, Baltic Sea, beach, foredune, shear velocity, surface roughness length.

INTRODUCTION

The action of wind on exposed sediments and friable rock formations causes erosion (abrasion) and entrainment of sediment particles. Aeolian processes play a significant role in the formation and evolution of coastal dunes. Wind-blown sand deposition changes dune topography, which in turn modifies the wind. Between dune relief and wind flow feedback mechanisms are formed, which maintain equilibrium of the dune profile (Pelletier 2009). Thus, dune topography is one of the main factors affecting near-surface wind flow transformation and sand transport.

The assessment of the dynamics of wind velocity in coastal areas has become an important research subject (Keevallik 2008). It allows estimation of the potential of sand transport (Svasek & Terwindt 1974; Kroon & Hoekstra 1990; Bauer et al. 1996; Davidson-Arnott & Law 1996; Gares et al. 1996; Nordstrom et al. 1996; Žilinskas et al. 2001), determination of the peculiarities of dune formation and development (Robertson-Rintoul 1990; Fraser et al. 1998; Li et al. 2004; Houser et al. 2008) and assessment of variations in coastal processes (Orviku et al. 2003). However, quite often the potential of sand transport is estimated on the basis of the characteristic of the wind recorded on the beach or at the nearest meteorological station, regardless of the transformation of the wind over dunes. Few works deal with the characteristics of wind transformation over the foredune (Arens et al. 1995; Wiggs et al. 1996; Van Boxel et al. 1999; Parsons et al. 2004; Hesp et al. 2005, 2009; Walker et al. 2006). Most of the existing studies are based on the measurements carried out in one coastal profile, thus reflecting the specific features of a particular coastal sector (Arens et al. 1995; Van Boxel et al. 1999; Hesp et al. 2009) or investigating near-surface wind transformation in boundary layer conditions according to wind tunnel investigation (Wiggs et al. 1996) and numerical modelling (Parsons et al. 2004). However, it has been found that the greater the topographic variability, the greater the transformation in wind flow and variability in dune profile development (Rasmussen 1989; Arens 1997; Hesp et al. 2005). Nevertheless, very few investigations are related to wind flow transformation over dune ridges with different topography (Parsons et al. 2004; Walker et al. 2009). Most of the studies deal with the influence of dune height and slope inclination on wind flow (Sarre 1989; Arens 1996; Parsons et al. 2004). Field research concerning the impact of dune topography (slope and top shapes) on wind flow transformation have not practically been carried out. The main objective of the present study is to evaluate the influence of foredune morphology on wind flow transformation in different coastal sectors, covering the widest possible spectrum of foredune morphology.

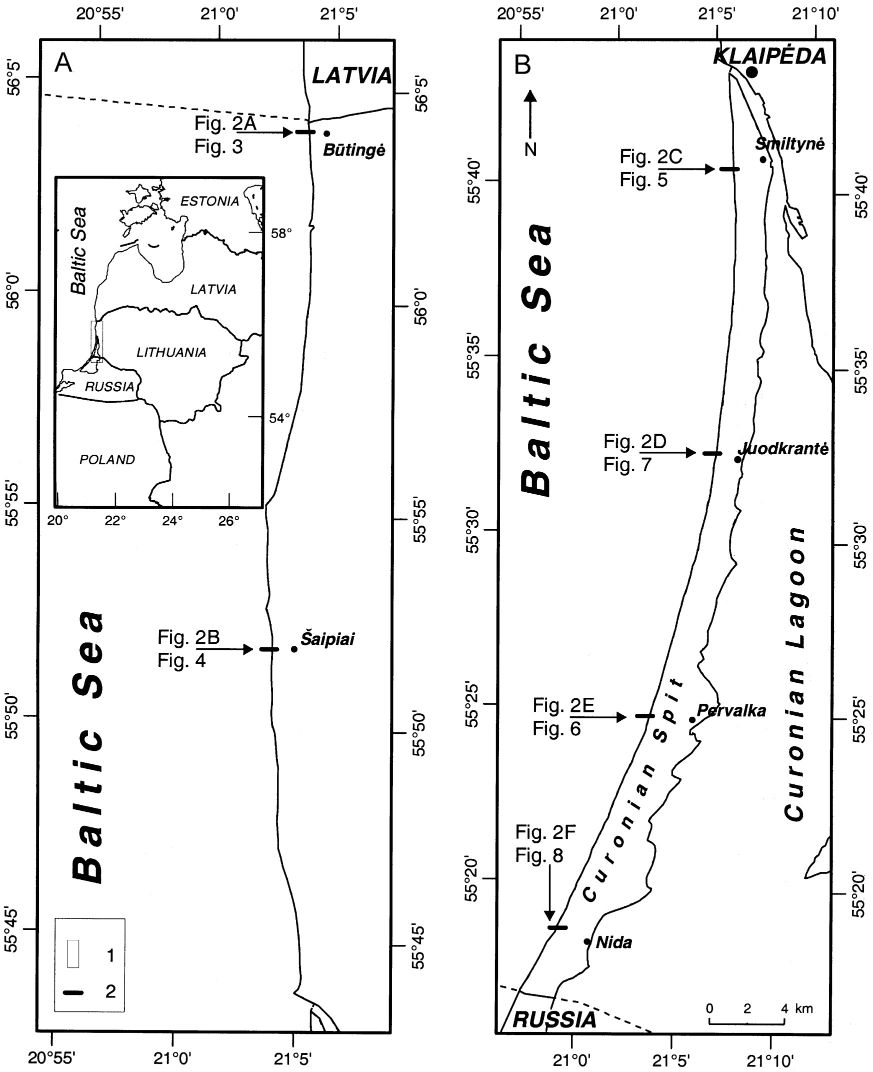

Fig. 1. Location map. 1, study area; 2, sites of measurements. **A**, mainland coast; **B**, Curonian Spit coast. The arrows show wind speed measuring and places of the cross section profile.

