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Article

Subaerial beach volume change on a decadal time scale: the Lithuanian Baltic Sea coast

Darius Jarmalavičius[1]*, Gintautas Žilinskas[1], Donatas Pupienis[1], Jūratė Kriaučiūnienė[2]

[1] Nature Research Centre, Akademijos 2, LT-08412 Vilnius, Lithuania. jarmalavicius@geo.lt, zilinskas@geo.lt, donatas.pupienis@gf.vu.lt
[2] Lithuanian Energy Institute, Breslaujos 2, LT-44403 Kaunas, Lithuania. hydro@mail.lei.lt
* Corresponding author: jarmalavicius@geo.lt

With 7 figures

Abstract: One of the most important problems in predicting future coastal evolution is determining the potential impacts of sea level rise on coastal systems. The influence of sea level and wind regime fluctuations on tideless coastal systems with different geomorphology and sand availability was assessed for the period of 2002–2013 along the Lithuanian Baltic Sea coast. The investigation showed no significant dependence between subaerial beach volume change and relative sea level rise on a decadal time scale. However, a minor relative sea level rise (up to 2 mm/yr) may determine even accretion processes in coastal zones with ample sediment supply and a gentle nearshore slope. Therefore we suppose, that extreme events, sand supply, coastal geomorphology, wind and wave climate, are among the most crucial factors affecting subaerial beach volume change. Our findings have implication to other wave-dominated barrier coasts faced with a variety of environmental forcing factors.

Keywords: Coastal evolution; beach erosion; Curonian Spit; sediment budget

1. Introduction

One of the most important problems in predicting future coastal evolution is determining the impact of relative sea level rise on coastal systems, as coastal erosion is largely driven by sea level rise (e. g. Bruun 1962, Zeidler 1995, Nicholls et al. 1995, Rotnicki et al. 1995, Zhang et al. 2004, Pruszak & Zawadzka 2005, Corbella & Stretch 2012). However, there are other significant factors which also influence coastal dynamics, including sand availability (Thom 1984, Carter et al. 1987, Healy 1996, Selivanov 1996, Storms et al. 2002), wave climate (Guillén et al. 1999, Cooper & Navas 2004), storminess (de Ruig & Louisse 1991, Corbella & Sttretch 2012), coastal morphology (Roy et al. 1994, Cowell et al. 2003, Aagaard & Sørensen 2012), the geologic framework (Riggs et al. 1995, Honeycutt & Krantz 2003), and human activity (Jarmalavičius et al. 2012a, Kriaučiūnienė et al. 2013, Pupienis et al. 2013, 2016).

Since there is a complex interrelationship between sea level change and other factors on a short-term time scale, it is difficult to separate the impact of sea level on coastal systems from other factors. Depending on the interaction between various factors, accumulation processes may predominate on the coast even against a background of rising sea level (e. g. Carter et al. 1987, Nichols 1989, Beets & van der Spek 2000, Storms et al. 2002, Pye & Blott 2008). To assess the impact of relative sea level rise (RSLR) on shoreline dynamics, it is important to filter wind and wave climate, coastal morphology, sand supply, currents and human activity.

This study tests the hypothesis that RSLR mediates, rather than controls, this parameter on the decadal time scale. Since 2002, the monitoring of annual changes of subaerial beach sand volume has been undertaken along the Lithuanian coast of the Baltic Sea. The changes in beach volumes for the 2002–2013 period was determined for coastal systems with different geomorphologies. The aim of this paper is to evaluate the impact of sea level fluctuation, wind regime and sand supply on the coastal systems behaviour, specifically the subaerial beach volume. Therefore, it has implications not only for physiographically similar regions in paraglacial non-tidal and

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microtidal settings, but also for many sand-dominated coastal barrier systems (wave-dominated coasts of U.S. Atlantic and Gulf Coasts, Australia; Gulf of Guinea, and the northern Black Sea, among others).

2. Study area

The Lithuanian coast consists of two different segments: the mainland shore (38.5 km) and the Curonian Spit (51.0 km) (Fig. 1). The nearshore of the Curonian Spit has a well-developed bar system consisting of 2 to 5 bars reaching 350–670 m in width (Bitinas et al. 2004, Žilinskas & Jarmalavičius 2007). The prevailing 30–80 m wide beaches are composed of fine and medium sand. The altitude of the foredune reaches up to 16 meters (Jarmalavičius & Žilinskas 2006). The foredune is densely covered by marram grass which stabilized sand. The volume of beach sediment ranges between 42 and 124 m^3/m.

