# Variability and correlations of shoreline and dunes on the southern Baltic coast (CRS Lubiatowo, Poland)

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Zbigniew Pruszak*
Rafał Ostrowski
Jan Schönhofer

Institute of Hydro-Engineering,
Polish Academy of Sciences
(IBW PAN),
Kościerska 7, PL–80–328 Gdańsk, Poland;

e-mail: zbig@ibwpan.gda.pl

*corresponding author

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**Abstract**

The paper analyses the results of field investigations into the evolution of the shoreline and dune toe positions in a multi-bar, dissipative coastal zone. The correlations between the changes in the shoreline and the dune toe range from −0.4 to 0.8. It is most often the case that the dune toe is stable while the shoreline moves. Consistent cross-shore migration is slightly more likely to happen than the divergent or convergent movements of both lines. Shoreline retreat and advance attain respective rates of 0.7 m day$^{-1}$ and 0.4 m day$^{-1}$. Deep-water wave energy of about 50 kJ m$^{-1}$ constitutes the boundary between shore accumulation and erosion.

## 1. Introduction

Coastal dunes, shoreline and nearshore bars constitute one large-scale interactive morphological system. The relationship between the bars and the shoreline on a dissipative, multi-bar (4 bars) shore at the IBW PAN Coastal Research Station (CRS) at Lubiatowo has been analysed by Pruszak et al. (1999). This analysis shows that the multi-bar system can comprise two distinct subsystems, i.e. inner (I, II) and outer (III, IV) bars. The location of the inner bars and the shoreline exhibit a reasonably high correlation (e.g. shoreline – bar I with correlation coefficient $R = 0.72$ and bar I – bar II with $R = 0.57$), so their onshore/offshore movements are very consistent. The location of the bars of the outer subsystem is much less correlated with the shoreline position (the correlation between the shoreline and bar III positions can even be negative). Recent investigations of medium-scale variations of bars, carried out on the basis of 15-year long measurements at Hasaki Field Station (Japan) and supported by Complex Empirical Orthogonal Function analysis, show that bar displacement has a cyclic character (Kuriyama et al. 2008). Similar conclusions were drawn by Różyński (2003) for the southern Baltic shore at CRS Lubiatowo.

Although the variability of bars and their links to environmental factors have been the objectives of many analyses, the direct interactions between dunes and the shoreline still seem to be insufficiently identified. Presumably, displacements of the shoreline and the dune toe can be mutually independent if the beach is wide. In the case of a cliff coast or narrow, intensively eroded beaches, variability of shoreline position is often related to a change in position of the dune/cliff toe. At smaller time scales (weeks, months), migration of the shoreline on sandy seashores is not always associated with the simultaneous evolution of dune forms. At a larger time scale (years, decades), which will include a number of extreme hydrodynamic events, the probability of more distinct links between shoreline and dune toe positions increases. Various studies have confirmed the fact that shoreline and dune toe variations depend strongly on the time scale of observations, see e.g. Komar (1998), Hobbs et al. (1999), Baquerizo & Losada (2008) and Kroon et al. (2008). Owing to its continuous contact with water, the shoreline responds to changes in hydrodynamic conditions more quickly and strongly than dunes and thus undergoes more dynamic migration. A dune is characterized by a much greater inertia, so investigations of the relationships between shoreline and dune movements should also incorporate long-term, possibly inter-decadal time scales that smooth out instantaneous, often purely random movements of the shoreline.

Nearshore wave energy and water surface elevation are key dynamic factors governing the intensity of coastal erosive and accumulative processes. Sea level variations cause changes in the instantaneous wave energy impact on the seashore. During high storm surges, large parts of a beach are submerged and wave run-up phenomena can affect dunes directly, which can result in their destruction. In such conditions, the range of simultaneous erosion of beach and dune depends on the intensity and duration of storm conditions.

Part of the wave energy is dissipated as a result of bottom friction and wave breaking in the coastal zone, while the remainder is reflected from the shoreface. If wave energy dissipation is the predominant process, the shore is referred to as a dissipative one, but if most of the wave energy is reflected, the shore is classified as a reflective one. Among several criteria of this classification, the parameter proposed by Wright & Short (1984) may be useful: $W = H_b/T \times w_s$ where $H_b$ is the representative (typical) breaking wave height, $T$ the representative wave period and $w_s$ the fall velocity of grains building the seabed.

On reflective shores ($W < 1$), with one bar or without bars, wave energy dissipation takes place mostly close to the shoreline. In a multi-bar coastal zone, wave energy is subject to gradual dissipation due to multiple breaking, so that only a small part of this energy reaches the vicinity of the shoreline. In such a case, one can expect the features of the shore dynamics to differ from those of a reflective shore (Komar 1998).

Aside from the short-term impact of wave phenomena, there is the long-term influence of climate changes on erosive/accumulative trends with respect to both shoreline and dune forms. Related to global climatic changes, the currently observed accelerating sea level rise is a reason for the heightened threat of coastal erosion. Analyses carried out hitherto (see e.g. Pruszak & Zawadzka 2005) show that as a result of climatic evolution and the greenhouse effect, the water level in the southern Baltic rose on average by about 15 cm in the period from 1956 to 2006. The long-term changes in sea level at the southern Baltic measuring stations indicate a distinct nonlinear increasing trend, especially since the second half of the 19th century. An example, relating to data collected at Świnoujście (southern Baltic, Poland) from 1810 to 2007, is shown in Figure 1.

Catastrophic sea level rise forecasts, also for the Baltic Sea, anticipate an increase of about 50–60 cm (or even more) by 2100. More realistic forecasts predict an increase of about 20–30 cm (see Figure 1). In any case, accelerating sea level rise will certainly result in increasing coastal erosion rates. The erosive processes will most probably spread to regions where the seashore has so far been stable or accumulative. Furthermore, coastal erosion will affect not only the shoreline and beach but the dune systems as well. Therefore, it seems necessary to extend our knowledge of the interactions and relations between erosive phenomena occurring at various coastal forms, including the shoreline and dunes.