METHODS AND THE STUDY AREA

The length of the Baltic coast of Lithuania is only 90.6 km. For the greater part of the distance (i.e. 82.9 km), the beach is adjacent to a foredune ridge, the absolute altitude (i.e. height above sea level) of which ranges from 1.5 to 16.2 m, and width from 3 to 240 m. The data on the dynamics of wind velocity were collected during field experiments in the summer, fall and winter of 1999–2001 and 2007–2009 at many sites (Būtingė and Šaipiai settlements on the continental coast, and Smiltynė, Juodkrantė, Pervalka and Nida settlements on the Curonian Spit) (Fig. 1). As previously mentioned, the locations were chosen in order to encompass the widest possible spectrum of beach and dune ridge morphology.

The geomorphologic features and vegetation patterns of each location are considered and characterized. The foredune at the Būtingė site (Fig. 2A) is flat and low: its average relative altitude (i.e. height above the ground surface) is 2 m and absolute altitude 4 m. The crest and the lee slope are overgrown with marram grass reaching 40–60 cm in height. The beach bordering the foredune in this area is narrow (with an average width of 20 m) and for the most part covered with inequigranular sand, gravel and shingle. The Šaipiai settlement (Fig. 2B) marks the beginning of moraine cliffs. The relative altitude of the cliff at the location where the measurements were carried out reaches 10 m (absolute altitude 11.5 m). The flat crest of the cliff is protected by an up to 30 cm high grass cover. The beach bordering the moraine cliff is

Fig. 2. Sites of measurements. **A**, Būtingė; **B**, Šaipiai; **C**, Smiltynė; **D**, Juodkrantė; **E**, Pervalka; **F**, Nida.

narrow (approximately 20–25 m), covered with medium-grained sand with gravel and shingle. The measurements conducted in this particular location where the moraine cliff has a steep scarp are especially useful in determining wind velocity patterns in the coastal areas affected by strong storms. In this place the erosion of the foredune toe by large waves leads to the formation of sand scarps that measure up to 6–10 m in height. Such developments occurred in many coastal sectors of Lithuania after the hurricane ‘Anatoly’ which took place in December of 1999 (Žilinskas et al. 2000).

The dune ridge at the northernmost site of the Curonian Spit, Smiltynė (Fig. 2C), is high, with an average relative altitude of 11 m (absolute altitude 14 m); at the toe of the incipient dune ridge a new stage has begun to evolve. The stoss slope of the incipient dune ridge is thickly overgrown with up to 60 cm high marram grass. The slope of the primary dune ridge is overgrown with grasses and mosses reaching 10–30 cm in height. The beach at Smiltynė is 50 m wide and covered with fine-grained sand. In contrast to Smiltynė, the foredune is low at Juodkrantė (Fig. 2D) (relative altitude 4 m, absolute altitude 8 m). Its stoss slope is strongly abraded by waves and covered with marram grass with height ranging from about 40 to 60 cm. The beach here is only 20 m wide and covered with coarse-grained sand. The next location, Pervalka (Fig. 2E), is best characterized by its double dune ridge. The relative altitude of the lower (i.e. foredune) ridge, which is closer to the sea, is 2.5 m (5 m above sea level), while the relative altitude of the higher backdune ridge, farther from the sea, is up to 6 m (10 m above sea level). The foredune ridge is protected by a thick cover of marram grass reaching 40–60 cm in height; the backdune ridge is overgrown with shorter (up to 10–30 cm) grasses and mosses. The two ridges are separated by a flat trough (40 m wide), likewise protected by a thick grass cover. The beach at Pervalka is 35 m wide and covered with medium-grained sand with shingle. At the most southerly site of the study area, Nida (Fig. 2F), the dune ridge is single-crested. Its relative altitude is 6 m (9 m above sea level). The height of the marram grass cover protecting the foredune reaches 30–40 cm. The width of the beach at this location is 45 m; it is covered with medium-grained sand.

The measurements were performed with manual anemometers MC-13, placed at five different sections: the middle point of the beach, the toe of a foredune, the stoss slope, the crest and the lee slope of a foredune. In certain locations with a more complicated foredune morphometry (such as Smiltynė and Pervalka), additional anemometers were placed on the crest of the backdune ridge and in the trough. Twenty-five to forty anemometers, fixed on stands, were used for synchronous measurement of wind velocity. At each measuring point wind velocity was recorded at heights of 0.2, 0.5, 1.0, 1.5 and 2.0 m above the ground surface. The representative measuring altitudes were found by a preliminary determination of wind velocity, by vertically spacing the anemometers every 10 cm, up to a height of 2 m. These measurements support the conclusion that measurements at the five heights mentioned above (0.2, 0.5, 1.0, 1.5 and 2.0 m) were sufficient to determine the dynamics of the velocity of the near-surface wind. Wind velocity is also measured at similar heights in other countries, following this standard method: 0.2, 0.4, 0.8, 1.6 m (Fraser et al. 1998); 0.3, 0.5, 1.0, 2.0 m (Sherman & Hotta 1990); 0.25, 0.5, 1.0, 2.0 m (Houser et al. 2008).

