Regional distribution of Heavy-mineral concentrations along the Curonian Spit coast of Lithuania

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ABSTRACT

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Heavy-mineral concentrations (HMCs) in coastal sands serve as important indicators of hydrometeorological and sedimentological conditions. Along the southeast Baltic Sea coast, quartz- and feldspar-rich sands contain variable amounts (1-8%) of heavy minerals, such as garnet, rutile, zircon, magnetite, ilmenite, hornblende, and other accessory minerals. Their concentrations are found along the Baltic Sea coast of the Curonian Spit, a 98-km-long barrier divided between the Russian Federation (47 km) in the south and the Republic of Lithuania (51 km) in the north. The open sea beach sites range from 25 to 80 m in width and are backed by 5-16 m height foredunes. To examine the patterns in HMC distribution, a total of 303 surface sand samples were collected from the middle of the beach, foredune toe, and stoss slope at 500 m intervals along the entire length of the Lithuanian section. To characterize the relative concentrations of heavy minerals (especially ferrimagnetic), a Bartington MS3 field scanning sensor was used for rapid and effective measurements of low-field volume magnetic susceptibility (MS). Along the Baltic Sea beach, in-situ MS values of $\kappa < 50$ µSI of background quartz-rich sands contrast with $\kappa > 150$ µSI in surface HMCs. On the beach, MS averages 38 µSI□, whereas on the foredune toe and stoss slope they decrease to 33 and 26 µSI□ respectively. Furthermore, alongshore variations in beach HMC characteristics follow a cyclic pattern with a wavelength of approximately 10 km. This pattern is likely related to wave runup during major storms, whereas on the foredune toe and stoss slope, HMCs reflect the secondary reworking by aeolian processes. Along the sectors with higher MS, coastal erosion processes dominate (Pervalka-Nida), whereas low values generally correspond to regions of sand accumulation (Kopgalis-Pervalka). Therefore, surficial HMCs have the potential for characterizing long-term patterns of regional distribution of hydrodynamic energy along drift-aligned sandy coasts.

ADDITIONAL INDEX WORDS: *Heavy mineral concentrations, magnetic susceptibility, sand, distribution, beach, Curonian Spit.*

INTRODUCTION

Along the southeast Baltic Sea coast, quartz- and feldspar-rich sands contain variable amounts (1-8%) of heavy minerals, such as garnet, rutile, zircon, magnetite, ilmenite, hornblende, and other accessory components (Linčius, 1966). In addition to provenance analysis, nature and distribution of heavy-mineral concentrations (HMCs) has been widely used by sedimentologists and geomorphologists to identify sedimentary environments, oceanographic and morphologic trends (Cascalho and Taborda, 2004; Dubois, 2012), past extreme oceanographic events (Babu *et al.*, 2007; Jagodziński *et al.*, 2009; Vijayalakshmi *et al.*, 2010; Nair *et al.*, 2011; Buynevich *et al.*, 2011), lithological marker horizons and paleo-wind proxies (Buynevich *et al.*, 2007a), and general coastal dynamics (Frihy and Komar, 1993).

From one site on the beach the heavy mineral take place where the intensity of the swash is adequate to promote hydraulic grain sorting processes that lead to the concentration of heavy particles (Komar and Wang, 1984; Komar, 1989; Eitner, 1995; Cascalho and Taborda, 2004). In a recent study, HMC trends as a function of wind regime (Mange and Wright, 2007) and gravitation forces have been described at several sites along the Lithuanian coast (Pupienis *et al.*, 2011).

Many authors noticed that HMCs form as a consequence of storm reworking accompanied by erosion of the beach and foredune (Rao, 1957; Žaromskis, 1982; Komar and Wang, 1984; Hamilton and Collins, 1998; Smith and Jackson, 1990; Linčius, 1991; Buynevich *et al.*, 2007b). Many previous studies on heavy mineral distribution involved analysis of short beach sections in order to assess their economic viability for mining (Linčius, 1965; Linčius, 1966; Ludwig and Figge, 1979; Kurian *et al.*, 2000; Aboudha, 2003; Behera, 2003) and to determine their genesis (Pustelnikov and Stauskaitė, 1979; Linčius, 1991; Eitner, 1995; Cascalho and Taborda, 2004).

