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Changes in wave dynamics at the south-eastern coast of the Baltic Proper during 1993–2008

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Using data gathered by visual wave observations at three Lithuanian coastal observation sites during 1993–2008, we make an attempt to relate the recent changes in the intensity of coastal processes on the Lithuanian coast to changes in the local wave regime. There exist considerable interannual variations in the overall wave activity but no statistically significant trends in wave heights for the study period. The directional distribution of wave approach directions has become considerably narrower since about 2002. This feature is most prominent at Palanga where since 2002 almost all waves have approached from SW. This change apparently leads to a decrease in the sediment supply to the Curonian Spit and to a certain starvation of the Lithuanian coast.

Introduction

The coasts of the World Ocean are under continuous pressure created by a multitude of marine coastal hazards and drivers of coastal processes (Kaplin 1973). A generic example of such a driver is the field of surface waves. Its properties and changes are commonly characterised in terms of wave heights, energy or energy flux. However, equally important from the viewpoint of coastal processes and coastal engineering solutions are the changes in wave periods (that may lead, e.g., to changes in the depth of closure) or in wave propagation directions. While the changes in wave periods and directions are usually extremely difficult to identify for the open-ocean coasts, the specific conditions of semi-enclosed water bodies, such as the Baltic Sea, offer options for their reliable detection and for estimates of the magnitude of related consequences.

Differently from the open ocean conditions, quite small changes in the wind regime in enclosed basins, for example changes in the wind direction, may lead to an increase in the fetch length and, consequently, may cause great changes in wave periods or directions (Valdmann *et al*. 2008). Such changes have recently been reported for the Gulf of Finland (Räämet *et al*. 2010). They are not only interesting in themselves but obviously important for many applications and also for better understanding of the changes to the local climate. The central aim of this paper is to establish whether substantial changes in the wave approach direction have occurred in Lithuania during the last decades.

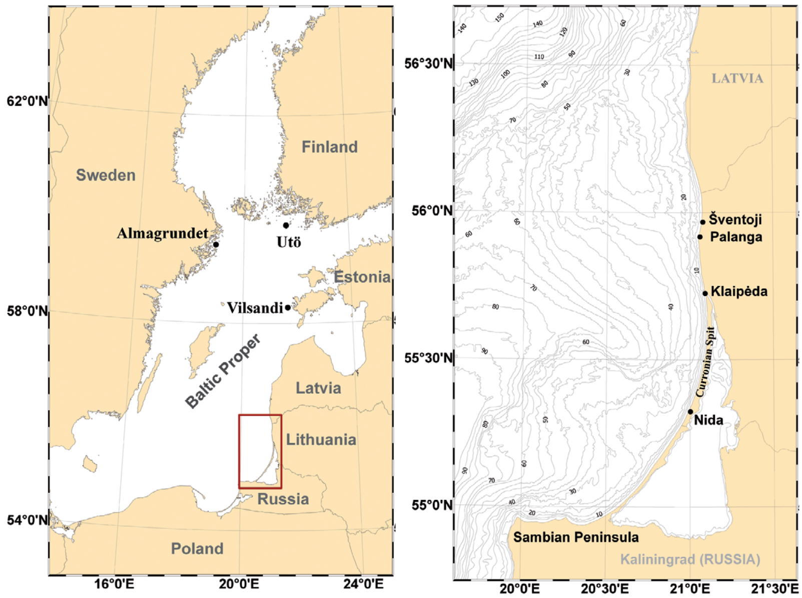

Fig. 1. The study area, and locations of the wave observation sites.

The Baltic Sea (Fig. 1) is a unique water body in many aspects, with complex form, specific hydrographic characteristics, complexity of circulation and limited connections with the World Ocean. It is large enough to host quite different long-term changes in wind speed (Pryor and Barthelmie 2003) and wave heights (Kelpšaitė *et al*. 2008, Räämet *et al*. 2010) in its different parts. The intricacy of its internal dynamics extends far beyond the typical features of basins of comparable size (Alenius *et al*. 1998, Soomere *et al*. 2008, Leppäranta and Myrberg 2009). On the other hand, the combination of the relatively small size of the Baltic Sea as compared with that of the World Ocean, the vulnerability of its ecosystem and its comparatively young coasts make this region extremely susceptible to both climate change and anthropogenic pressure. The susceptibility of this water body to various adverse impacts has been internationally recognised by the International Maritime Organization: the Baltic Sea was declared as a particularly vulnerable sea area at the end of 2005 (Kachel 2008).