Three measurements were made at each coastal profile, with an interval of 10 min. In order to carry out the analysis and compare the impact of different coastal morphologies on the dynamics of wind velocity, the data obtained under similar meteorological conditions (i.e. when wind was blowing perpendicular or nearly perpendicular (270°) to the coast, at an average speed of 10–12 m s^{-1}) were selected. In total, 23 measuring series were selected during which 69 measurements were performed in 14 cross-shore profiles of different morphology and surface features. In addition to wind velocity measurements, the study also included levelling of the cross profile of the beach and foredune, as well as an estimation of the height and thickness of the grass cover at each chosen location.

The curves of the wind velocity profile in the near-surface layer (up to 2 m above the ground surface) were drawn based on the collected data. The surface roughness length (z_0) was determined on the logarithmic altitude scale by extending the wind velocity curves to zero. The variation in near-surface wind flow isovels was drawn for each cross profile of the coast. The wind flow isovels were drawn not on the basis of the values of absolute wind velocity, but on the percentage expression of wind velocity (where a 100% isovel corresponds to wind velocity in the middle point of the beach, at a height of 2 m above the ground surface). The wind above 2 m was calculated by extending the curve of the vertical wind velocity distribution.

The shear velocity of wind (U^*) was calculated by the formula

$$U^* = k \frac{U_z}{\ln z / z_0},$$

where U_z is wind velocity at an altitude z, z_0 is the surface roughness parameter (the height at which wind velocity is zero), k is von Karman's constant (approximately 0.4).

The parameters z_0 and U^* were chosen as the main parameters because they best reflect the entire vertical profile of wind velocity, do not change with different heights and are used as constant values in the medium wind velocity regression equation. It should be pointed out that, despite the interdependence between the studied parameters, these are used as independent indices when describing wind velocity.

The measurements showed that in several cases the logarithmic distribution of wind velocities on the stoss slope and the crest of a foredune exhibited an almost linear character. This happens due to the increase in the wind velocity gradient in the air layer of 0.5–2.0 m above the ground surface, while in the lower layer (0–0.5 m) the gradient decreases. The deviation of wind velocity from the logarithmic distribution is greater on the leeward side of a foredune due to air eddies. This deviation from a 'Law of the Wall' in the boundary layer is also stated by other authors (Mulligan 1988; Rasmussen 1989; Arens et al. 1995; Wiggs et al. 1996; Van Boxel et al. 1999; Wiggs 2001; Walker et al. 2006). Considering surface roughness, vegetation and topography, calculated shear velocity describes from 50–70% (Rasmussen 1989; Walker et al. 2006) to more than 96% (Arens et al. 1995; Parsons et al. 2004) of the measured wind profile. The measured and calculated wind profiles did not match each other, ranging from 2% in the beach to 50% at the lee slope. These deviations were greater where foredune topography was more complex. On the beach the greatest deviations of the wind profile from theoretical values were recorded at the beginning of sand transport. For these reasons shear velocity was estimated on the basis of all measured vertical velocity profiles. Despite these deviations, shear velocity can be used to describe the general patterns of changes in dune morphometry (Luna et al. 2011) and sand transport (Arens 1997).

SPATIAL DIFFERENCES IN WIND FLOW OVER FOREDUNES

Būtingė site

During the observations on the foredune at Būtingė the wind was blowing at 7–10 m s^{-1} from 210°. On the basis of the variations in wind velocity at different heights it is estimated that, from the middle point of the beach towards the foredune toe, the wind velocity within the 0.2–1.0 m layer decreased as a result of changes in topography and the presence of marram grass, but increased (convergence in upper isovels of the wind flow) above that level (1.5–2.0 m) (Fig. 3). A rather similar trend was observed rising up the windward slope. Within the 0.2–0.5 m layer wind velocity was reduced due to the thicker marram grass cover and change in slope inclination. On the contrary, in higher layers (2.0 m), sloping upwards, wind velocity increased. Wind velocity decreased dramatically directly behind the foredune crest (divergence of isovels (Fig. 3)).

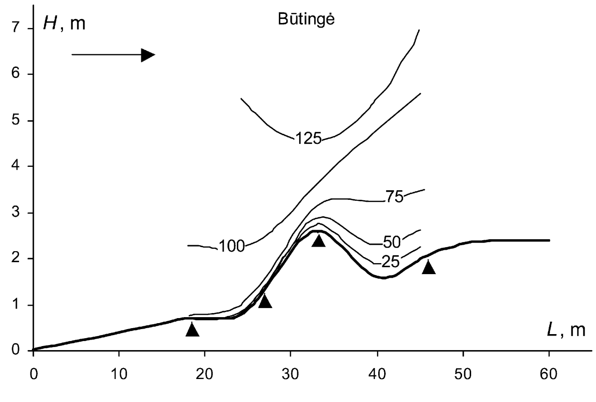

Fig. 3. Variations in wind speed (%) in the cross-shore profile near Būtingė. In Figs 3–8: *H* – height (m) above sea level, *L* – distance (m) from the coastline, wind direction is marked by arrows, wind speed measuring sites are denoted by small triangles, numbers on lines show per cent of wind speed, where a 100% isovel corresponds to wind velocity in the middle point of the beach, at a height of 2 m above the ground surface.