The bar system in the mainland coast is not well developed. It usually has 1–3 bars, but in some places they do not exist at all (Bitinas et al. 2004). Locally, moraine is exposed at the nearshore seabed (at depth of 1.5–3.0 m). The 20–85 meter wide beaches are mostly composed of fine and medium sand (Jarmalavičius et al. 2012b). The highest foredune at Šventoji reaches 12 meters in height; whereas in Būtingė in the North and Melnragė II in the South it is only 4 meters high. The foredune is densely covered by marram grass. It should be noted that the shore between Šaipiai and Karklė over a distance of 5 km is dominated by moraine cliffs above the beach. The volume of beach sediments is 16–160 m^3/m.

As the tide–ebb amplitude on the south-eastern Baltic coasts barely reaches 4.0 cm (Medvedev et al. 2013), the wind-generated waves (Kelpšaitė & Dailidienė 2011), prevailing alongshore currents (and accordingly alongshore sand transport) from South to North (Žaromskis and Gulbinskas 2010, Pupienis et al. 2017) and aeolian processes (Jarmalavičius et al. 2015) are the main beach-forming factors in the Lithuanian Baltic Sea coast. Most significant short-term (particularly yearly) sea level fluctuations near Lithuanian coast occur due to storm surges. The most extreme storm surges are observed in the winter season (November–February). In extreme cases sea level rises up to 185 cm above mean sea level (Jarmalavičius et al. 2016) and wave height may reach 4–6 m (Kelpšaitė & Dailidienė 2011). Storm surges essentially depend on high wind speed and wind direction. The most frequent recurrences of stormy wind direction are observed for south-westerly (35.6%) and westerly winds (24.3%) (Kriaučiūnienė et al. 2006).

3. Methods

The changes in subaerial beach sand volume were used in this study as the main indicator of coastal dynamics, reflecting both the accretion/erosion of the coastal system and the sand budget. Subaerial beach sand volume comprises coastal profile volume from the foredune toe to the intersection of mean sea level (Farris & List 2007). The total volume between adjacent profiles was calculated by multiplying the volumetric change (in m^3 per metre of beach length) by distance. To access volumetric change yearly, coastal cross-profile was measured by levelling at fixed coastal positions in May of each year. 70 profiles (41 on the mainland coast and 29 on the Curonian Spit coast) were measured in total (Fig. 1). The period of observation was from 2002 to 2013. To evaluate the beach volume change on different time scales, both decadal changes and year-to-year variabilities were calculated. In the first case, changes in the subaerial beach volume were calculated over time from 2002 to 2013. In the second case, yearly variations in volume were calculated between two consecutive years.

To avoid random local fluctuations due to small-scale alongshore topographic variations and small accidental errors, the data were averaged for the entire mainland coast and the Curonian Spit coast separately. In such a way the determined changes reflect regional changes instead of individual profile changes (de Ruig & Louisse 1991, Thom & Hall 1991, Davis et al. 2000, McLean & Shen 2006). Spacing between individual profiles in the mainland coast is up to 1 km. On the Curonion Spit, where coastal morphological characteristics variation is less, spacing between profiles is on average 1.5 km. Since the lengths of distinguished coastal sectors were different, the sand volume was calculated in cubic meters per meter of shoreline length (m^3/m).

Monthly mean gauge data, wind speed and direction were collected from the Department of Marine Research of the Environmental Protection Agency. Since coastal monitoring of the depicted transects (Fig. 1) took place in May, the sand volume variations reflect the changes from May of one year to April of the subsequent year. Therefore, the yearly averages of sea level, and wind speed and direction were calculated for the same period using monthly means.