Although dunes and the shoreline constitute a coherent and interactive large-scale coastal system, most analyses have treated these morphological

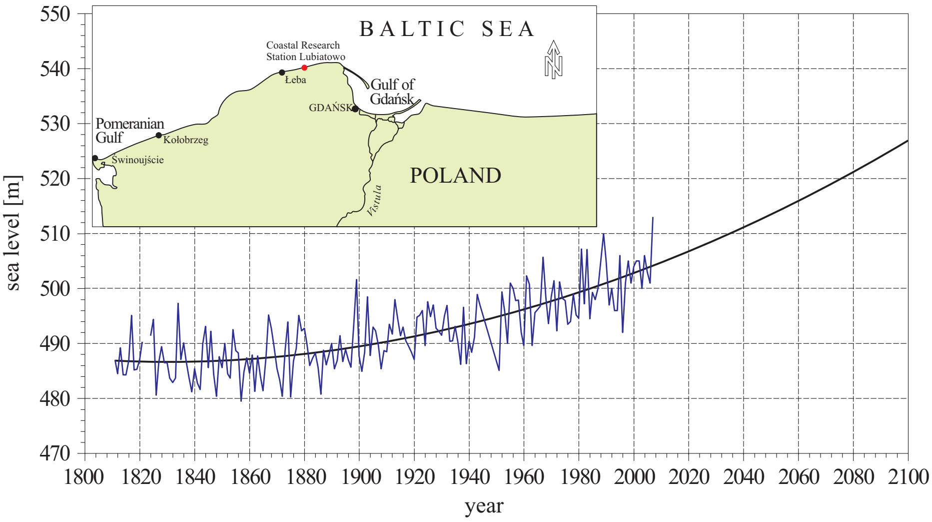


**Figure 1.** Increasing trend of sea level rise detected in long-term data registered at the southern Baltic measuring station at Świnoujście (Poland)

components separately (Guillen et al. 1999, Stive et al. 2002). Shoreline evolution is often investigated with the use of statistical methods, e.g. eigenfunctions (Hsu et al. 1994, Miller & Dean 2007), remote sensing (Maiti & Bhattacharya 2009), or deterministic theories, e.g. one-line models of various kinds (Hanson & Larson 1987, Reeve & Fleming 1997). The partly theoretical description and modelling of dune variability, mainly their erosion, e.g. Dette & Uliczka (1987) and Van Rijn (2009), unfortunately belong to the other (dune-related) group of studies. Nearshore water flow patterns are closely related to the features of many coastal forms. A description of the interactions between rhythmic morphological elements (mega-cusps), rip currents and dunes was presented in the study by Thornton et al. (2007): those investigations were carried out on an intermediate shore ($0.5 < W < 5$) where rip currents occur due to distinct mega-cusps. It was found that a significant correlation exists between the cusp space and the longshore dimensions of rip currents and the locations of dune erosion. In the case of a multi-bar, purely dissipative coast, as shown in earlier studies by Pruszak et al. (2007), rhythmic hydrodynamic and morphological phenomena are of secondary importance for large-scale on-offshore shoreline movement.

Assuming that coastal dunes and the adjacent shoreline constitute one large-scale interactive morphological beach system, the objective of the present study was to carry out a joint empirical (statistical) analysis of these two basic coastal parameters; the determination and analysis of the degree of mutual correlation between the above parameters was its main point. The assumption is that in the time scale considered these correlations reliably represent the mutual relations between the evolution of shoreline position and dune toe displacement, which can be directionally compatible (positive correlation) or incompatible (negative correlation).

In addition, an attempt was made to identify a relationship between the position of the shoreline (the most dynamic component of the coastal system) and the amount of wave energy reaching the shore. The search for such a relationship was carried out on a hydrological annual scale, where seasonal extreme events (storms) are clearly visible, which is not always the case at long-term (multi-year averaged) time scales. The analysis related to a complicated dissipative multi-bar seashore (with $W > 5$), at which only part of the wave energy reaches the vicinity of the shoreline, namely a 2600 m long section of the southern Baltic coast near CRS Lubiatowo (Poland) (see Figure 2). With its natural dunes and beaches, this site can be assumed representative of the southern Baltic sandy coast. The spatial resolution of the measured cross-shore profiles is 100 m and the analysed geodesic data cover a period of 25 years.

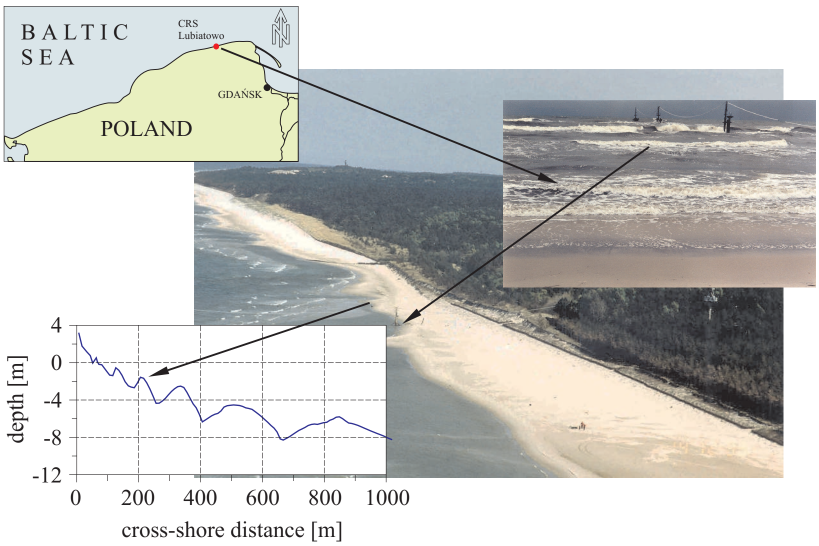


**Figure 2.** The shore section under investigation: the Coastal Research Station at Lubiatowo, Poland

The measurements of beach topography from shoreline to a dune were taken on an approximately monthly basis, during calm weather. Earlier, traditional surveying equipment had been used for this purpose, but since the mid-1990s an electronic total station and GPS equipment has been employed. The currently achieved accuracy of shoreline and dune toe positioning is about 0.1 m. The measurements are not carried out if the shoreline or dune toe position cannot be identified because ice and snow are covering the beach and the nearshore water surface, which sometimes happens in the winter months. In addition, there are some gaps in the data for technical reasons: from 16 August 1989 to 7 November 1991, from 15 December 1992 to 14 September 1994, and from 10 November 1994 to 4 October 1995.

## 2. Study area

### 2.1. Morphology

The shore at CRS Lubiatowo has a gently sloping beach from several to tens of metres wide. The dune toe lies from 1 to 2 m above the mean water level, whereas all points of the dune crest are at least 2 m higher than the dune toe (adjacent to the landward edge of the beach). Locally, there is a small beach berm near the shoreline. Both the beach and dunes consist of fine quartz sand with a median grain diameter of around $d_{50} \approx 0.22$ mm.

Since there are practically no tides (a maximum of 6 cm), swell and wind waves are the only drivers of water motion in the nearshore zone. The complex shape of the sea bed (see the example of a multi-bar cross-shore transect in Figure 2) causes multiple wave breaking and the dissipation of much wave energy over the bars. According to investigations by Pruszak et al. (2008), only about 40% of the wave energy actually reaches the immediate proximity of the shoreline.

The sea bed on the shore section of interest is characterized by bars, of which there may be from 3 to 5. The first stable bar is located at about 100–120 m, the second bar about 250 m and the third one 400–450 m from the shoreline; the fourth and fifth bars occur (sometimes as a single morphological entity) at a distance of 650–850 m offshore. In addition, there is often one more irregular sea bed form very close to the shoreline – a flat shoal that migrates in various directions and disappears periodically. The shoreface has a mean slope of $\tan\beta = 0.015$ (locally, at the shoreline, with a maximum of 0.04). The complicated nature of this coastal area, implying complex hydrodynamic and lithodynamic processes, is illustrated in Figure 3.