Šaipiai site

On the foredune at Šaipiai the wind was blowing at 7–10 m s^{-1} from 210°. Due to a higher cliff and inclination of the slope, wind speed decreased throughout the 0.2–2.0 m layer from the beach towards the cliff toe (foot). This deceleration continued also on the cliff stoss slope. On the brink of the cliff crest, because of the generated streams ascending along the steep slope (58°) as well as the appearing grass cover, the wind velocity decreased dramatically at the height of 0.2 m, while at a higher level (0.5–2.0 m) it increased significantly (convergence in isovels of the wind flow; Fig. 4). Farther from the cliff crest, wind velocity increased at 0.2 m, but decreased at 0.5–2.0 m height.

Smiltynė site

During observations at Smiltynė the wind was blowing from 230° at 10–14 m s^{-1}. In observations made from the beach towards the land at the toe of the foredune wind velocity decreased throughout the 0.2–2.0 m layer. The largest velocity reduction occurred within the layer nearer to the ground surface. At the higher level the deceleration was not so sharp (Fig. 5). Up the slope, the wind velocity at 0.2 m continued to decrease due to the occurrence of marram grass, while in the higher layers it increased because of the convergence of isovels over the incipient dune crest (Fig. 5). Directly behind it, at a little trough, wind velocity

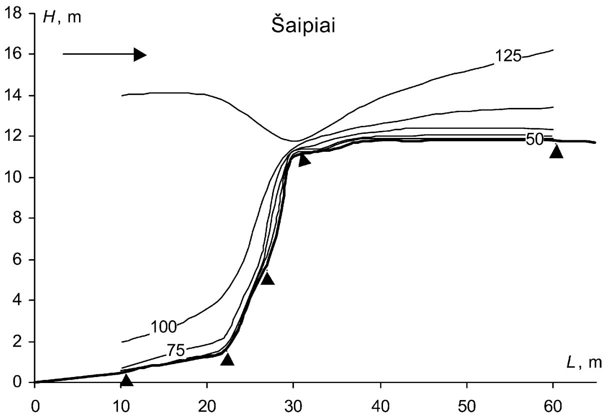

Fig. 4. Variations in wind speed (%) in the cross-shore profile near Šaipiai.

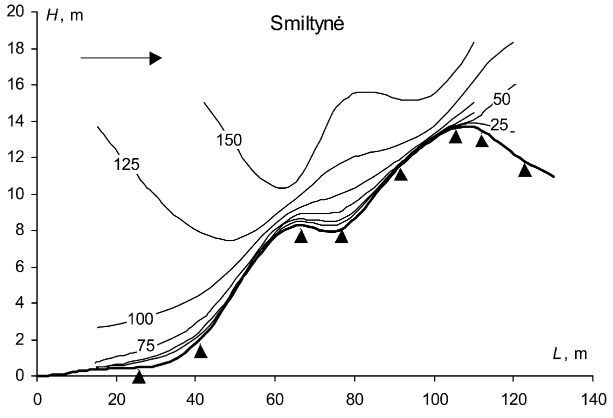

Fig. 5. Variations in wind speed (%) in the cross-shore profile near Smiltynė.

decreased throughout the 0.2–2.0 m layer. The highest wind velocity was recorded at the foredune crest; immediately behind it, drastic deceleration was observed at the lee slope (divergence of isovels of wind flow (Fig. 5).

Pervalka site

At the Pervalka site the wind velocity of 6–10 m s^{-1} and wind direction of 338° were measured. From the middle of the beach towards the crest of the foredune, wind velocity decreased nearer to the ground surface (0.2–0.5 m), whereas an increase was observed within the higher layer (1.0–2.0 m) (Fig. 6). Landwards, wind velocity was reduced both on the trough and at the crest of the backdune. It should be noted that on the lee side an increase in wind velocity was recorded within the 0.5–2.0 m layer. This can be explained by the fact that (the established) old generation ridge is not continuous. A number of blowouts that cross the ridge allow the wind of greater velocity to reach the lee side.

Juodkrantė site

At Juodkrantė the wind direction of 340° and speed of 6–9 m s^{-1} were recorded. Due to a small relative height and simple topography of the foredune, the variations in wind velocity at 2.0 m are comparatively minor (Fig. 7) and vary from 8.7 m s^{-1} on the beach to 9.5 m s^{-1} at the crest. Greater velocity transformations in the wind field occur nearer to the surface at the 0.2 m height. Here the wind speed of 6.1 m s^{-1} is reduced to 2.1 m s^{-1} at the crest.

Nida site

During measurements at Nida the wind blew from the direction of 340° at 7–8 m s^{-1}. Due to the relatively simple cross profile of the foredune morphology, the wind field experienced a comparatively minor transformation. The wind velocity at 0.2 m height decreased gradually from the beach (5.4 m s^{-1}) to the crest (2.5 m s^{-1}). At the lee slope the wind velocity increased slightly (up to 3.0 m s^{-1}) due to eddy formation. Within the higher layer (0.5–1.5 m) the wind velocity decreased gradually until the foredune windward slope, and then increased slightly at the crest. At the 2.0 m height the wind velocity, from the middle of the beach towards the stoss slope, practically remained unchanged, and only increased at the crest (Fig. 8).