Wind characteristics reflect storminess by indicating wave height and wave-run-up height (Kriaučiūnienė et al. 2006). When assessing the wind impact on a shore, it is important to take into account both the wind speed and direction. The index of wind magnitude includes both; the wind speed and direction:

$$V_i = \Sigma(-sin\alpha V)/n,$$

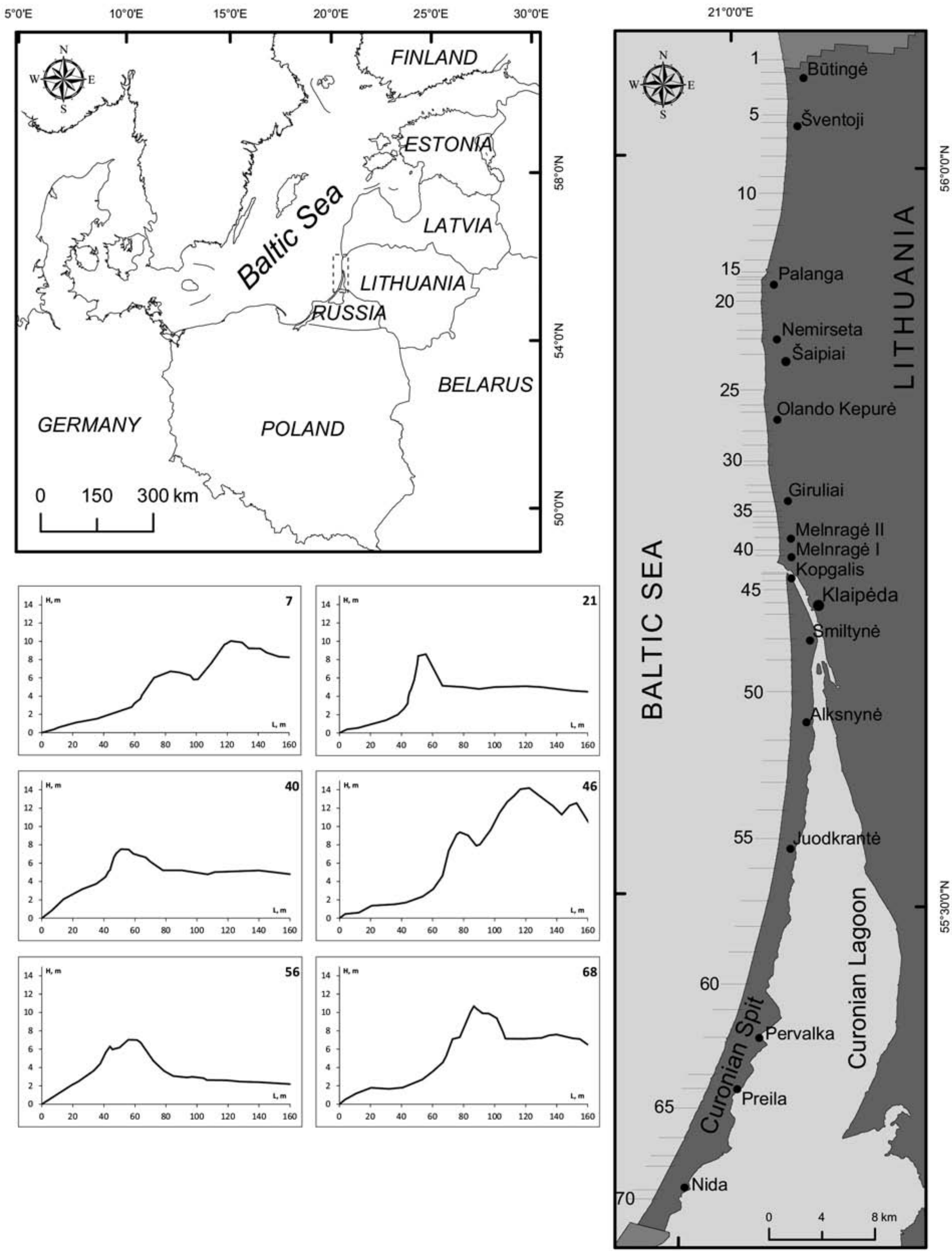

Fig. 1. Location map. Lines with numbers show cross-shore levelling sites. Bottom left – cross-shore profiles.

where V_i – wind index; V – wind speed (m/s); $-sin\alpha$ – sine of wind direction; n – case's number.

As the Lithuanian coastline of the Baltic Sea is oriented in the N-S direction (Fig. 1), the value of the wind index was the highest from the west ($-sin\alpha = +1.0$) and the lowest from the east ($-sin\alpha = -1.0$). For the northern and southern directions, a 0.01 coefficient was used instead of $-sin180°$, or $-sin360°$. In this way, the prevalence of offshore winds V_i is negative. The wind index as well as the subaerial beach volume and sea level were calculated based on an annual average.