Since 1983, geodesic surveys of the dunes and beach have been carried out every month along the 2.6 km section of shore. The tachymetry comprises cross-shore profiles every 100 m along the shore. This gives 27 measured transects.

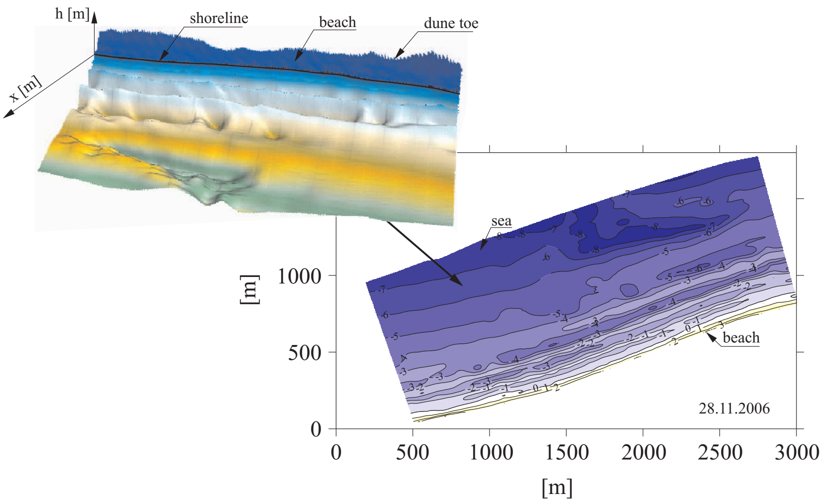


**Figure 3.** Spatial configuration of the coastal section at Lubiatowo

The results of the field investigations described above are plotted in Figure 4. The data comprising, by way of example, a short-term annual period from September 2006 to September 2007 are shown in Figure 4a, whereas the data collected during the entire 25 year time span (1983–2007) are shown in Figure 4b. The shoreline position, interpreted as the distance of the shoreline point from a certain geodesic baseline, is denoted by $y_s$, while the dune toe position, interpreted as the distance of the dune toe point from the geodesic baseline, is denoted by $y_d$. Figure 4 shows that the range of shoreline migration $y_s$ is much larger than the range of changes of dune toe position. This is evident both at the short-term (monthly) time scale and in the long-term (multi-year) domain.

## 2.2. Water level oscillations

Variations of sea water level in the southern Baltic Sea depend mostly on anemometric and baric conditions. High water levels occur due to wind blowing from the northerly and westerly sectors. The inflow of water from the North Sea through the Danish Straits is an additional factor driving sea level rise. The characteristic annual atmospheric cycle on the southern Baltic coast most often causes a decrease in sea level in spring and early summer (owing to the frequent offshore winds) and a rise in the sea level in the autumn and winter (see Figure 5, showing results of the analysis for Łeba harbour in Poland). As the wave energy impact on the shore depends on the instantaneous sea level, the spring-summer season with its lower sea level is favourable to shore stabilization and even accumulation. On the

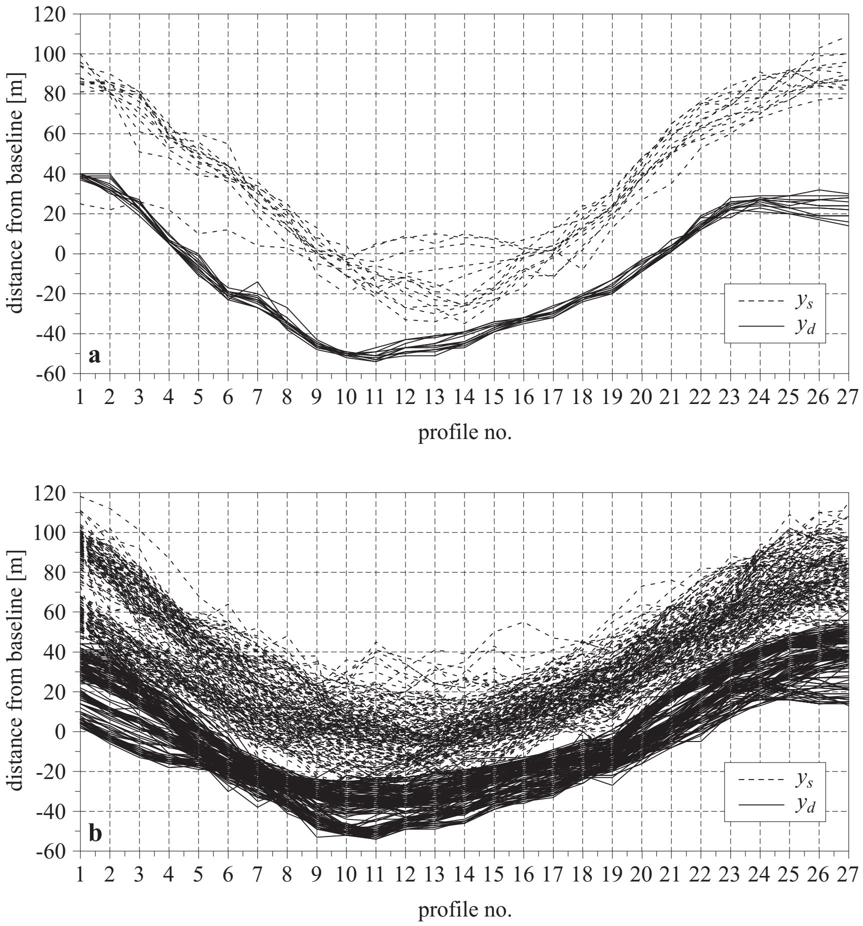


**Figure 4.** Shoreline and dune toe positions $y_s$ and $y_d$ in the period from September 2006 to September 2007 (a) and in the period from 1983 to 2007 (b)

other hand, the strong winds generating storm waves in autumn and winter, together with higher water levels, bring with them a greater threat of coastal erosion. Additionally, the predominance of W and NW winds in autumn and winter drives the previously mentioned inflow of water from the North Sea to the Baltic. Thus, although the monthly mean sea level at Łeba varies only from 4.90 m in May to 5.12 m in December (5.00 m is the conventional long-term mean corresponding to the so-called Amsterdam zero), the mean monthly maximum is 5.56 m in January, which is about 0.5 m higher than the mean monthly maximum of May (Figure 5).

Short-term sea level changes are related to instantaneous wind-driven surges. On the southern Baltic coast, strong onshore winds can locally result in extreme storm surges exceeding 1.5 m above the long-term mean sea level.