This paper presents the results of field research carried out along the Baltic Sea beaches of the Curonian Spit, Lithuania during a relatively calm hydro-meteorological (summer) period. The aims of this paper are to report the first comprehensive assessment of HMC occurrence along this stretch of the coast and to examine the factors controlling their distribution.

PHYSICAL SETTING

The study region is located along the Baltic Sea coast of Lithuania (Figures 1a and 1b). The Curonian Spit, a UNESCO World Heritage Site, is a 98 km-long and 0.4-4.0 km width barrier

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Spit (Gudelis, 1998) divided between Russian Federation (47 km) in the south and Lithuanian (51 km) in the north. this time on a sandy barrier.

The study spans the 50.5-km-long coastal strip from Kopgalis to Nida (Figure 1c). The open sea beach sites range from 25 to 80 m in width and elevation of foredune toe ranged from 2.6 to 4.3 m above mean sea level, with an average beachface gradient of 0.073 (~4.2°) and backed by 5-16-m-high foredunes (Jarmalavičius *et al*., 2012a). The beach consists predominatly of medium and coarse quartzoze sand which a mean grain size is 0.30 mm.

In the study area, three sections with different morpho-lithological characteristics are distinguished: Northern (Kopgalis – Juodkrantė), Central (Juodkrantė – Pervalka) and Southern (Pervalka – Nida; Figure 1).

The Northern section from Kopgalis to Juodkrantė stretches up to 19 km (profiles 1-39). It is characterized by the widest beach sites and the highest foredunes. An average beach width and elevation are 45 m and 3.6 m, respectively (Figure 1d) with an average beachface gradient of 0.08 (~4.6°) and an average foredune elevation of 13 m. The mean grain size of surface sediments in this section is 0.23 mm.

The central 9 km-long section (40-56 profile) (Figure 1e) is marked by the narrowest beach sites (average 35m width) and the lowest foredunes (an average elevation – 8.0 m). Juodkrantė – Pervalka section has the highest beach sites elevation of 3.9 m on average, where an average beachface gradient rises up to 0.11 (~6.3°). A mean grain size of surface sediments is 0.33 mm.

In the Southern (57-101 profile) 23 km-length section, Pervalka-Nida, an average beach site width is 40 m, elevation – 3.6 m, and slope – 0.09 (~5.2°). An average foredune elevation does not exceed 9.5 m (Figure 1f). The sector has an average grain size of 0.31 mm.

Due to the fact that the Baltic Sea is non-tidal, wind-generated waves are the main beach-forming factor. During the fieldwork in 3-5 August 2011, the mean wave height was 35 cm, with a mean sea level of +7.0 cm. Through the sampling period, the wind speed