4. Results

4.1. Coastal changes on a decadal time scale

A difference between the mainland and the Curonian Spit coasts was determined during the analysis of cumulative sediment volume dynamics for the 2002–2013 period (Fig. 2). On the mainland coast, there was a rising trend in cumulative sediment volume of 0.04 m^3/m per year on average. Since the-inter annual variations were significantly larger than the long-term ones, this trend is not significant (significance level – p-value > 0.05; at the 0.05 level). On the other hand, an apparently increasing trend in the cumulative sediment volume was determined on the Curonian Spit coast, reaching an average of 2.90 m^3/m per year ($p < 0.05$).

During the analysis of sea level change, an increasing trend of 0.16 cm/yr was determined (trends were calculated using a simple *linear regression* (Fig. 3). It should be noted that there are no significant trends ($p > 0.05$) for such a short-time. Nevertheless, general tendencies can be clearly seen. Notably, a consistent rise in sea level has been observed on the Lithuanian coastline since the beginning of the 20th century. During the period 1898–2013, the sea level rose by 0.16 ± 0.02 cm/yr ($p < 0.05$). Therefore, the sea level trend for the period 2002–2013 corresponds with the sea level trend of the previous century. Thus, despite the rise in the sea level, the sand volume increased on the Curonian Spit and was stable on the mainland coast.

The variation in wind magnitude index (V_i) throughout the 2002–2013 period had a slight decreasing trend with an average of 0.018 m/s per year. Similar to the rising sea level trend, the V_i trend is not significant ($p > 0.05$). However, a similar decrease in V_i has been observed since 1960 with a negative trend of 0.02 m/s per year ($p < 0.05$) during the previous decades.

4.2. Year-to-year variability

The annual subaerial beach volume variations are similar on both the mainland and the Curonian Spit coasts (Fig. 4). The changes in beach volume vary from –13 (period 2003–2004) to +8 (period 2002–2003) m^3/m per year on the mainland coast and from –8 (period 2003–2004) to +16 (period 2012–2013) m^3/m per year on the Curonian Spit coast. Since year-to-year variability

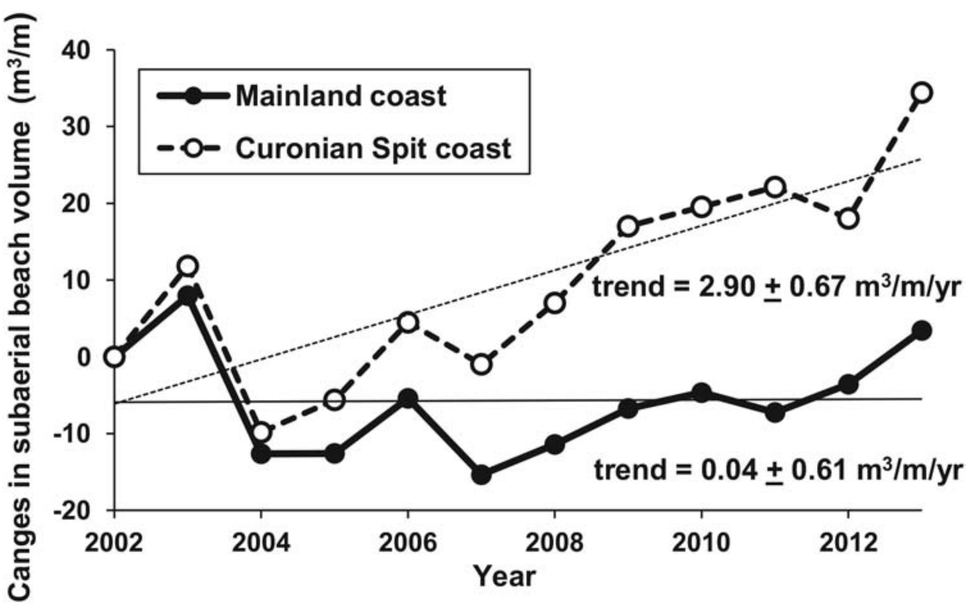

Fig. 2. Cumulative subaerial beach volume changes in the mainland and the Curonian Spit coast between 2002 and 2013 and their linear trends.