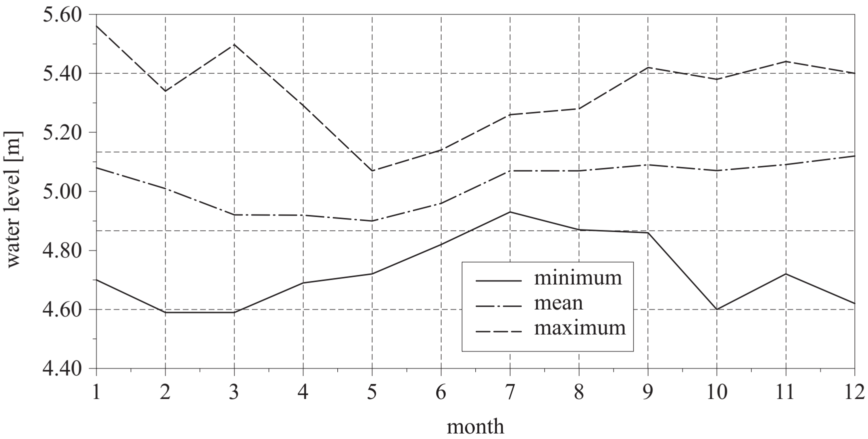


**Figure 5.** Monthly mean and mean monthly extreme sea levels at the Łeba gauge in 1951–2000; data after Girjatowicz (2009)

In such conditions, the ultimate wave energy dissipation takes place closer to the dune toe (on the instantaneously submerged beach) and can damage or destroy the dune forms. During winds blowing seawards, the ordinates of the water surface decrease considerably. According to Girjatowicz (2009), the highest-ever water level in the southern Baltic occurred at Kołobrzeg on 10 February 1874 (2.20 m above the long-term conventional mean sea level), while the absolute minimum was registered at the gauge in Świnoujście on 18 October 1967 (1.34 m below the mean sea level). These quantities yield an amplitude of absolute extremes of 3.54 m.

The wave set-up phenomenon is an additional factor influencing the short-term (at the scale of a storm) nearshore water level. The assessment of this impact can be made by the use of a simple formula describing the maximum rise of the mean sea level at the shoreline: $\xi = 5/16\ {H_{br}}^2/h_{br}$. Assuming a breaking wave height to water depth ratio $H_{br}/h_{br}$ equal to 0.5–0.6 and a breaking wave height $H_{br}$ in the nearshore zone of 1–2 m, one obtains $\xi = 0.16$–$0.38$ m.

Analysis of long-term and short-term sea level changes indicates that the water surface dynamics is much bigger in smaller time domains. Consequently, short-term water level variations are presumably more important in the coastal evolution process and are likely to produce distinct correlations between various morphodynamic features of the sea shore.

## 2.3. Wave energy dissipation

The presence and geometry of bars, together with instantaneous wave conditions, govern the characteristics of the surf zone, i.e. the numbers and locations of wave breakers. During mild to moderate wave conditions, wave breaking takes place above the first or second bar, which for this particular site corresponds to a distance of 100–250 m from the shoreline. During severe wave conditions, the waves are subject to multiple breaking, also above the bars located farther offshore. The surf zone is thus relatively wide, with a few regular, distinct breaker lines parallel to the shoreline. When wave motion is very weak, waves break at the nearshore shoal (if it exists at all) or in the swash zone. During moderate storms, the significant offshore wave height (at depth $h = 15$–$20$ m) is $H_s = 2.5$ m (and corresponds to the root-mean-square wave height of $H_{rms} \approx 1.8$ m). The wave period $T$ attains values of 5–7 s. As a wave approaches the shore, its energy is dissipated due to multiple breaking, which results in a decrease of the wave height to $H_{rms} \approx 1.2$ m at depth $h = 2$–$3$ m and $H_{rms} \approx 0.5$ m at $h < 1$ m. Closer to the shoreline, owing to changes in the wave energy spectra (narrowing of the wave spectrum), the mean wave period is slightly smaller than the deep-water wave period (Pruszak et al. 2008).

The analysis of offshore wave heights (at water depth $h = 15$ m), registered in the period from 12 September 2006 to 12 September 2007, yields a mean annual deep-water wave energy ($E = 0.125 \rho g {H_{rms}}^2$) at Lubiatowo of $0.88 \times 10^5$ J m$^{-2}$, with a maximum of $3.4 \times 10^5$ J m$^{-2}$ and minimum of $0.1 \times 10^5$ J m$^{-2}$. Taking into account the seasonal variability of the wave energy, one obtains $E = 0.46 \times 10^5$ J m$^{-2}$ in the spring and summer and $E = 1.33 \times 10^5$ J m$^{-2}$ in autumn and winter. Obviously, the above quantities might be quite different for other annual periods.

The wave transformation from a location at depth $h = 15$ m to a nearshore location at depth $h = \text{ca}\,0.5$ m is due to a significant loss of wave energy (as defined in the previous paragraph). The wave energy at depth 0.5 m was determined by the waves measured close to the shoreline by a string electric wave gauge, whereas the offshore wave energy at depth 15 m was calculated on the basis of deep-water wave buoy records. During the field survey described here, the relative nearshore wave energy ($k = E_{h=0.5\,\text{m}}/E_{h=15\,\text{m}}$), averaged for all recorded wave conditions, was $k = 0.42$.

This clearly indicates that, on average, 60% of the wave energy is subject to dissipation (including wave breaking) on the multi-bar sea bed profile. Hence, the mean nearshore wave energy $E_{h=0.5\,\text{m}} = k\, E_{h=15\,\text{m}} = 0.42 \times 0.88 \times 10^5 \approx 0.37 \times 10^5$ [J m$^{-2}$]. Obviously, for higher waves, a relatively smaller amount of energy reaches the shore. This is represented by the parameter $k = 0.15$–$0.2$. For small waves, in turn, almost the entire wave energy arrives near the shoreline. In such cases, the parameter $k$ may reach a value close to 1. The parameter $k$, representing the nearshore wave energy in relation to the offshore wave energy for all encountered wave conditions, is illustrated in Figure 6.

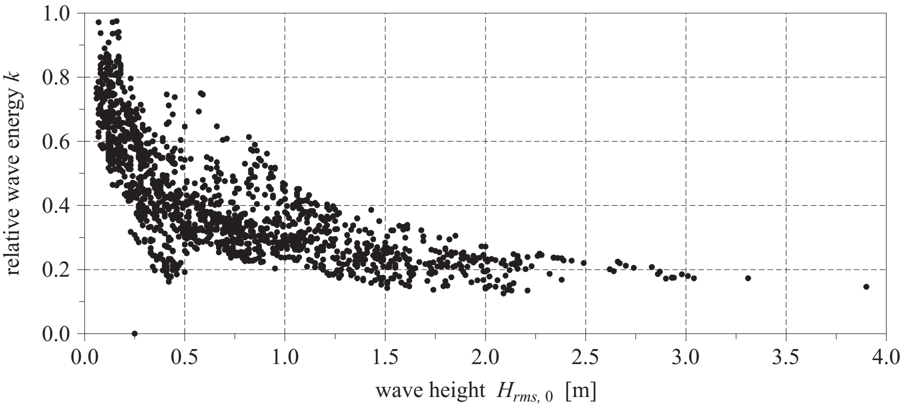


**Figure 6.** Variability in relative nearshore wave energy $k$ at depth $h \approx 0.5$ m with respect to deep-water energy (at $h = 15$ m) for root-mean-square offshore wave heights $H_{rms,0} \in (0.06; 3.9)$ m

Apart from coastal swell and wind waves, there may also be oscillatory motion of the water, characterized by longer periods. Such waves, called infragravity waves, are said to have a significant influence on coastal morphodynamic processes (Aagaard & Greenwood 2008, Coco et al. 1999, 2001, Pruszak et al. 2007). The study of Pruszak et al. (2007) concerns the southern Baltic coast, and includes the Lubiatowo site considered in the present paper. It appears that both standing and progressive infragravity waves can occur in a multi-bar dissipative coastal zone. These latter waves are generally much smaller than gravity waves, and decrease rapidly in height seawards of the shoreline. Infragravity waves are therefore likely to create and modify rhythmic shoreline forms, but are unlikely to affect the onshore and offshore movement of the entire shoreline (Pruszak et al. 2007).