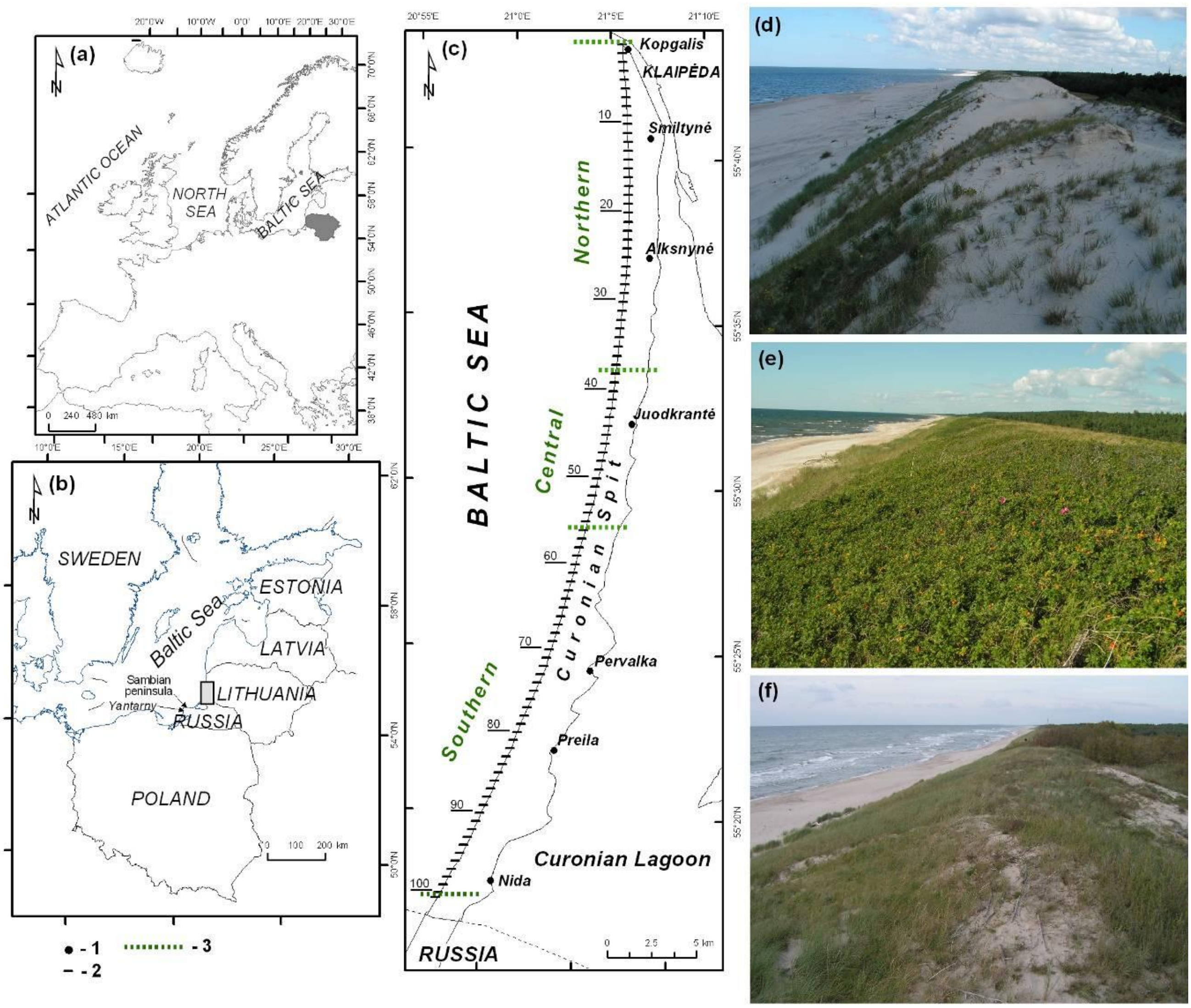

Figure 1. Location of the study area along the Curonian Spit coast of the Baltic Sea. Numbers in legend: 1 – settlements, 2 – magnetic susceptibility (MS) profiles, 3 – morpholithological section boundary. Morpho-lithological sections: (d) – Northern (Kopgalis – Juodkrantė), (e) – Central (Juodkrantė – Pervalka), (f) – Southern (Pervalka – Nida).

increased from 1.8 to 2.8 m/s and direction changed from SW to SE (hydrometeorological data from the Department of Marine Research, Klaipėda). In the summer (July-August) prevailing westerly winds attain speed of 4.2 m/s. The wave mean height (H_{mean}) and wave period (T_p) is 0.65 m and 5.8 s respectively (hydrological data from the Department of Marine Research, Klaipėda). The dominant SW, W wave's direction (Kelpšaitė and Dailidienė, 2011) causes a predominant sediment transport along the Lithuanian coast from south to north (Kirlys, 1965; Gudelis, 1998).

METHODS

During the study period, a total of 303 surface sand samples were collected from 101 profiles at 500 m intervals along the entire length of the Lithuanian section (Figure 1c.). Along each transect, sediment samples were obtained from the middle of the beach, foredune toe (base), and stoss slope (seaward flank) of the foredune. A single, discrete sample collected from one location at one point in time. The sand samples were taken from the "active" layer (upper 5 mm). This strategy ensures that only sediments representing the current hydrometeorological conditions are reflected in the analysis (Aboudha, 2003). Georeferencing was provided by a hand-held GPS system.