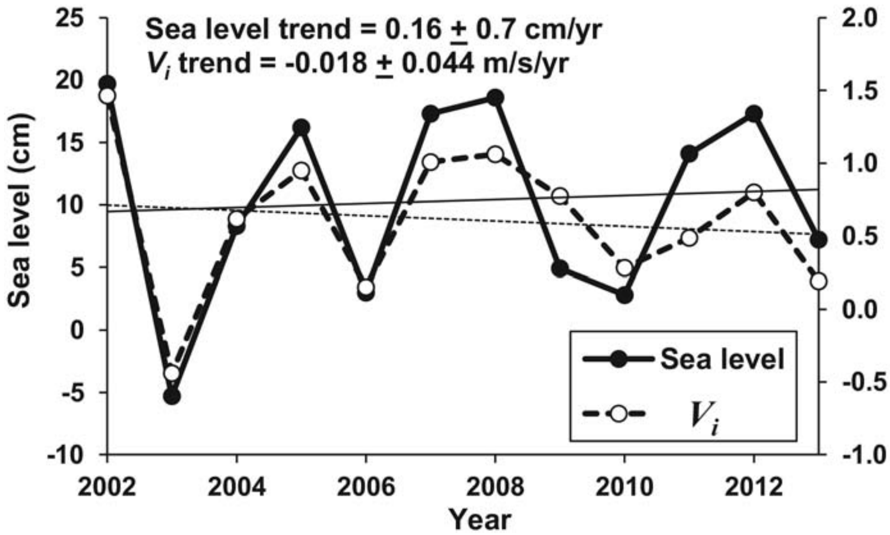

Fig. 3. Sea level and V_i changes between 2002 and 2013 and their linear trends.

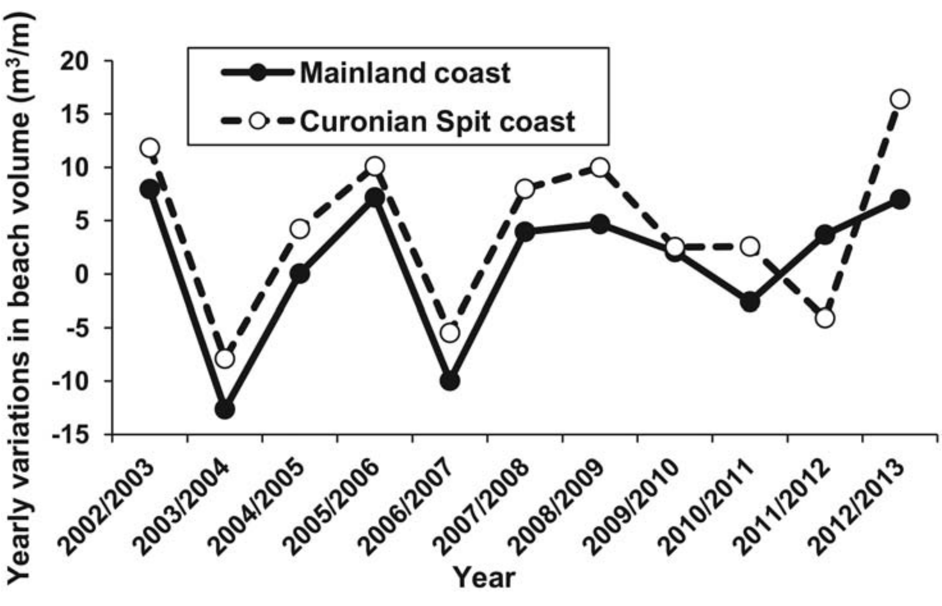

Fig. 4. Yearly variations in cumulative subaerial beach volume between 2002 and 2013.

indicate the differences between beach volumes for two consecutive years, data 2002/2003 in Fig. 4 indicate relative beach volume changes between May 2002 and May 2003. Thus values above 0 denote accretion, below 0 – erosion.

Yearly variations in sea level and V_i were calculated between annual mean values of two consecutive years. For examples, as can be seen in Fig. 3 mean sea level of 2002 was 19.7 cm, and in 2003 it was –5.3 cm, then yearly variation is –25 cm (Fig. 4). Thus annual mean sea level reflect mainly annual meteorological (storminess, wind speed and direction) and hydrological (waves, storm surges) conditions. Synchronic annual changes in sea level and V_i (Fig. 5) were observed. Peaks on the sea level graph coincide with those of V_i. A direct dependence between these two indicators was determined (r = 0.93).