## 3. Analysis and discussion

### 3.1. Relationship between wave energy and shoreline changes

An important indicator of beach resilience, especially for dunes on the beach hinterland, is beach width. Owing to possible large variations at shorter time scales, the behaviour of beach width in the long term is of considerable importance. Long-term field data (1875–1979) collected from the ca 500 km long non-tidal coast of Poland suggest that a sandy seashore with dunes is relatively safe and stable when the beach width ($y_s$–$y_d$) is no less than 40 m (Dubrawski & Zawadzka (eds.) 2006). Similar conclusions, defining the safety of a sandy shore by a beach width of at least 40–50 m, can be drawn from investigations of other southern and south-eastern Baltic shores (Boldyrev 2008, Bobykina & Boldyrev 2008). Observations of the shore at Lubiatowo, comprising measurements of shoreline and dune toe positions carried out since 1983, indicate that this coastal section has been rather stable in the long term. Nevertheless, beach safety criteria are different for tidal shores where the hydrodynamic loads are more complicated. On tidal coasts, the mean beach width during the ebb tide can be 2–3 times larger than at high tide. Moreover, unlike dissipative non-tidal shores, the beach width is bigger in winter than in summer (Quartel et al. 2008).

Previous surveys at CRS Lubiatowo have shown that it is difficult to make out any clear seasonality of variations in the parameter ($y_s$–$y_d$): this can be assumed as evidence that the randomness of morphological processes plays a more important role than seasonal climatic fluctuations. A certain regularity is discernible only for the autumn months (decrease of beach width): this can probably be explained by the storms and other extreme events that usually occur at that time and cause periodic intensification of beach erosion and shoreline retreat.

To assess and validate the stability criterion ($y_s$–$y_d$) $\in$ (40; 50 m) on the basis of the analysed data and site, minimum, average and maximum beach widths in the 1983–2007 period have been plotted in Figure 7. This plot shows that the average beach width varied from 30 to 50 m depending on the profile, although periods with quite intensive erosion and accumulation must have occurred. The result is evidence in support of the usefulness and

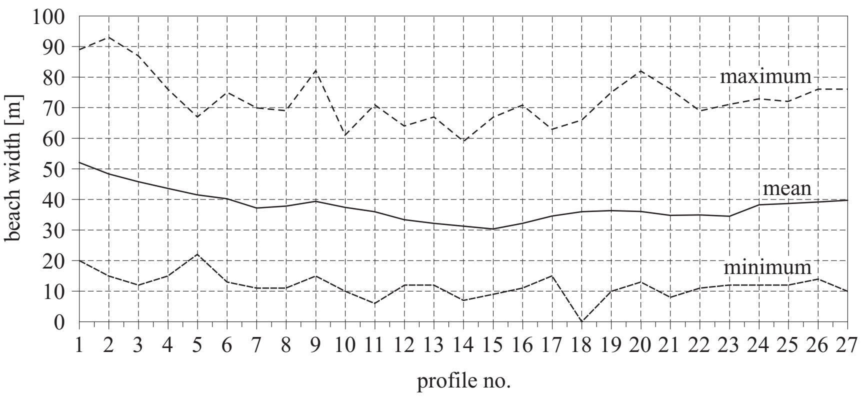


**Figure 7.** Mean beach width and its minimum and maximum envelope for 27 profile lines

validity of the proposed stability criterion for the shoreline-dune system on the dissipative coast in the long term.

As already mentioned, the dynamics of the shoreline much exceeds that of the dune. The shoreline is always exposed to wave impact, whereas the dune toe faces wave action only if the beach is submerged and the wave run-up reaches the beach's landward edge. At short-term time scales, shoreline migration (erosion and accumulation) is a function of regional wave energy. The annual wave energy at the Lubiatowo site was evaluated in the previous section. The considerations below aim to provide a detailed analysis of wave energy together with shore evolution for the period from 12 September 2006 to 12 September 2007. In this analysis, the wave energy was determined on the basis of the significant wave height $H_s$.

The time of observations was divided into several ranges $\Delta t_k$, corresponding to time spans between measurements of shoreline position. Instantaneous quantities of wave energy $E_i$ per wave length (in joules per metre) were calculated from the records of offshore wave parameters with a resolution of 1 hour using the following formula:

$$E_i = \frac{\rho g (H_{si})^2 L_i}{8} = \frac{\rho (g H_{si} T_i)^2}{16\pi} \,. \qquad (1)$$

Next, by averaging the hourly wave energy values $E_i$ over time steps $\Delta t_k$, the mean energy quantities, representative of individual time ranges $\Delta t_k$ between shoreline measurements, were obtained as follows:

$$\overline{E} = \sum_{1}^{N} E_i / N \,, \qquad (2)$$

where $N$ is the number of hourly significant wave heights $H_{si}$ (and related hourly energy values $E_i$) recorded in the time range $\Delta t_k$, i.e. 3–4 weeks (except for the winter season). Such a procedure and time range $\Delta t_k$ provides a good representation of the sequence of hydrodynamic and morphodynamic events, which are of different intensities during the year. A similar approach was applied by Quartel et al. (2008).

The significant wave heights, that is, the hourly records $H_s$ and time-averaged quantities $\overline{H}_s$, as well as the wave energies $\overline{E}$ for the considered one-year period, are shown in Figure 8.

The time intervals in Figure 8 are not equal, because the measurements were not conducted on a strictly defined time basis. The assumed approximate one-month interval was sometimes shortened or prolonged, according to weather conditions (the precise positioning of the shoreline and dune toe points requires a calm sea). The longest interval between two consecutive surveys, at the beginning of December and at the end of

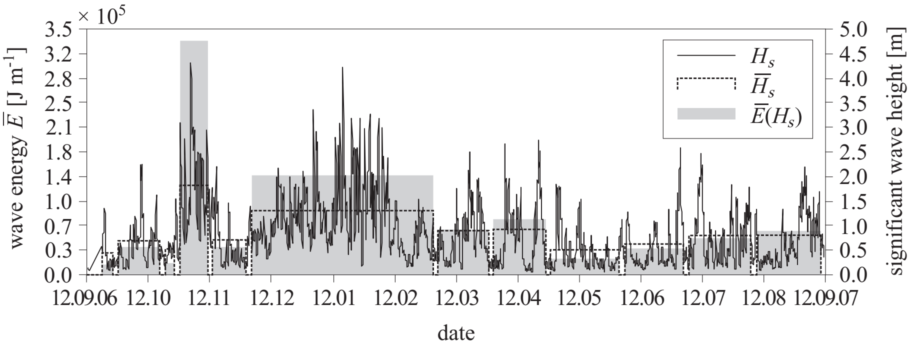


**Figure 8.** Hourly ($H_s$) and time-averaged ($\overline{H}_s$) significant wave heights together with wave energy $\overline{E}$ averaged over time periods $\Delta t_k$

February, was due to severe ice and snow phenomena in the winter of 2006 –2007.