The assessment of the degree of heavy-mineral concentration in beach sand employed involved both *in situ* measuremnets and laboratory analysis of ferrimagnetic (e.g., magnetite) and paramagnetic mineral concentration in diamagnetic quartz-rich background sands (see Shankar *et al*., 1996; Pupienis *et al*., 2011). A Bartington MS3 field scanning sensor was used for rapid measurements of low-field volume (κ, μSI) magnetic susceptibility (MS). The results below are based on laboratory MS analyses of the surface samples. The Curonian Spit sea shoreline change rate data is based on comparative analysis of cartographic material, i.e. topographic maps from 1910 to 1991 as well as orthophotos created from 1997 to 2010 (Pupienis et al., 2012). Rates of shoreline change were generated within ArcMap version 10.1 using the Digital Shoreline Analysis System (DSAS) version 4.3, an ArcGIS tool developed by the USGS (Thieler *et al*., 2009). Shoreline change rates were calculated using linear regression rate (LRR), as confidence interval was 95%. The reference point of shoreline change rate was shoreline position chosen as for 1910.

RESULTS

The analysis of MS values revealed a number of differences between heavy-mineral content in the middle of the beach, and foredune toe and stoss slope. The mid-beach MS values fluctuate

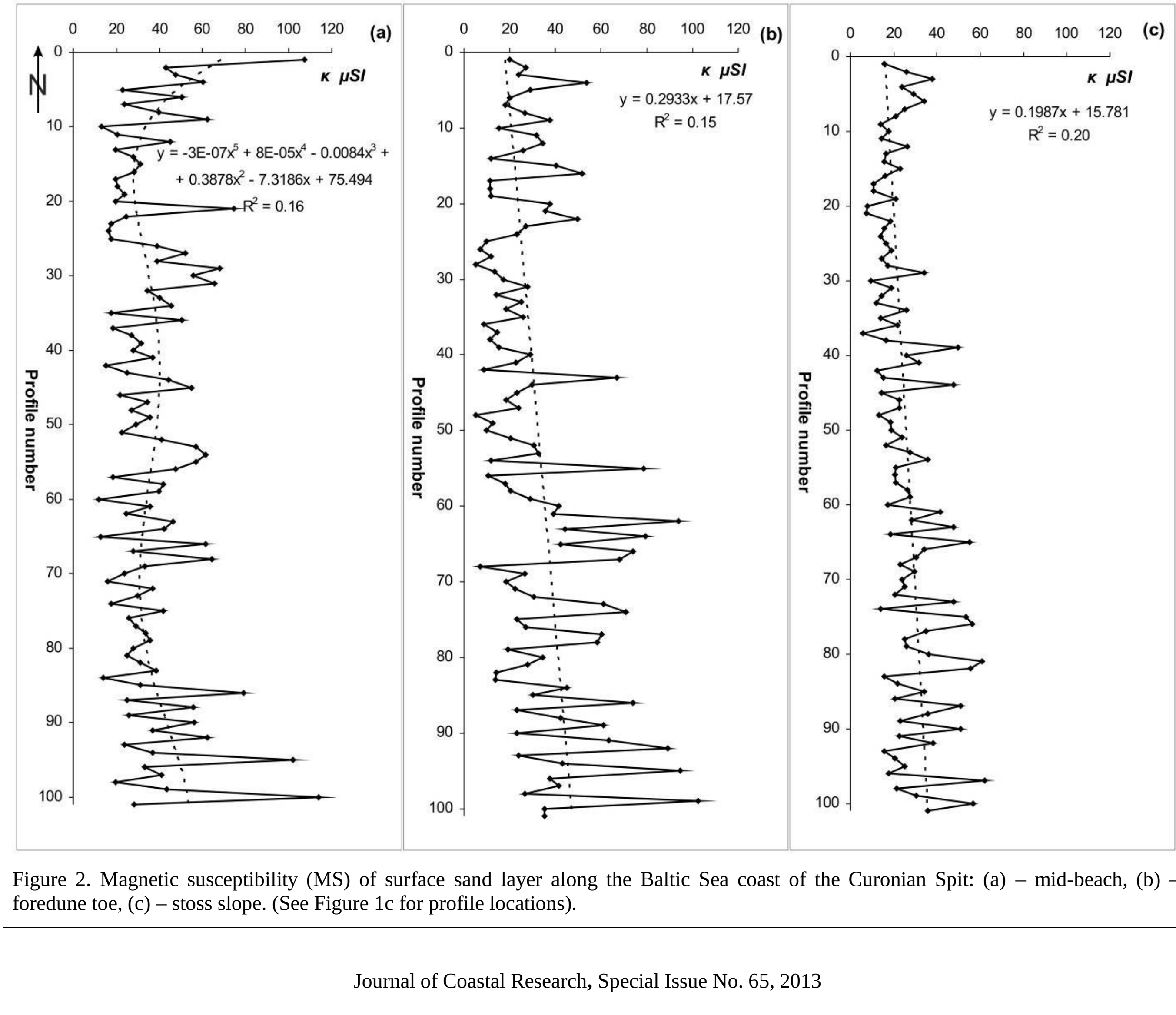

Figure 2. Magnetic susceptibility (MS) of surface sand layer along the Baltic Sea coast of the Curonian Spit: (a) – mid-beach, (b) – foredune toe, (c) – stoss slope. (See Figure 1c for profile locations).