An inverse dependence was observed between the yearly variations in subaerial beach volume and the yearly variations in sea level and V_i. The increase in subaerial beach volume coincides with the fall in sea level

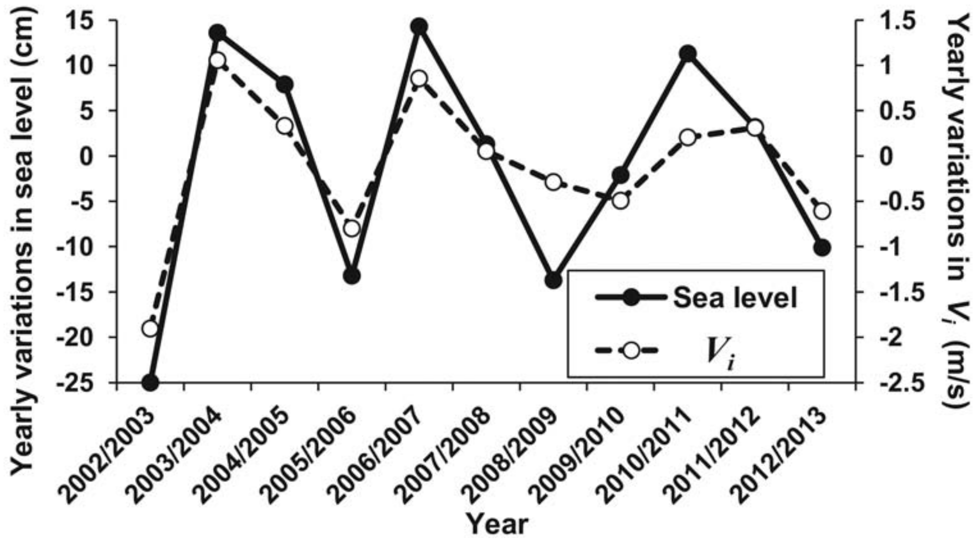

Fig. 5. Yearly variations in sea level and V_i between 2002 and 2013.

and V_i, and *vice versa* (Figs. 6 and 7). The correlation coefficient between the yearly variations in sea level and the subaerial beach volume on the mainland coast is r = –0.84 and on the Curonian Spit coast r = –0.80.

5. Discussion

On a geological time scale, the coastal system does not necessarily undergo retrogradation when the sea level is rising. Depending on the rate of rise and volume of sand supply accumulation processes can occur (Parkinson 1989). For example, a slow relative sea level rise during the Holocene coincided with periods of increasing sedimentation rates (Hoselmann & Streif 2004, Madsen et al. 2007), the development of a coastal barrier system (Thom 1984, Carter et al. 1987, Hoffmann & Lampe 2007, Lima et al. 2013), and coastal dune evolution (Arbogast et al. 2002, Szkornik et al. 2008, Badyukova & Solovieva 2015). These processes are observed on the Curonian Spit over a timespan of 11 years. As a result of intensive Semba Peninsula (south of Curonian Spit) erosion during the Littorina Transgression (about 7.0 ka BP), a large amount of sand was transported in a northerly direction. That was the beginning of the Curonian Spit formation (Damušytė 2011, Jarmalavičius et al. 2013). Therefore, coastal accumulation may take place even when the sea level is rising if there is a large sand supply. In this manner, a feedback mechanism is established between sea level rise and sediment supply. When the sea level rises and erodes coasts, an additional amount of sand emerges and stimulates accumulation processes on the Curonian Spit coast. On the other hand, due to changes in cyclonic activity the mean annual wind speed has been decreasing from the end of the 20th century (Dailidienė et al. 2011, Phillips et al. 2013). This decreasing may be another factor enhanced accumulation processes.

The Curonian Spit and mainland coasts have a strongly different volume of sand. The subaerial beach sand amounts to an average of 81 m^3/m on the Curonian Spit and 69 m^3/m on the mainland coast and also the long term (decadal) suaberial beach volume accumulation is much higher at the Curonian Spit than on the mainland coast. Larger amounts of sand are observed on the Curonian Spit nearshore, where a well-developed bar system exists (Žilinskas & Jarmalavičius 2007). The bar system is not as well developed on the mainland nearshore: in some places, bars are not present at all or there are outcrops of moraine (Bitinas et al. 2004). It is also determined that accumulation processes may take place on a coastal gentle slope even while the sea level is rising (Roy et al. 1994, Aagaard & Sørensen 2012). The average nearshore slope inclination of the Lithuanian mainland coast is 0.8°, while the Curonian Spit nearshore slope is more gentle – 0.6°. Roy et al. (1994) found that in cases of coastal slope inclination lower than 0.8°, the greater part of the sand volume is transported up the slope (landward) even when the sea level is rising.