The relation between shoreline displacement $\Delta y$ (spatially averaged for the 2.6 km long shore section under scrutiny) in time $\Delta t_k$ and the mean wave energy $\overline{E}$ affecting the shore during the period between shoreline measurements ($\Delta t_k$) is shown in Figure 9 in the form of both discrete points (resulting from the measurements and calculations) and an approximating power curve (which will be commented on in the following paragraphs).

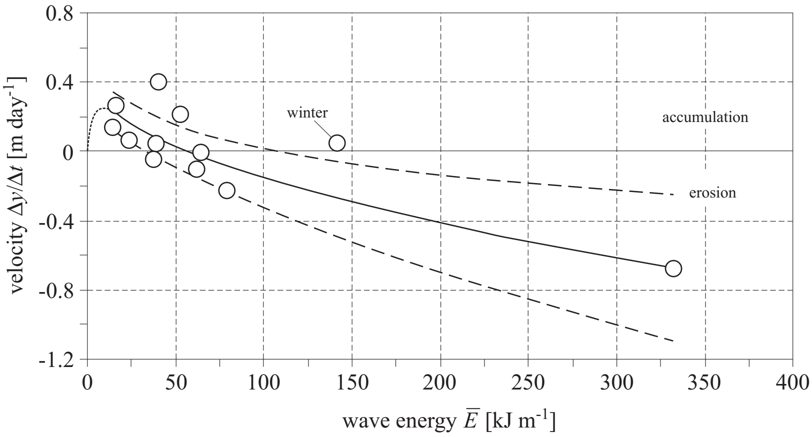


**Figure 9.** Velocity of shoreline migration as function of wave energy $\overline{E} \in (14; 333)$ kJ m$^{-1}$

It can be seen in Figure 9 that the velocity of shoreline displacement averaged for $\Delta t_k$ can attain values of ca 0.7 and 0.4 m day$^{-1}$ for erosion and accumulation respectively. The erosion rate of 0.7 m day$^{-1}$ corresponds to an energy of 332 kJ m$^{-1}$, which is the mean energy for this two-week period of measurements (cf. Figure 8). Obviously, some of the daily wave energy values were higher and caused a more intensive shoreline retreat, much exceeding 1 m day$^{-1}$. The results represent the wave energies and shoreline displacements averaged over the assumed time ranges $\Delta t_k$ in the one-year data. Obviously, one ought to expect smaller or larger quantities of $\overline{E}$ and $\Delta y$ at long-term (multi-year) time scales.

The function $\Delta y\,/\Delta t = f(\overline{E})$ reveals a certain boundary quantity, about 50 kJ m$^{-1}$, dividing shore evolution into accumulation and erosion. Of course, this value can be treated as a very rough boundary because shore behaviour depends not only on wave energy but on many other factors as well. Under Baltic conditions, ice phenomena are such an additional factor. Although a hard frost in Poland (almost every winter) does not last for longer than 1–3 months, it results in the appearance of a nearshore ice cover and an ice berm along the shoreline, locally in the form of small icebergs. This berm is a seasonal, natural seawall protecting the beach and dune from wave impact. Therefore, the shoreline in winter conditions is very often stable despite the storm events occurring in this season. This case is represented by the 'winter' point in Figure 9, indicating that the shoreline position has not changed, although a considerable portion of wave energy must have influenced the shore. As the shoreline was 'frozen' in winter 2006 –2007, its position was not measured and the quantity $\Delta t_k$ corresponding to the winter season is larger than for the remaining part of the time domain under consideration.

The discrete points given in Figure 9 were approximated by the power curve (with the exclusion of the specific 'winter' result) using the least squares method, yielding the following relationship:

$$\frac{\Delta y}{\Delta t} = -0.063\overline{E}^{\,0.5} + 0.475 \quad \text{for} \quad 14 \text{ kJ m}^{-1} < \overline{E} < 333 \text{ kJ m}^{-1} \tag{3}$$

with the determination coefficient $r^2 = 0.74$, i.e. the correlation coefficient r= 0.86.

Figure 9 also shows the 95% confidence level limits plotted using dashed lines. It can be seen that two points (apart from the ignored 'winter' point) lie distinctly beyond these limits. Furthermore, the approximating curve is not valid for very small wave energies, as it is obvious that zero wave energy corresponds to zero shoreline displacement. For this range of wave energy (between 0 and 14 kJ m$^{-1}$), a hypothetical curve was plotted using a dotted line.

### 3.2. Relationship between shoreline and dune toe location

As was concluded for the Lubiatowo site in subsection 3.1, the beach width, defined as the distance between the shoreline and the dune toe positions ($y_s$–$y_d$), is a useful criterion of shore stability. The 25-year field measurements show that the average beach width varied from 30 to 50 m depending on the profile, with respective minimum and maximum values of 0–20 m and 60–90 m (see Figure 7). As the beach width depends on both shoreline and dune toe positions, any variability in these quantities and the correlations between them are very important in analyses of the long-term changes in beach width.

The variability in the locations of the shoreline and dune toe in the period from 1983 to 2007 is shown for six cross-shore profiles (Nos. 4, 9, 14, 18, 20 and 23) in Figure 10, which also contains values of the correlation coefficient (R) between the two time series. The correlation coefficients for the long-term period presented in Figure 10 lie in a very wide range from −0.085 (no correlation or even a small inverse correlation) to 0.758 (moderate correlation).