within a wide interval (from κ=11.9 to 113.7 μSI), with a standard deviation (σ) of 19.5 μSI. This sample suite lacks a distinct alongshore MS trend, but exhibits a general cyclic pattern with a wavelength of approximately 10 km (Figure 2a)

For the toe of the foredune, MS values range within a similar interval to the middle of the beach (from 5.2 to 102.5 μSI; σ =21.9 μSI (Figure 2b) A more pronounced alongshore trend characterizes foredune toe and stoss slope, where MS values decrease from south to north (from Nida to Kopgalis). Meanwhile, on the stoss slope, the amplitude of changes in MS values is half that of the dune base. MS values range from 5.9 to 62.1 μSI (σ=13.0 μSI; Figure 2c). In shore-normal profile, the highest κ values occur in the middle of the beach, with a decrease by a factor of 1.5 on the stoss slope. Average MS values are as follows: middle of the beach: 37.6 μSI; foredune toe; 32.5 μSI, and the dune slope: 25.9 μSI.

Greater differences in the average MS value are revealed in Northern, Central, and Southern sections. Average MS values are as follows: Northern section – 26.4 μSI; Central section – 28.8 μSI, and Southern section – 38.0 μSI (Figure 3). In the Northern and Central sections, an average MS value decreases from the middle of the beach to the stoss slope (Figures 3a and 3b). In the Southern section, the maximum of an average MS value occurs at the foredune toe (43.4 μSI), with the minimum on the stoss slope (32.9 μSI), similar to the Northern (18.5 μSI) and Central (24.3 μSI) sections (Figure 3).