There are distinct different trends for the mainland and Curonian Spit coastal dynamics, even while the sea level change is the same. No dependence between sea level rise and coastal erosion on a decadal time scale was determined in other different regions with negligible sea level rise (up to 3 mm/yr) and ample sand supply either

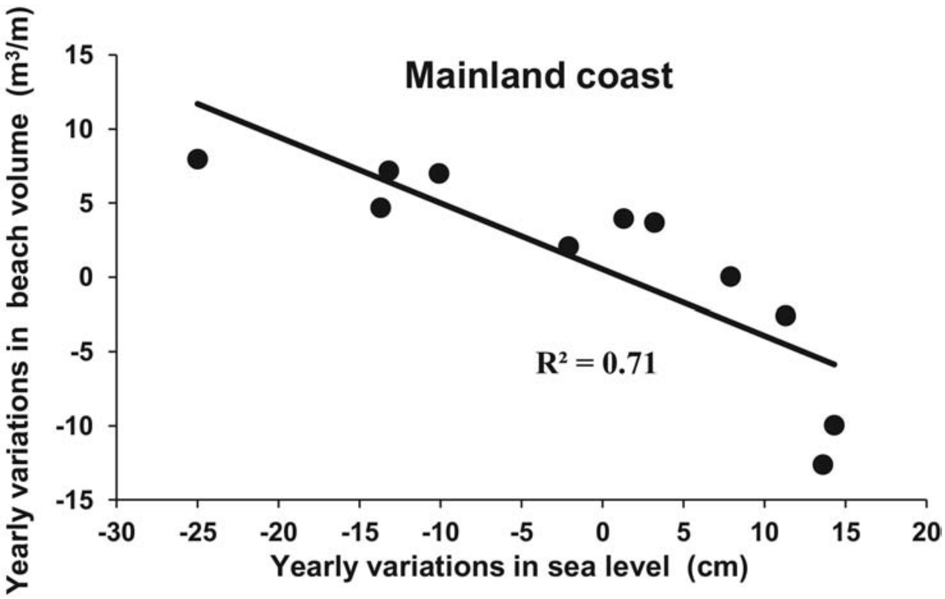

Fig. 6. Correlation between yearly variations in sea level and subaerial beach volume in the mainland coast.

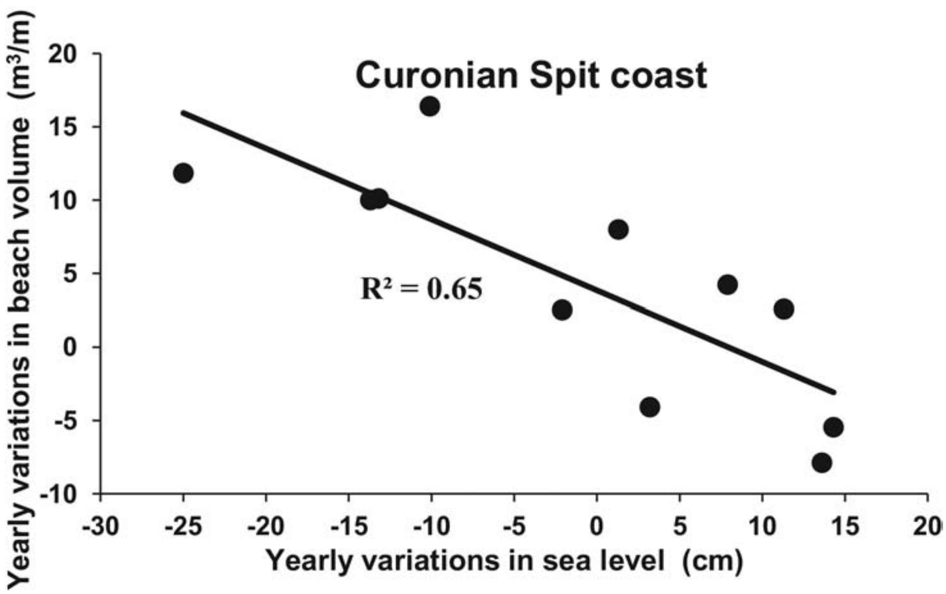

Fig. 7. Correlation between yearly variations in sea level and subaerial beach volume in the Curonian Spit coast.

(Clarke & Eliot 1983, Pye & Blott 2006, Le Cozannet et al. 2013).