The eastern coast of the Baltic Sea includes largely different coast types. The coast at the northern part of the Baltic Proper has a large number of semi-sheltered bays, which are protected from relatively large waves except for a few wind directions. The coast of Lithuania, contrariwise, represents a generic type of more or less straight, high-energy (in the Baltic Sea conditions), actively developing coasts that (i) contain a relatively large amount of finer, mobile sediments, (ii) are open to predominating wind directions in this water body and (iii) are exposed to wave activity for a wide range of wave approach directions (Žilinskas 2005).

The combination of the angular distribution of winds and the geometry of the coast is such that the wave-induced longshore sediment transport is, on average, to the north over the entire Curonian Spit (Fig. 1) and along the mainland coast of Lithuania (Gudelis 1988). This predominant sediment flow pattern means that changes in sediment availability or transport patterns along these areas substantially affect sediment budget northwards from Klaipėda. Sediment supplies for the Curonian Spit coastal zone are replenished by the sediment eroded from cliffs and beaches of the Sambian Peninsula (Fig. 1). While sediment flow along the spit largely occurs in natural conditions, further transport of sediment to the mainland coast of Lithuania is obstructed by jetties and breakwaters of Klaipėda Port, out-flowing currents from the Klaipėda Strait, dredging of the port entrance channel and other factors (Žilinskas 2005).

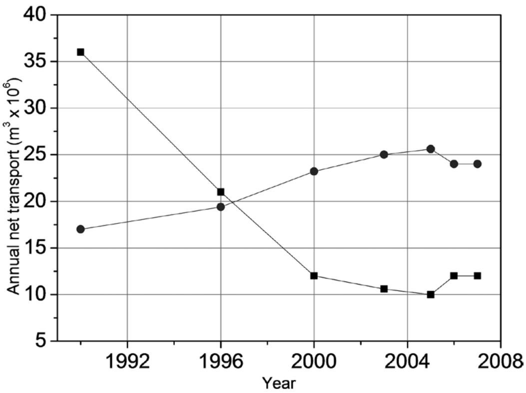

Fig. 2. Lengths of the accumulative (squares) and eroding (circles) sections of the Lithuanian marine coast in 1990–2007 (based on Žilinskas 2005: fig. 4).

Additionally to the relatively intense net transit along the entire Lithuanian coast, its several sections reveal local accumulative features. Analysis of the field data of 1976–2007 revealed that the length of accumulative sections was considerably reduced (Fig. 2). Accordingly, the length of the gradually eroding sectors increased in the end of the 20th century (Žilinskas 2005, 2008). The total length of stable coastal sectors has also increased. This has happened at the expense of formerly accumulative sectors and not as a result of stabilization of eroding beaches.

It is natural to expect that the listed changes in the coastal dynamics are mostly driven by the changes in the wind-wave regime at the Lithuanian coast. These changes not necessarily match those established for the northern part of the Baltic Proper. While there is evidence on substantial increase in the annual average wave activity in the northern part of the basin in 1954–2005 (Broman *et al*. 2006, Soomere and Zaitseva 2007), there were almost no changes in the average wave heights along the Lithuanian coast in 1993–2005 except for certain interannual variability (Kelpšaitė *et al*. 2008). Therefore the retreat of Lithuanian sedimentary coasts similarly to that observed in Estonia (Orviku *et al*. 2003) should be unlikely.

The intensity of wave-driven potential longshore sediment transport, Q_t, to a first approximation, is proportional to the rate of the longshore component of the beaching wave energy flux Ec_g per unit length of the coastline (Dean and Dalrymple 2002). This quantity is a function of wave energy E and the approach angle of waves (*see* below). Consequently, changes in the wave approach direction may lead to major changes in the intensity (or even direction) of littoral flow.

There is recent evidence about important changes in the directional structure of winds in regions adjacent to the study area (Kull 2005). During the last four decades there was a significant increase in SW winds, almost by a factor of two, from about 15% to about 25% in terms of frequency in the 8-rhumb system. This occurred at the expense of southern and eastern winds all over Estonia. The probability of SE winds decreased simultaneously with an increase in SW winds during the same period in Lithuania (Dailidiene *et al*. 2006). At present, a single predominant wind direction cannot be clearly distinguished, but generally westerly wind blows most often on the Lithuanian coast of the Baltic Sea (*see* below). Such a change may well cause large changes in wave approach directions on Lithuanian coasts similar to the phenomena reported on the Estonian coast of the Gulf of Finland (Räämet *et al*. 2010) and, thus, may be one of the factors affecting the intensification of the coastal processes in the area in question.

Observation sites and data

Regular wind-wave observations along the entire eastern coast of the Baltic Proper have been carried out since the middle of the 20th century in the framework of routine marine observations by the USSR hydrometeorological service. Although the number of observation sites and the set of observed parameters decreased over the course of time, several sites have been operational almost permanently. Unfortunately, only a small part of the data has been digitized and properly analysed.