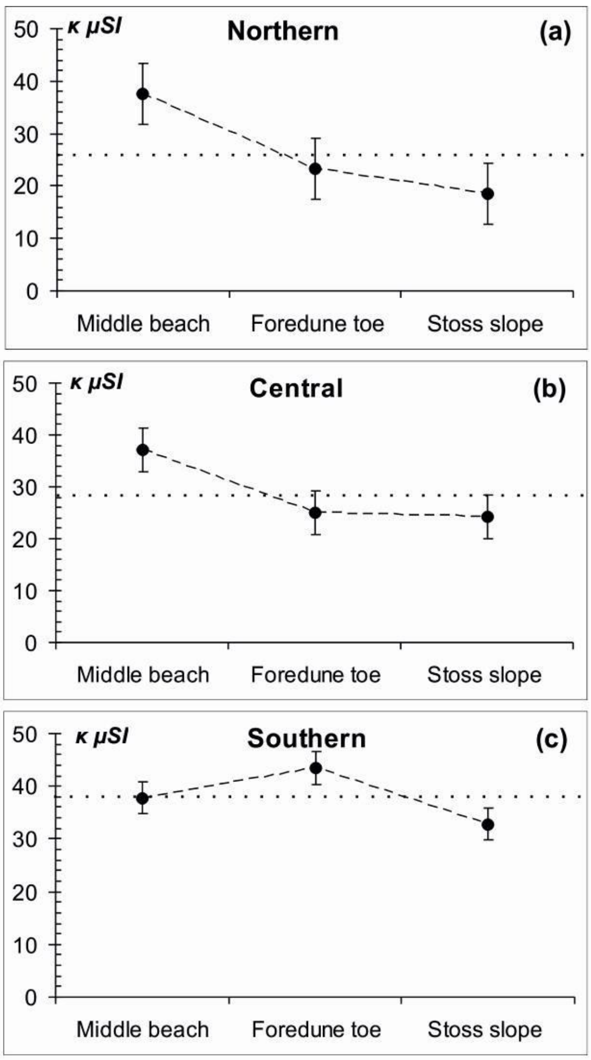

Figure 3. Magnetic susceptibility (MS) of the surface sand layer in three sections: (a) – Northern, (b) – Central, (c) – Southern. Dotted line – average MS value.

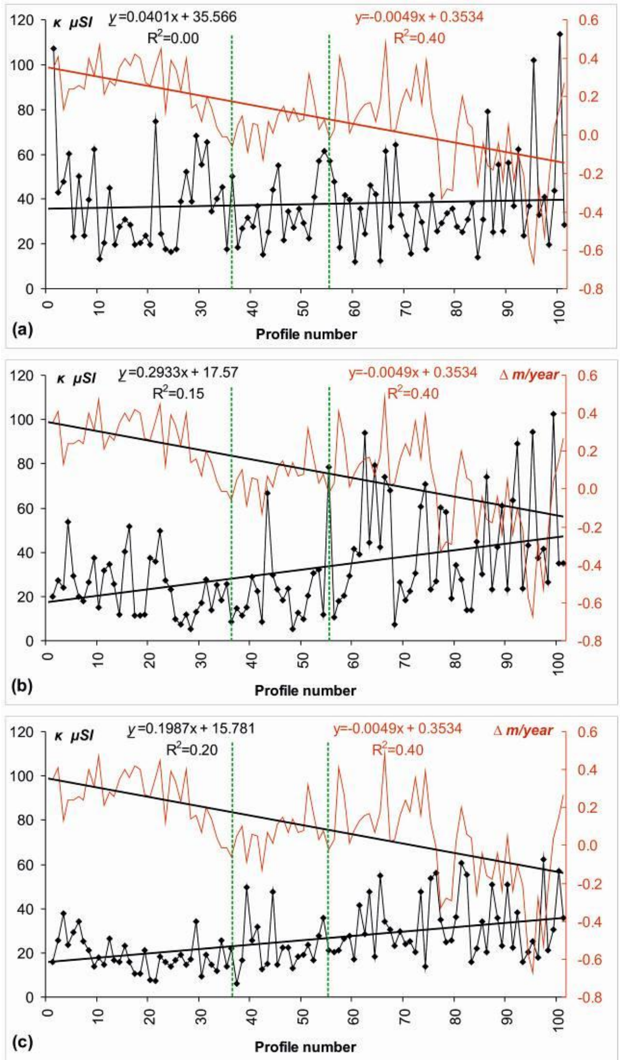

Figure 4. Shoreline change rate (solid red line) during the 1910-2010 observation period (Pupienis *et al*., 2012) and magnetic susceptibility (κ) of sand (solid line with dots): (a) – mid-beach, (b) – foredune toe, (c) – stoss slope. Morpholithological section boundary (dotted green line) (See Figure 1c for profile and section locations).

The smallest distribution differences of an average MS value among all sections were identified in the middle of the beach (0.5 μSI), and the greatest – at stoss slope (14.4 μSI) and foredune toe (20.2 μSI).