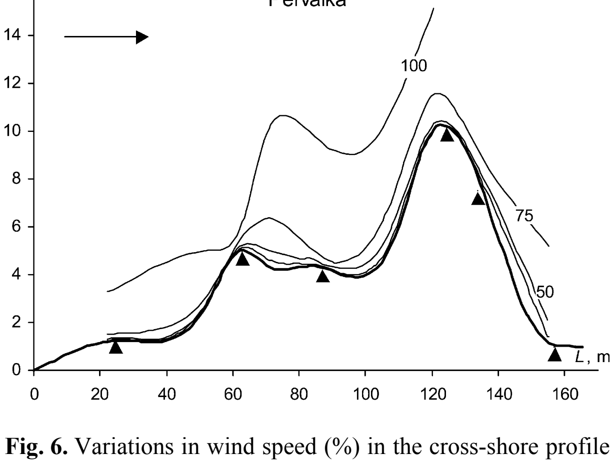

Fig. 6. Variations in wind speed (%) in the cross-shore profile near Pervalka.

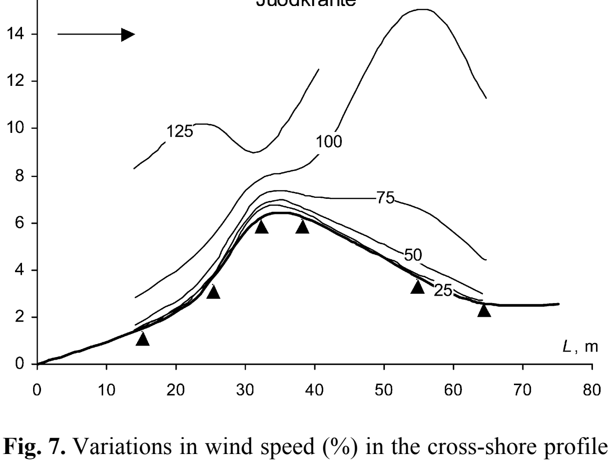

Fig. 7. Variations in wind speed (%) in the cross-shore profile near Juodkrantė.

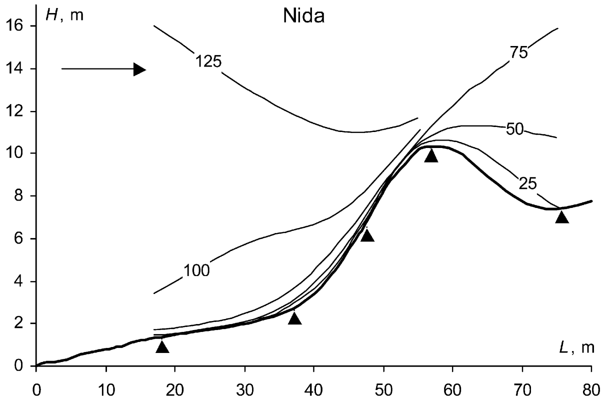

Fig. 8. Variations in wind speed (%) in the cross-shore profile near Nida.

WIND FLOW TRANSFORMATION OVER FOREDUNES

Despite differences in wind transformation, common patterns of wind transformation around foredunes can be identified. According to the collected data, the average shear velocity U^* at the middle point of the beach is 0.43 m s^{-1}, ranging from 0.22 to 0.72 m s^{-1}. In contrast to previous studies (Svasek & Terwindt 1974), which reported that z_0 typically ranges from 0.0001 to 0.0010 m above a smooth sand surface, the present study showed that the upper limit of z_0 may be higher. On the basis of the present calculations, z_0 ranges from 0.0001 to 0.0070 m. The higher values of z_0 may be a result of several factors:

– a slight deviation of the wind velocity curve from the logarithmic distribution from the sea towards the shore;
– small surface irregularities (ripple marks, pebble accumulation, etc.);
– sand transport. When sand transport begins, which was the case during the majority of our measurements, the wind velocity closer to the surface (up to 1 m above the ground) increases more rapidly than it would without sand transport (for example, during rain or if the beach surface was covered by snow), while the wind velocity above 1 m increases at a slower rate than it would with no sand transport taking place.

An even more notable change in wind velocity occurs closer to the foredune. At the toe of a foredune, with the change in the surface slope angle and the appearance of the first plants, the wind velocity 0.2 m above the ground is 0.5–1.0 m s^{-1} lower than on the beach. The reduction in wind velocity at the toe of a dune is also stated by other authors (Arens et al. 1995; Wiggs et al. 1996; Walker et al. 2006). Since near the surface (0.2 m) wind velocity decreases more than at 2.0 m height, U^* also increases, ranging from 0.35 to 1.60 m s^{-1}. Wiggs et al. (1996) observed a slight increase in shear velocity at the toe of a dune in a wind tunnel. However, they obtained an opposite result, i.e. significant decrease in shear velocity at the toe of the dune, calculated from the field data recorded at 0.25 m height (Wiggs et al. 1996). Likewise, there are observable increases in z_0 values on the windward dune toe, ranging from 0.0007 to 0.1430 m. It should be noted that z_0 values increase consistently inland, i.e. from the shoreline to the toe of a dune. Already at the middle point of the beach the value of z_0 may be 0.0010 m greater than at the shoreline. Up a slope, depending on the height and thickness of the grass cover, the wind velocity 0.2 m above the ground decreases by 1–5 m s^{-1} (in comparison with the velocity at the beach). However, U^* increases at the stoss slope of a foredune where wind isovels become compressed, reaching 0.44–1.28 m s^{-1}. Upwards, with the change in the surface angle and the thickening of the grass cover, z_0 also increases, ranging from 0.0007 to 0.16 m.