The most representative data for the northeastern part of the Baltic Proper, and with the largest temporal coverage, are the recently digitised data for 1954–2005 from the island of Vilsandi and Pakri Peninsula, western Estonia (Soomere and Zaitseva 2007, Zaitseva-Pärnaste *et al*. 2009). The longest instrumentally measured wave data from the NW Baltic Proper at Almagrundet (Broman *et al*. 2006) apparently characterize well the decadal changes in wave activity in the northern Baltic Proper.

In Lithuania, wave observations started after the establishment of the hydrometeorological station in Klaipėda in 1949 (Klimienė 1999). Since the 1950s, wave properties have been recorded at three observation points (Nida, Klaipėda and Palanga/Šventoji; Fig. 1 and Table 1). Palanga and Klaipėda observation sites are fully open to the dominant wind directions (SW and NW), but are mostly sheltered from waves excited by eastern (offshore) winds. The geometry of the coastline at Nida is such that only properties of waves approaching from the western direction (W, NW) can be properly observed. As Palanga is located on an almost straight coastline and the observations have been made with the use of the pier, the directional extent of adequately observable waves is the largest of the Lithuanian sites and the relevant wave data are probably the most representative for the Lithuanian coastline (Klimienė 1999, Kelpšaitė *et al*. 2008).

The duration of daylight usually allowed for two observations per day at the Lithuanian stations. The potential influence of the different number of observations a day on the interpretation of long-term changes in wave activity is usually eliminated by using the daily mean wave height at all sites (*see* Soomere and Zaitseva 2007, Kelpšaitė *et al*. 2008). No averaging procedure, however, is applied to the wave direction data and all sensible observations of wave direction are processed separately in what follows.

In the Baltic Proper, the duration of a wave storm seldom exceeds 10 hours (Broman *et al*. 2006). Therefore, some wave events, if they were not long enough or occurred at night or were accompanied by low visibility, are not necessarily present in the data set. Consequently, the observations cannot be used for a reconstruction of the time series of the sea state. Instead, they are interpreted as a set of regular samples reflecting the sea state. When the number of observations is large enough, the data reflects the basic features of the wave climate at the site. This viewpoint is adopted in the analysis below where we concentrate on the long-term evolution of statistical features of wave fields such as the average wave height and predominant propagation directions.

The data set from Lithuanian observation stations contains information about the wave direction, the maximum and the mean wave height, and the wave period. The observation diaries and databases are now kept at the Center of Marine Research (CMR) in Klaipėda. Unlike Vilsandi, wave periods were recorded at Lithuanian sites only if they were larger than 7 s. Since wave conditions with such periods form a clear minority of the Baltic Sea wave fields (Kahma *et al*. 2003, Broman *et al*. 2006, Soomere 2008), it is not possible to reliably identify changes to wave periods and observations of periods will not be analysed here.

The observational procedure of wave heights mirrors the background idea of the classical zero-up/downcrossing method (IAHR 1989) in which the wave height is directly inferred from the surface time series at a fixed point as the distance from the wave trough to the crest. The observer noted the five highest waves during a 5-min interval with an accuracy of 0.25 m for wave heights < 1.5 m, 0.5 m for wave heights 1.5–4 m, and 1 m for higher waves. The highest single wave and the mean height of these 5 waves were filed. A thorough overview of the procedure and the discussion of the reliability of visual wave observations from the Baltic Sea coasts can be found in Soomere and Zaitseva (2007). Although the observers' estimates represent well the significant wave height at site (Gulev and Hasse 1998), we still call the observed quantity the mean wave height.

The overall appearance of the distributions of the frequency of occurrence of different daily mean wave heights at Vilsandi and on the Lithuanian coast (Fig. 3) is quite similar. Both resemble analogous distributions for wave heights in semi-

Table 1. Wave observation sites.

Site	Coordinates	Data available
Vilsandi	58°23´N, 21°51´E	1954–2005
Nida	55°18´N, 21°00´E	1993–2008
Palanga	55°55´N, 21°03´E	1993–2008
Klaipėda	55°42´N, 21°07´E	1993–2008