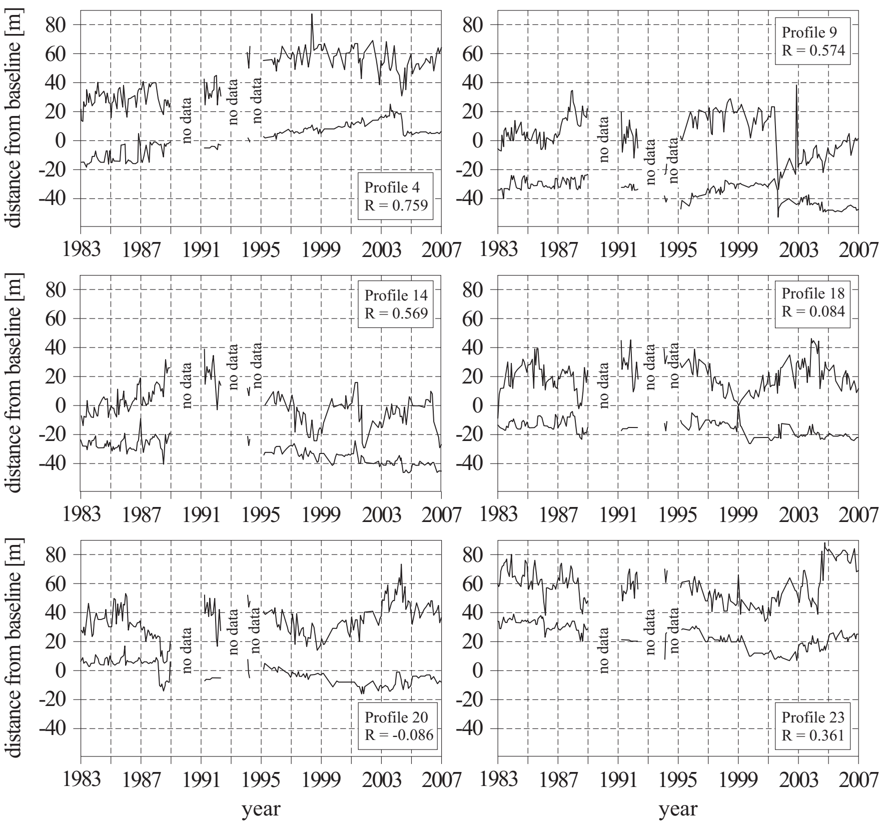


**Figure 10.** Variability in shoreline and dune toe locations for selected cross-shore profiles at CRS Lubiatowo in 1983–2007

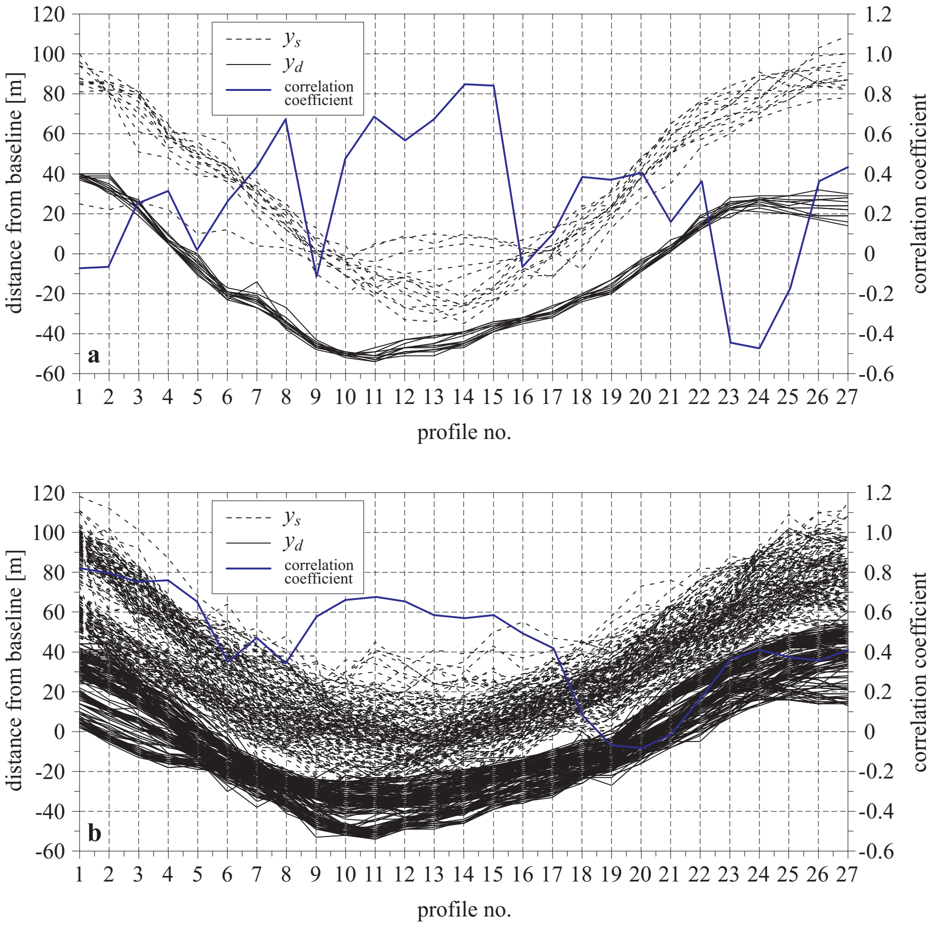


**Figure 11.** Variability in shoreline and dune toe locations at CRS Lubiatowo in the year from September 2006 to September 2007 (a) and in the long-term period from 1983 to 2007 (b)

The detailed analysis carried out for the entire data set confirms the considerable spread of the correlation coefficients in both the short and the long term (see Figure 11). This spread is definitely broader in the analysis covering the annual observations (Figure 11a) than in the multi-year monitoring. The generally higher correlations between shoreline and dune toe evolution in the long-term measurement run may be due to the natural time-smoothing of the shoreline's response to wave impact. The shoreline is subject to immediate changes under instantaneous wave conditions, whereas the dune toe is affected only by extreme events, which occur only rarely. In addition, the dune is affected much more by aeolian sand transport. These two coastal forms are therefore rarely well correlated.

**Table 1.** Probability of occurrences of shoreline ($\Delta y_s$) and dune toe ($\Delta y_d$) displacements – from observations at CRS Lubiatowo (1983–2007)

| Cross-shore profile | Consistent onshore movement $\Delta y_d$ (−), $\Delta y_s$ (−) | | Consistent offshore movement $\Delta y_d$ (+), $\Delta y_s$ (+) | | Divergent/convergent movements $\Delta y_d$ (+), $\Delta y_s$ (−) or $\Delta y_d$ (−), $\Delta y_s$ (+) | | No movement of one or both lines | |
|---|---|---|---|---|---|---|---|---|
| | N | P [%] | N | P [%] | N | P [%] | N | P [%] |
| 1 | 32 | 17% | 28 | 15% | 49 | 26% | 80 | 42% |
| 2 | 38 | 20% | 32 | 17% | 54 | 29% | 65 | 34% |
| 3 | 39 | 21% | 20 | 11% | 53 | 28% | 77 | 41% |
| 4 | 36 | 19% | 25 | 13% | 62 | 33% | 66 | 35% |
| 5 | 30 | 16% | 35 | 19% | 63 | 33% | 61 | 32% |
| 6 | 38 | 20% | 29 | 15% | 54 | 29% | 68 | 36% |
| 7 | 37 | 20% | 33 | 17% | 62 | 33% | 57 | 30% |
| 8 | 35 | 19% | 31 | 16% | 49 | 26% | 74 | 39% |
| 9 | 37 | 20% | 33 | 17% | 63 | 33% | 56 | 30% |
| 10 | 37 | 20% | 32 | 17% | 52 | 28% | 68 | 36% |
| 11 | 40 | 21% | 36 | 19% | 56 | 30% | 57 | 30% |
| 12 | 32 | 17% | 32 | 17% | 53 | 28% | 72 | 38% |
| 13 | 35 | 19% | 37 | 20% | 50 | 26% | 67 | 35% |
| 14 | 28 | 15% | 32 | 17% | 50 | 26% | 79 | 42% |
| 15 | 36 | 19% | 20 | 11% | 48 | 25% | 85 | 45% |
| 16 | 32 | 17% | 30 | 16% | 46 | 24% | 81 | 43% |
| 17 | 38 | 20% | 33 | 17% | 44 | 23% | 74 | 39% |
| 18 | 19 | 10% | 28 | 15% | 67 | 35% | 75 | 40% |
| 19 | 37 | 20% | 39 | 21% | 48 | 25% | 65 | 34% |
| 20 | 26 | 14% | 28 | 15% | 56 | 30% | 79 | 42% |