The described indices reach their maximum values at the crest of the foredune, where the wind velocity at the height of 0.2–2.0 m above the ground increases by 7–8 m s^{-1}. In comparison with the wind velocity at the middle point of the beach, at the crest the wind velocity 0.2 m above the ground is 2–6 m s^{-1} lower (due to grass cover), whereas 2.0 m above the ground it is 1–3 m higher. In addition, this location, with the densest isovels, is characterized by the highest U^* which reaches 0.46–1.80 m s^{-1}. The observations showed that the average of the surface roughness parameter on the foredune crest increases up to 0.0842 m (ranging from 0.0020 to 0.1800 m), regardless of the absence or presence of grass cover.

The presented data have demonstrated that both U^* and z_0 values not only increase from the middle point of the beach towards the crest, but also fluctuate within an increasingly wider range. The standard deviation of the surface roughness length is 0.0020 at the middle point of the beach, 0.0460 at the toe of a dune, 0.0640 at the stoss slope and 0.0630 at the dune crest. The standard deviations of shear velocity at the middle point of the beach, the toe of the dune, the stoss slope and the crest are 0.135, 0.317, 0.301 and 0.407, respectively. Wind velocity decreases down the lee slope of the dune ridge and the form of the wind velocity profile becomes more varied, due to wind eddies. At the lee slope, due to the divergence of the wind speed isovels, shear velocity decreases to 0.26–1.83 m s^{-1}, thus becoming more similar to the value of U^* at the middle point of the beach. At the lee slope of the dune ridge, however, z_0 increases to 0.0032–0.2200 m.

THE INFLUENCE OF FOREDUNE MORPHOLOGY ON WIND FLOW TRANSFORMATION

The distribution pattern of wind velocity may vary depending on the foredune morphology. It was established that changes in wind velocity tend to increase with the windward slope of dune becoming steeper. As the data presented in Table 1 show, at equal relative heights of the foredune the increase in $U*$ from the beach towards the foredune is more rapid in the locations where the stoss slope of the dune ridge is steeper. At the crest of the foredune with the slope angle of 19°, $U*$ accounts for 212% of its value at the beach (assuming that at the middle point of the beach the value is 100%). At the crest of the foredune with the slope inclination of 25°, $U*$ increases by 343%, and at the crest of a steep (58°) foredune, this value rises to 469%.

The relative altitude of the foredune is another important factor predetermining the character of wind velocity on the coast. As seen from Table 1, at the crest of the flat (10°) but rather high (11 m) foredune at Smiltynė, the $U*$ value accounts for 317% of its value at the middle point of the beach, while at the crest of the foredune at Būtingė, which has the same slope angle but is considerably lower (1.5 m), $U*$ accounts only for 145% of its value at the beach. Furthermore, at the crest of a considerably steep (25°) but relatively low (4.5 m) foredune at Juodkrantė, the $U*$ value accounts only for 268% of its value at the middle point of the beach.

The obtained data show that in the locations of a steep stoss slope, the wind velocity at the height of up to 0.5 m above the ground is slightly lower, and at the height of 2.0 m above the ground slightly greater than in the locations of a gentle slope. Thus, the increase in $U*$ from the middle of the beach to the foredune is more rapid in the areas of higher and steeper foredunes. The fact that at locations with similar slope inclination (25° and 24°) in some places $U*$ accounts for 269% of its value at the middle point of the beach, while in others it is only 136%, can be explained by differences in macrorelief and in the distribution of the plant cover, as well as by differences in wind speed and direction during individual experiments. Divergence of wind field isovels and increase in pressure result in flow deceleration at the toe of the foredune. Successive decrease in pressure up to the stoss slope towards the crest causes flow acceleration. This general pattern is described in previous works (Wiggs et al. 1996; Van Boxel et al. 1999). It was also observed that velocity reduction at the toe is more marked near the surface (Wiggs et al. 1996). However, this change varies depending on different dune morphometrics. The graphs in Fig. 9 show that from the beach towards the toe of the foredune, the wind velocity at 0.2–0.5 m height decreases less on the lower dune ridge of lesser inclination (Būtingė, Nida) than on the higher and steeper one (Šaipiai, Smiltynė). Closer to the stoss slope, the wind velocity at 0.2 m height is more dependent on the thickness of vegetation cover than on foredune morphology. Within the higher layer (1.0–2.0 m from the surface) the wind velocity practically remains unchanged between the middle of the beach and the foredune toe; however, up the stoss slope towards the foredune crest, greater changes in wind velocity occur on the higher and steeper dune ridge (Šaipiai, Smiltynė) than on the lower one of smaller inclination (Būtingė, Nida) (Fig. 9).

In addition to the above-mentioned differences in altitudes and slope angles, different foredunes have other individual morphological features. The influence of these on the wind velocity in the coastal area is demonstrated in the schemes presented in Figs 3–8.