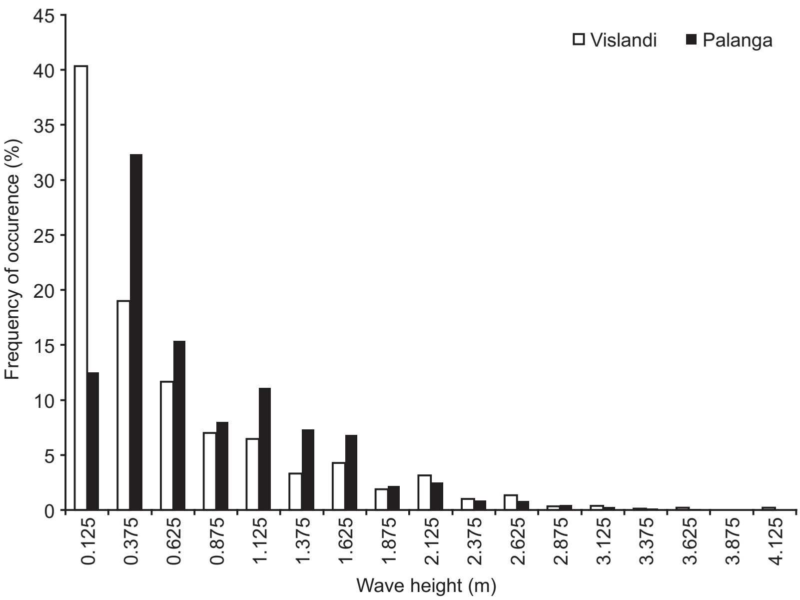

Fig. 3. Frequency occurrence of different daily mean wave heights at Vilsandi 1954–2005 and at Palanga 1993–2008. (Modified from Kelpšaitė *et al.* (2008); published with permission from the Estonian Academy Publishers).

sheltered bays such as Tallinn Bay (Soomere 2005). These distributions have a very large percentage of almost calm situations that frequently correspond to offshore winds. Another (probably observer-specific) feature of the wave statistics is that the percentage of wave heights slightly above 1 m, 1.5 m, etc. is considerably larger as compared with the number of wave conditions slightly below these values (Soomere and Zaitseva 2007). This peculiarity frequently occurs in older semi-visual observations of wind speed with the use of weather vanes.

Unlike at Vilsandi, calm conditions do not dominate at Palanga where wave heights 0.25–0.5 m are the most frequent (Fig. 3) and the entire distribution of wave heights resembles similar distributions in the open parts of the Baltic Sea (Soomere 2008). Yet, a large fraction of (almost) calm situations apparently reflects the near-coastal conditions. As expected, at Klaipėda and Nida, where the observations were made from the coast and thus the details of the sea state were more difficult to observe, almost calm conditions (wave heights below 0.25 m) are the most frequent (Kelpšaitė *et al*. 2008).

Relatively small waves (0–0.5 m) form about a half of all the observations at all Lithuanian sites, where the median wave height is close to 0.5 m as at Vilsandi. Waves with heights from 1 to 2 m also occur with an appreciable frequency whereas waves higher than 2 m form less than 5% of all observations. Analogous distributions of different wave heights at Klaipėda and Nida are similar to that for Vilsandi. The largely coinciding shapes of these distributions along the Lithuanian coast suggests that the historical visual wave observations are generally reliable and that they more or less adequately reflect the statistics of wave conditions in this part of the Baltic Proper.

Changes in wave regime

The wave activity (understood in terms of the annual mean wave height calculated based on daily mean wave heights) rapidly decreased in the northern part of the Baltic Proper in 1997–2005 (Broman *et al*. 2006, Soomere and Zaitseva 2007). At the same time, there existed almost no trend (only very weak increase, statistically not significant) in the wave intensity on the SE coast of the Baltic Proper in this period (Kelpšaitė *et al*. 2008). Short-term (time scales 1–3 years) variations of the wave activity, however, were mostly in phase in the northern and south-eastern part of the Baltic Proper.

There is, however, a clear increase in the wave activity at Lithuanian measurement sites during the last few years since 2005. In particular, the annual mean wave heights were relatively large in 2007 and 2008 (Fig. 4). These peaks may be connected to the recent beach degradation, but they obviously cannot be responsible for the long-term intensification of erosion processes discussed above. Such short periods of a high wave activity are not unique in the area in question where the annual mean wave height may vary substantially. A similar period occurred in 1993 when the average wave height was 0.8–0.9 m at all measurement sites. Within a few years, however, the wave activity dropped significantly, almost by a factor of two, and in 1996 the annual mean wave height was as low as 0.4 m at Nida, and dropped from 0.85 m to 0.5 m at Palanga. The annual mean wave height fluctuated around 0.7 m most of the time during 1993–2008.