**Table 1.** (*continued*)

| Cross-shore profile | Consistent onshore movement $\Delta y_d$ (–), $\Delta y_s$ (–) | | Consistent offshore movement $\Delta y_d$ (+), $\Delta y_s$ (+) | | Divergent/convergent movements $\Delta y_d$ (+), $\Delta y_s$ (–) or $\Delta y_d$ (–), $\Delta y_s$ (+) | | No movement of one or both lines | |
|---|---|---|---|---|---|---|---|---|
| | N | P [%] | N | P [%] | N | P [%] | N | P [%] |
| 21 | 29 | 15% | 38 | 20% | 43 | 23% | 79 | 42% |
| 22 | 28 | 15% | 26 | 14% | 60 | 32% | 75 | 40% |
| 23 | 31 | 16% | 30 | 16% | 50 | 26% | 78 | 41% |
| 24 | 24 | 13% | 27 | 14% | 49 | 26% | 89 | 47% |
| 25 | 29 | 15% | 21 | 11% | 53 | 28% | 86 | 46% |
| 26 | 35 | 19% | 24 | 13% | 50 | 26% | 80 | 42% |
| 27 | 29 | 15% | 24 | 13% | 49 | 26% | 87 | 46% |

N – number of occurrences in the entire data set,
P – probability of occurrence.

It can be seen in Figure 11 that the shoreline and dune toe positions are best correlated in the middle of the broad bay that is the section of coastline under scrutiny. This effect can be justified by the relatively narrow beach in this region (cf. Figure 7). In addition, there are some irregularities in the system of bars in this area. All this means that more wave energy can reach the dune toe (not only the shoreline) than in the adjacent shore sections. In this context, we can assume that the influence of nearshore bathymetry on the shoreline and dune toe positions, resulting in longshore variability of the correlations of these coastal forms, is more significant for dissipative shores than for reflective shores. Moreover, a dissipative coast has a more complicated bathymetric layout, frequently with a highly irregular bar system.

The probabilities of consistent (the same directions), divergent or convergent (opposite directions) and single (one line moves, the other stays put) movements of shoreline and dune toe, determined on the basis of the observations carried out at CRS Lubiatowo in the period from 1983 to 2007, are given in Table 1. It should be noted that the last column in Table 1 represents mainly the cases when the dune toe does not move but the shoreline does (the opposite situation is extremely rare).

Both Figure 10 and Table 1 show that there was no clear tendency in shoreline and dune toe dynamics during the study period. We can only speak about the slightly greater probabilities of events, when both lines are immobile or only one of them is moving (30–50%). Also, consistent (onshore or offshore) migration is slightly more likely to happen (25–40%) than the divergent or convergent movements of both lines (25–35%). A more typical situation is when one line stays put while the other migrates. In such instances the migrating line is the shoreline, whose dynamics is usually dominant. Therefore, either erosion or accumulation is observed at shorter time scales, whereas in the long term the beach will remain in equilibrium. This therefore confirms that empirical observations and assessments of beach evolution and condition are time-scale dependent (Guillen et al. 1999).

## 4. Conclusions

Under the natural conditions of a southern Baltic multi-bar dissipative shore, the coefficient of correlation R between the shoreline and dune toe displacements lies in wide ranges, from about 0 to 0.8 at a long-term time scale (25 years) and from about $-0.4$ to about 0.8 at a short-term scale (annual). Negative values of R in the annual analysis mostly represent instantaneous situations of short but intensive storms during which the dune toe retreats and the sandy material from dune erosion is deposited on the beach, causing the shoreline to advance (accumulation). In the long run, such specific cases are dominated by more typical shore behaviour, namely, the evolution of the shoreline position only (small correlations between shoreline and dune toe motions) or the simultaneous movement of shoreline and dune toe in the same direction (high correlations). The latter occurs either during severe, prolonged storms, causing both the shoreline and the dune toe to retreat, or during long periods of weak wave impact, which are favourable to the accumulation of sand at the shoreline (onshore sediment transport) and at the dune toe (aeolian deposition). All the above response patterns of emerged coastal forms (shoreline with beach berm, dune) depend on features of the shoreface, e.g. on nearshore submerged forms (bars). The bar system is a kind of time- and space-variable energy filter, dissipating most of the wave energy during storms and allowing waves to cross undisturbed towards the shoreline in calmer periods.

The most common situation (30–50% of all cases) is when waves are weak and moderate, when the dune toe is stable and the shoreline is subject to seaward or landward displacement, and is most frequently observed on a relatively wide beach. When the beach is narrow or the wave conditions are very severe, both the shoreline and dune toe move. The movement of these two coastal forms can be divergent/convergent (25–35% of all cases analysed) or consistent in the onshore/offshore direction (25–40%).

These observations have shown that the dynamics of the shoreline is significantly greater than that of the dune toe. The velocity of shoreline displacement, averaged over the time between two consecutive shoreline measurements at Lubiatowo, attains respective values of about 0.4 and 0.7 m $day^{-1}$ for accumulation and erosion. A more intensive shoreline retreat, well in excess of 1 m $day^{-1}$, may result in the short term from high daily wave energy values. The analysis has revealed a quantity of about 50 kJ $m^{-1}$, dividing shore evolution into accumulation and erosion. This value can be treated as a rough boundary for all seasons except winter, when a nearshore ice cover and an ice berm often form along the shoreline. The latter is a seasonal, natural seawall protecting the beach and dune from wave impact. The shoreline in winter may therefore remain stable despite the storm events occurring in this season.

Time scales are crucial in any assessment of changes to the shoreline and dune toe, as well as in analyses of the correlations between these evolutionary processes. In general, the spread of these correlations for various cross-shore profiles is smaller for long-term (25 year) observations.

The stability criterion assumed for a shoreline-dune system such as the one discussed here is a beach width of 40–50 m. Of course, during short-lived extreme events, these values may fluctuate very considerably, sometimes by as much as 50–60%.

For a typical dissipative shore such as this section of the southern Baltic coast, the destruction of dune systems implies threats to the hinterland. The climatic changes observed in recent decades, namely, global warming, can reduce the intensity and duration of winter ice phenomena, making the Baltic shores less resilient to storm attacks. The lack of a seasonal nearshore ice cover and ice berm at the shoreline, together with increased storminess, will certainly increase the vulnerability of the coast to erosion.

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