Conversely, on a short-term time scale (year), there is good agreement between the yearly variations in sea level and the yearly variations in subaerial beach volume (Figs. 6 and 7). Nevertheless, it is difficult to assess the direct impact of sea level separately from other factors such as wave activity and intensity of extreme events. It is worth to note that during period of 2002–2013 there was only one extreme event on January 8–9, 2005 with recorded gale of the mean maximal wind speed exceeding 25.0 m/s (gust reached 33.0 m/s). The sea level rose to 154 cm at that time. Consequently, the coast beaches lost on average 3.1 m^3/m of sand (Jarmalavičius et al.

2016). However, due to fast post-storm beach recovery the effect of this extreme event is not reflected in yearly variation in beach volume. Therefore during period of 2002–2013 more reliable indices reflecting storm activity is V_i. So usually sea level fluctuation serves as a proxy for the storm activity on a short time scale. This illustrates good agreement between sea level and V_i yearly variations (Fig. 5). Other factors like temperature variations resulting in thermal expansion of the water body, tectonic movement are not significant on a short time scale (year).

It was found that a yearly sea level variation of up to 5 cm on the mainland coast (Figs. 5–7) and of up to 10 cm on the Curonian Spit coast does not have a significant influence on subaerial beach volume variation and does not exceed 5% of the total subaerial beach volume change. It should be noted that comparative beach volume stability is not related with complete coastal system shifting landward, because during period between 2002 and 2013 there was not an appreciable shoreline migration (Jarmalavičius et al. 2014). Moreover, a small yearly sea level rise of up to 4 cm on the mainland coast produces accumulation (Fig. 6). On the Curonian Spit coast even sea level rise of up to 8 cm can determine accumulation processes (Fig. 7). Therefore, it is assumed that coastal erosion processes start only when the sea level rise reaches a threshold value. As can be seen in Figs. 6 and 7, this change should be higher than an average of 10 cm on the Lithuanian coast of the Baltic Sea. If the current rate of sea level rise (0.16 cm/yr) is retained, it will take around 60 years for the sea level to rise by 10 cm. This corresponds to Pye & Blott's (2006) conclusion that the effects of these changes might not be significant for at least 30–50 years. However, it is worth noting that it is impossible to strictly predict that the total rise of 10 cm would be a threshold determining erosional processes to be started because the aforementioned changes happen very slowly, so the coastal system can adapt to these alterations. It is also unclear what variations may happen to the wind and wave regime, sand supply, etc.

6. Conclusions

1. Changes in external factors (sea level change, storm frequency and magnitude) or individual coast elements (sediment volume) are reflected in coastal system dynamics. Therefore, the condition of the coast is more dependent on the changes in external factors rather than their absolute magnitude. For example, from 2006 to 2007 mean sea level rose by 14 cm (from 3 up to 17 cm) and during this period mainland coast lost on average 9.9 m^3/m of sand and the Curonian Spit coast –5.5 m^3/m. In the following years i.e. from 2007 to 2008, the mean sea level was nearly unchanged (rose only by 2 cm, from 17 up to 19 cm). Although the absolute sea level remained high, however, due to its low relative changes, erosion processes did not take place. Moreover, the period of 2007–2008 was dominated by accumulation (on average 4 m^3/m on the mainland coast and 8 m^3/m on the Curonian Spit).
2. On a short-term time scale (year) annual mean sea level reflect mainly annual meteorological (storminess, wind speed and direction) and hydrological (waves, storm surges) conditions. Nevertheless, it is difficult to assess the direct impact of sea level separately from other factors such as wave activity and intensity of extreme events.
3. On a decadal scale at the Curonian Spit and mainland coast sediment accumulation takes place at sea level rise of 0.16 ± 0.7 cm/yr probably due to surplus sand availability in the nearshore zone and/or supplied by eroded coastal cliffs in the south.
4. There is a much higher beach volume accumulation at the Curonian Spit compared to the mainland coast. This may be explained by high sediment supply and more gentle nearshore slope of 0.6° providing a better sediment transport up the slope even during sea level rise. Another factor is sand supply.
5. Therefore, it is assumed that coastal erosion processes start only when the sea level rise reaches a threshold value higher than an average of 10 cm on the Lithuanian coast of the Baltic Sea. However, it is impossible strictly predict that total rise of 10 cm would be a threshold determining erosional processes to be started because changes happen very slowly, so the coastal system can adapt to these alterations.

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