The described changes, especially the slightly increasing trend in Fig. 4, may reflect the gradual increase in the wind speed over this sea area (Pryor and Barthelmie 2003) that apparently continued during the last decade. A large spatial variability in the trends in the long-term wave activity has recently been identified for the southern Baltic Sea for 1970–2007 by means of long-term wave simulations with the use of the WAM model forced with properly adjusted geostrophic winds (Räämet 2010). Similarly to visual observations, wave hindcast based on geostrophic winds is not always capable of reproducing the exact time series of wave parameters (that are frequently strongly affected by local geometry and ageostrophic wind components) (Räämet *et al*. 2009) but adequately captures many basic features of seasonal and long-term variations in the wave fields (Räämet and Soomere 2010, Räämet *et al*. 2010). According to these calculations, the Lithuanian coast should experience a very slight increase in wave heights over the last decades (Räämet 2010).

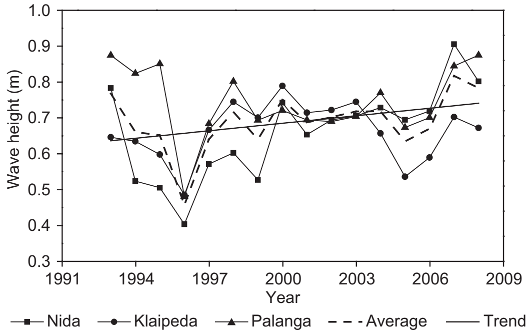

Fig. 4. Annual mean wave heights on the SE coast of the Baltic Sea. The linear trend is calculated for the average over all three sites. Modified from Kelpšaitė *et al*. (2008), with permission from the Estonian Academy Publishers.

Excerpts from the relevant model results (Fig. 5) demonstrate a qualitative match of the simulated and observed short-term (1–3 years) interannual variations in the wave intensity whereas decadal variations of these quantities show considerable mismatch. Such a mismatch apparently is typical to the simulations of the Baltic Sea waves based on the geostrophic wind data (Räämet *et al*. 2010). The basic message from the comparison is, however, that there apparently has been no substantial increase in wave heights on the Lithuanian coast since the 1970s. The observed increase is fairly small and only evident in single years, and cannot explain the drastic change in coastal processes discussed above.

It is well known that both wind and wave climates are highly anisotropic in the Baltic Proper

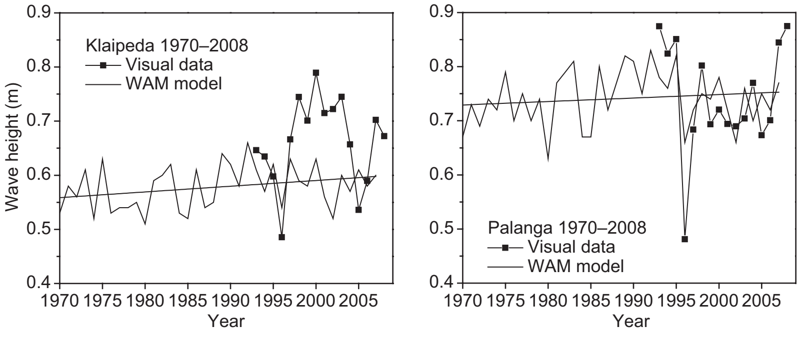

Fig. 5. Modelled and visually observed annual mean wave heights on the SE coast of the Baltic Sea. Modelled data were kindly provided by Dr. A. Räämet.

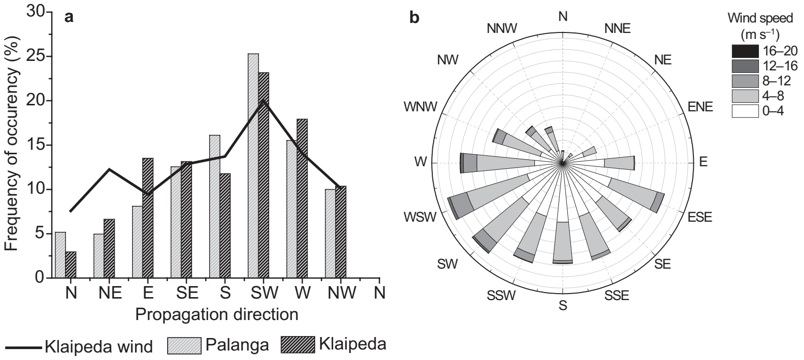

Fig. 6. (**a**) Angular distribution of wind directions and wave approach directions at the eastern coast of the Baltic Sea in 1993–2008; (**b**) wind rose at Klaipėda for 1993–2008.

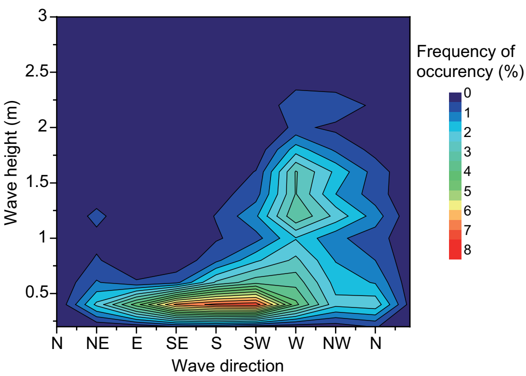

Fig. 7. Joint distribution of wave heights and approach directions at Palanga (1993–2008). The resolution in wave directions is 45° and varies from 0.25 to 0.5 for wave heights as in the observation procedure.