As mentioned previously, the foredune ridge at Smiltynė (Fig. 5) is notable not only for its high altitude, but also for its two ridges: the higher established one, farther from the sea, is connected to a lower incipient one. The shear velocity increases evenly from the beach to the foredune, reaching its first maximum value ($U* = 1.0$ m s^{-1}) above the crest of the first ridge. A divergence of isovels occurs behind the crest of the incipient dune ridge and, consequently, the shear velocity decreases. On the lee side of the ridge, eddies may be

Table 1. Variations in shear velocity ($U*$) above foredunes with different slope inclinations and relative heights. In brackets – portion of $U*$ (%) in the beach value

	$h = 7$ m, inclination 19°	$h = 7$ m, inclination 21°	$h = 7$ m, inclination 25°	$h = 9.5$ m, inclination 58°	$h = 1.5$ m, inclination 10°	$h = 4.5$ m, inclination 24°	$h = 11$ m, inclination 10°
Beach	0.74 (100)	0.37 (100)	0.46 (100)	0.32 (100)	0.40 (100)	0.50 (100)	0.52 (100)
Toe	0.95 (128)	0.35 (95)	0.66 (143)	0.50 (156)	0.47 (118)	–	0.70 (135)
Stoss	1.28 (173)	0.66 (178)	1.23 (269)	0.51 (159)	–	0.68 (136)	1.10 (212)
Crest	1.57 (212)	1.14 (308)	1.58 (343)	1.50 (469)	0.58 (145)	1.34 (268)	1.65 (317)

– no data.

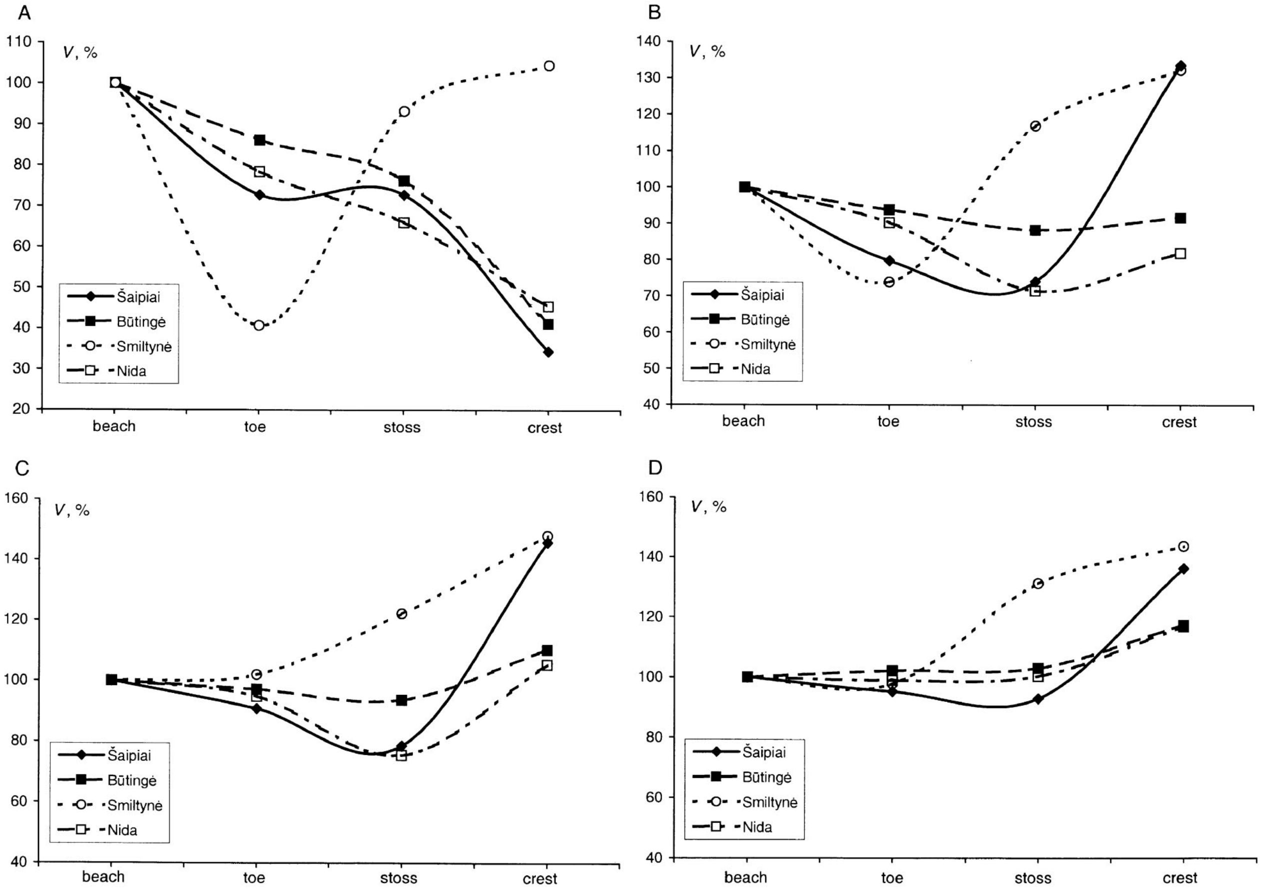

Fig. 9. Near-surface wind velocity dynamics in the coastal cross-shore profile with different foredune topography. **A**, 0.2 m height above surface; **B**, 0.5 m height; **C**, 1.0 m height; **D**, 2.0 m height. Wind velocity (*V*) is given in per cent from the middle of the beach.

formed by strong winds; in the lower parts of these eddies, the resultant wind direction becomes opposite to the main wind flow. The second greater convergence of wind flow isovels can be observed above the crest of the established dune ridge ($U^* = 1.23$ m s^{-1}). On the lee slope here, the divergence of wind flow isovels is notably stronger than on the lee side of the incipient dune ridge (Fig. 5).