DISCUSION

Differences in the nature of the bulk heavy-mineral content along the beach and adjacent foredune sections can be explained by a combination of hydro-meteorological factors, such as wave runup onto the Baltic Sea beaches (Dolotov and Stauskaitė, 1970) and primary or secondary reworking by wind on the upper beach and foredune (Linčius, 1966; Pupienis *et al*., 2011). Since the main source of heavy minerals is the the Sambian peninsula (Figure 1b) and Yantarny amber mines (Lukoševičius, 1972; Kairytė *et al*., 2005), the occurrence of HMCs decreases from south to north (Figure 2) with increasing distance from their source. The alongshore decrease can be also explained by reduction in wave energy in the direction of transport (Kirlys, 1968). HMC magnitude is a combination of distance from source and degree of winnowing/energy input.

According to Komar (1989), regardless of the mean grain size, heavy minerals are typically found in the fine-to-medium fraction of a particular sand horizon. The study demonstrates that higher average MS values prevail in Central and Southern sections, which are characterized by 0.31-0.33 mm fraction. Along the Curonian spit, the heavy minerals are concentrated in erosional Southern and the adjacent Central zones, which are in a hydrodynamic equilibrium (Kirlys, 1968; Komar and Wang, 1984; Linčius, 1991).

It is worth noting the high degree of variability in heavy-mineral content along the mid-beach section may be also affected by episodes of minor storminess (Kirlys, 1964; Žaromskis, 1982; Komar and Wang, 1984; Linčius, 1991). Heavy-mineral concentrations are formed by wave-generated winnowing of the lighter fraction and longitudinal (alongshore) sediment transport (Slingerland, 1977) along the Curonian Spit from south to north (Linčius, 1991). Beach cusps formed by edge waves may explain local (10s of meters) HMC variations, but with consistent sampling strategy, the large-scale signal argues for regional trends.The mid-beach HMCs are then reworked, and often accentuated, due to aeolian transport toward the foredune (Jarmalavičius *et al*., 2012b). Since the effect of wind is weaker than that of waves, the bulk of denser minerals is accumulated along the foredune toe. Similarly, Linčius (1991) concluded that the greatest heavy-mineral concentration takes place on foredune toe (Komar and Wang, 1984; Komar, 1989; Hugues *et al*., 2000).

Therefore, if only textural analysis is used, the presence of HMCs in beach samples may mislead the assessment of short-term trends in longshore sediment patterns. In contrast, the foredune HMCs are formed largely without any major fluctuations and better reflect the general patterns of heavy-mineral distribution along the coast. The present dataset demonstrates that key shoreline dynamics rate are reflected in the MS values on foredune toe and stoss slope (Figures 4b and 4c). The calculated correlation coefficients between MS values and shoreline change rate showed that the weakest correlation is in mid-beach ($r = -0.11$), stronger on stoss slope ($r = -0.22$) and the strongest on foredune toe ($r = -0.27$).

An important finding of our study is the general increase in MS values in coastal sections dominated by erosion, with lower values characteristic of the accumulation zones (Figure 4; Rao, 1957; Komar and Wang, 1984; Frihy and Komar, 1991; Pupienis *et al*., 2011).

The residence time of heavy-mineral assemblages in the nearshore zone during periods of lower sea level has not been investigated, but is expected to reflect the general trends of northerly decrease noted above.

CONCLUSIONS

Heavy-mineral content of the surface beach sands are dependent upon ambient wave and wind conditions, with aeolian dynamics dominating the foredune sectors. Thus any changes in hydrodynamic conditions may be reflected in surface HMCs. It should be noted that due to the increased waves energy, the spatial and temporal shifts in beach HMCs may be masked by short-term fluctuations. Because aeolian processes are weaker than wave-induced bottom stresses, only a small fraction of heavy minerals is transported from the beach to foredune (with maximum accumulation at the foredune toe). For this reason, short-term mineralogical patterns on the foredune are time-averaged and reflect prevailing long-term hydrodynamic conditions. Therefore, heavy-mineral distribution patterns along the Curonian Spit and their dependence on shoreline dynamics are best manifested at the base of the foredune, highlighting the potential for reconstructing past changes in coastal dynamics through the study of buried foredune HMC horizons.

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