(Mietus 1998, Soomere 2003). The predominant strong wind (and high wave) directions in the northern part of the Proper are SW and N-NW. There is, however, very limited amount of information on decadal changes in the wind direction except for the recent evidence about the increase in frequency of SW winds (Kull 2005, Dailidienė *et al*. 2006). This change in wind properties implies subsequent changes in the wave approach direction and may thus be responsible for the above-discussed intensification of coastal processes in Lithuania.

Wind and wave regimes are both anisotropic also in the nearshore of Lithuania. The most frequent wind direction and the most frequent wave approach direction are SW (Fig. 6). The second most frequent wind and wave direction is either from the south or from the west. North and north-east winds are the least frequent.

The joint distribution of the frequency of occurrence of waves of different directions and heights (Fig. 7) reveals that waves approaching from S or SW are the most frequent among relatively low waves. Formally, SW is the most frequent wave approach direction accounting for about one quarter of all the wave observations.

The highest waves, however, approach mostly from W and less frequently from NW. These directions also coincide with the typical direction of strongest winds and have longest fetches (400–500 km) for the Lithuanian coast. Note that owing to the geometry of the Baltic Proper (Fig. 1) the fetch for W-NW winds is much smaller, about 300 km. This feature apparently is smoothed out in Fig. 7 owing to relatively coarse angular resolution of the observations.

Previous field observations and geomorphic studies (*see* e.g. Gudelis 1998, Žilinskas 2005, 2008) have shown that waves approaching from SW are the major driver for the coastal processes and cause predominant sediment transport along the Lithuanian coast from the south to north (Gudelis 1998). The discussed features of the directionality of the wave field at Palanga gives clear support to this conjecture. Moreover, the relatively small difference between the approach direction of the largest waves and the coastline signifies that even small changes to the propagation direction of the highest waves may considerably modify not only the intensity but also the direction of coastal processes in some sections of the Lithuanian coastline. The set of wave observations allows to some extent to estimate whether or not there have been any consider-

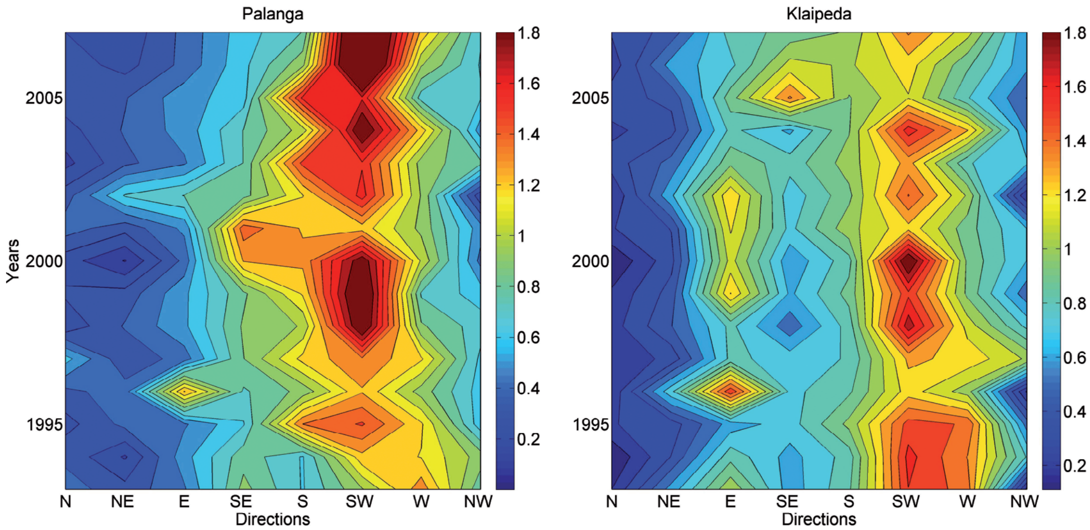

Fig. 8. Temporal course of the frequency of waves from different directions in 1993–2007 at Klaipėda and Palanga. The color scale shows the frequency of occurrence (%) of different wave propagation directions.

able changes in the directional structure of wave fields on the Lithuanian coast during the last decades. Ideally, such estimates should be based on the estimates of the potential changes to the long-term wave-induced sediment flux. Unfortunately, there is no information about wave periods for most of wave situations. For this reason, to a first approximation we rely on the changes to the wave approach direction.