A similar distribution pattern of isovels was observed above the double dune ridge at Pervalka (Fig. 6). As described previously, the two ridges at this location are separated by a flat trough, thickly overgrown with grasses, which is considerably wider than the one at Smiltynė. In contrast to Smiltynė, the greatest shear wind velocity at Pervalka occurs above the foredune located closer to the sea ($U^* = 1.20$ m s^{-1}), behind which U^* decreases and z_0 increases. The convergence of wind flow isovels at the crest of the backdune ridge here is not as strong as at the established ridge at Smiltynė, and the shear velocity above the backdune ridge is rather low ($U^* = 0.44$ m s^{-1}). Such differences in shear velocity are conditioned by the wide trough (about 50 m) between the ridges.

It was estimated that the wind blows differently at flat (Fig. 4) and pointed and sharply sloping crests of foredunes (Fig. 8) of similar height. The lee slope behind a flat and wider crest is not as marked as that behind a pointed, sharply sloping crest. Our data show that z_0 increases to 0.111–0.125 m at the western edge of a flat crest. At 6 m from the edge, z_0 decreases to 0.080 m on average, and at the foot of the lee slope it decreases ultimately, ranging between 0.025 and 0.044 m. At the top of a foredune with a pointed crest, z_0 reaches 0.02–0.16 m and increases to 0.08–0.22 m towards the foot of the lee slope.

The monitoring of perturbations of the wind field over foredunes with various morphological features (Figs 3–8) revealed increasing compression of wind flow isovels at the foredune crest. The reason for this is that within the field of higher velocity (125–150% from the measured wind velocity in the middle of the beach at 2.0 m height), isovels get closer to the surface, thereby increasing shear velocity. Such high-speed isovels approaching nearer to the surface immediately behind the dune crest above the flow separation cell were observed both by Walker & Nickling (2002) and Parsons et al. (2004) when analysing the models of airflow dynamics over dunes. The phenomenon of wind flow isovels coming closer to the surface of upper isovels above the foredune crest (Figs 3–8) was caused by lack of measurements immediately behind the foredune crest, where the zone of flow separation begins.

CONCLUSIONS

In the boundary layer between the open sea and the coastal environment the velocity of the onshore wind varies due to the contact with the rough surface, which is reflected by the indices $U*$ and z_0. The shear velocity ($U*$) increases consistently from the coastline to the toe of the foredune. From the toe of the foredune up to the stoss slope, $U*$ starts to increase rapidly, reaching its maximum at the foredune crest. Behind the crest, the shear velocity decreases. The surface roughness length (z_0), from the foreshore towards the toe of the foredune, remains virtually unchanged, but significantly increases from the toe to the crest, regardless of the presence or absence of grass cover. It increases further at the lee slope behind the crest of the foredune. Above the beaches and dune ridges of different morphology, the near-surface wind field experiences unequal transformation. The greatest transformations in the near-surface wind field occur over the beaches with steep, high, pointed foredune crests. In addition, strong deformations are detected in the locations characterized by double-ridged dunes. In these cases, the values of shear velocity and surface roughness length increase considerably from the coastline to the crest of the dune ridge. The wind field undergoes smaller transformation over the flat beaches bordering with the foredunes having low gentle slopes and flat crests that gradually merge into the area behind the dune ridge. The increase in the $U*$ and z_0 values from the coastline towards the foredune is not sharply pronounced in such locations.

The largest perturbations of wind velocity from the beach towards the foredune take place within the lower (0.2–0.5 m) layer; here the major amount of wind-blown sand is transported. The influence of dune ridge morphology on this decrease is distinctly visible at the toe of the foredune where the wind velocity is lowered at high and steep slopes compared to the toe of the dune. This fact may explain the pattern of foredune development. With the increase in dune height, growth rates decrease until the foredune reaches a certain critical height, at which the formation of an incipient dune begins on the toe of the dune ridge rather than further growth of the established ridge.

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Ranniku morfoloogia mõju tuule dünaamikale

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Aastate 1999–2001 ja 2007–2009 suvel, sügisel ning talvel teostatud mõõtmiste põhjal on analüüsitud tuule kiirust Leedu ranniku mitmes paigas (Būtingė, Šaipiai, Smiltynė, Juodkrantė, Pervalka ja Nida). Vaatluskohad valiti nii, et oleksid esindatud morfoloogiliselt võimalikult erinevad rannad ja luitevallid. Luidete kaldenurga, kõrguse ja luite harja kuju, aga samuti eelluidete valli taga oleva pinnavormi mõõtmiste alusel tuvastati seaduspärasused tuule dünaamika ning ranniku morfoloogia vahel. Maapinnalähedase tuule kiiruse vertikaalprofiilidest arvutati hõõrdumiskiirus (U^*) ja aluspinna kareduspikkus (z_0). Selgus, et U^* kahaneb ranna keskelt eelluite jalamini, siis kasvab eelluite harjani ja kahaneb allatuuleküljel. Hõõrdumiskiiruse U^* ja luite tuulepealse osa kalde ning eelluite suhtelise kõrguse vahel on otsene korrelatsioon. Kareduskoefitsient kasvab rannast eelluite harjani.