The distributions of the frequency of occurrence of waves from different directions in 1993–2008 (Fig. 8) first demonstrate that the "wave roses" were relatively wide at the beginning of the 1990s. The peak for waves from S and SW was quite wide at Klaipėda (from the west at Palanga) whereas there was a noticeable share of waves coming from E (SE at Palanga) in 1993–1994. (Note that this actually means that the waves were propagating offshore, to the west or north-west, respectively). The year 1996 was exceptional: it was by far the mildest (Fig. 4) and hosted a very large amount of waves from the east. The share of the waves from the east in 1997–1998 was similar to that in 1993–1994 at both sites. At the same time, the peak for waves from SW became much more narrow and pronounced.

Although the secondary peaks for waves from eastern directions became evident again, starting from about 1999 the observed wave directions show a clear tendency towards a gradually increasing concentration to the south-west at both sites. The directional distribution has a particularly sharp peak for waves from the south-west in 2004–2008 at Palanga. At Klaipėda the analogous peak is somewhat more weakly pronounced and an appreciable number of waves approach from the east. Finally, starting from about 2005 almost all waves approach Palanga from SW and a new peak for SE waves, not observed in previous years, is evident at Klaipėda.

The nature and consequences of the described changes obviously need further research which requires much larger amounts of wave data and is beyond the scope of this paper. Although the wave propagation data reflect almost all wave conditions at the sites in question, the number of wave conditions for each direction is quite small and thus the reliability of the resulting distributions (Figs. 7 and 8) is much lower than that for the wave heights. There is, however, increasing evidence that the predominant wave propagation directions may be subject to changes in the Baltic Sea basin. For example, recent studies have indicated even much more clearly expressed decadal changes in wave propagation directions for the eastern part of the Gulf of Finland (Räämet *et al*. 2010). These turns evidently reflect certain changing features in the Baltic Sea wind and wave fields.

Another phenomenon potentially affecting the interpretation of the results in terms of coastal processes is that the observer may overestimate the role of relatively short waves whereas long low swell frequently remains undetected as has been documented for the Tallinn Bay conditions (Soomere 2005). This feature may thus lead to a certain overestimation of the frequency of locally generated wave fields. This shortage of visual observations may to a certain extent affect the interpretation of combining the wave field properties and sediment transport. Long waves have larger group velocities and therefore larger energy flux and more effect on the sediment transport. The proportion of wave fields dominated by long and low swell is, however, quite small in the entire Baltic Proper (Broman *et al*. 2006). Moreover, the observation sites are fully open to the sea and the predominant wave direction is onshore even among the low waves. Therefore, it is reasonable to assume, that swell is more or less correctly accounted for in the observations.

The joint course of the annual mean wave height and the frequency of waves from SW (which have largest impact to the coastal processes) gives, at least, a qualitative explanation of the above-discussed changes in the intensity of coastal processes. First, the increase in the rate of lengthening of coastal sections suffering from sediment deficit (Fig. 2) in the late 1990s and at the turn of the century may be caused by the joint influence of an increase in wave heights and the concentration of the waves to the southwestern direction. The decrease in the above rate in the early 2000s may reflect a temporary drop in the annual mean wave height in 2001–2005 but it may be also connected with relaxation of the peak for SW waves during this period.

The presented qualitative explanation also agrees with the fact that in 1995–2004 the angular distributions of wave directions were relatively wide at Klaipėda and Palanga (with exception of some atypical years). This character changed in 2005–2008. The peak for waves approaching from SW almost disappears for 2005–2006 at Klaipėda whereas a large amount of offshore-propagating waves were observe. This change may be to some extent related with the short-time increase in the length of accumulative sections of the Lithuanian coast since 2006 (Fig. 2).

A reason behind the apparent difference in the temporal course of the distributions for Palanga and Klaipėda in the recent years (*see* Fig. 8) may partially stem from reconstruction and prolongation works done in Klaipėda Port in 2002–2003 (Gailiušis *et al*. 2004, Kriaučiūniene *et al*. 2006). As observations were performed in the vicinity of the new harbour configuration, local changes to the wave propagation and refraction properties may have affected the readings to a certain extent.

In this context, we note that in many cases it is extremely difficult to distinguish natural changes to coastal processes from those triggered by human intervention. For example, Kriaučiūniene *et al*. (2006b) claim that the extensions of breakwaters towards offshore, construction of new quays and fairway dredging for Klaipėda Port have significantly altered sediment transport processes in Klaipėda Strait and nearshore. This conjecture is in line with the general understanding of the coastal engineering community (Dean and Dalrymple 2002). Therefore, such large-scale coastal engineering activities may additionally distort the existing predominant sediment transport from the south to north at the Lithuanian coast and to induce abrasion processes in some sections of the coast. For example, the extended breakwaters surrounding Klaipėda Strait (Kriaučiūniene *et al*. 2006a) most probably hold back the sand transfer from south to north and lead to an enhanced deficit of sand to the north of Klaipėda.

Changes to the alongshore sediment flux

To a first approximation, we estimate the temporal course of the intensity of alongshore sediment transport in terms of the annual average potential immersed weight transport rate (U.S. Army Corps of Engineers 2002) called (annual) transport below:

$$I_t = (\rho_s - \rho)g(1 - p)Q_t, \quad (1)$$

where ρ_s and ρ are the densities of sediment particles and sea water, respectively, g = 9.81 m s^{-2} is the acceleration due to gravity, p is the porosity coefficient and Q_t is the potential transport intensity of the alongshore sediment flux (equivalent to the volume of sediments carried through a cross-section of the beach in ideal conditions within a unit of time). The sign for Q_t is chosen so that the motion from the left- to the right-hand-side of the person facing the sea is positive. Note that the actual transport is usually much smaller than its estimated value because the sediment layer is not always continuous and frequently has a limited thickness. However, the long-term course of this quantity qualitatively characterises the difference between the magnitudes of transport in different years and, therefore, also the potential for coastal erosion.

We used the CERC (Coastal Engineering Research Council) method to estimate the potential transport rate (U.S. Army Corps of Engineers 2002) and follow its implementation for the Baltic Sea conditions described by Soomere *et al*. (2008). The potential transport intensity Q_t is assumed to be proportional to the shoreward wave energy flux $\vec{P} = E\vec{c}_g$, where E is the wave energy and $\vec{c}_g$ is the group velocity of the predominant waves. If waves approach the coast from the angle α, the shoreward component of the energy flux is $P_t = Ec_g\cos\alpha$ and the rate of its beaching per unit of the coastline is

$$P_t = Ec_g\sin\alpha\cos\alpha, \text{ where } c_g = |\vec{c}_g|. \quad (2)$$

The wave properties in Eq. 2 are expressed at the seaward border of the surf zone. The breaking waves are reasonably well described as long waves. To a first approximation, their energy E_b and group velocity c_{gb} at the breaker line are

$$E_b = \frac{\rho g H_b^2}{8}, c_{gb} = \sqrt{gd_b},$$

where H_b is the wave height, $\kappa = H_b/d_b$ is the breaking index and d_b is the breaking depth (U.S. Army Corps of Engineers 2002). The quantities P_t and I_t are related through so-called CERC formula $I_t = KP_t$, where $K = 0.05 + 2.6\sin^2 2\alpha_b + 0.006u_{mb}/w_f$ depends on the properties of the wave field and sediments (U.S. Army Corps of Engineers 2002). Here, α_b is the angle between the wave crests and the isobaths, $u_{mb} = 0.5\kappa\sqrt{gd_b}$ is the maximum orbital velocity in breaking waves within the linear wave theory, $w_f = 1.6\sqrt{gd_{50}(\rho_s - \rho)/\rho}$ is the approximation of fall velocity in the surf zone and d_{50} is the mean grain size (U.S. Army Corps of Engineers 2002: part III-1). Combining the above formulae leads to the following well-known expression for the potential transport rate:

$$Q_t = \frac{K\rho\sqrt{g}}{16(\rho_s - \rho)(1-p)\sqrt{\kappa}} H_b^2\sqrt{H_b}\sin 2\alpha_b. \quad (3)$$

The calculation scheme follows the one described by Soomere *et al*. (2007, 2008) hence here we give only a short overview of its basic steps. The modifications of the wave properties owing to the propagation from about 6-m deep wave observation area to the surf zone were estimated based upon linear wave theory and the assumption that the wave energy is concentrated in monochromatic plane waves with the period equal to the observed period and the direction of propagation equal to the observed propagation direction. The data set contains only wave periods ≥ 7 s (Kelpšaitė *et al*. 2008). As most of the wave conditions in the Baltic Sea (both offshore and nearshore) are close to saturated wave fields (Räämet *et al*. 2010), the missing periods T were estimated using the wave height and the assumption that the wave field is saturated.

For each observed wave situation, the wave length L and phase velocities $c_f = L/T$ of waves at the observation site were found from the following approximation, allowing determination of the wave length with an error not exceeding 1.7% (Dean and Dalrymple 2002: p. 90):

$$L = L_0\left\{\tanh\left[\left(2\pi\sqrt{\frac{h}{gT^2}}\right)^{3/2}\right]\right\}^{2/3}. \quad (4)$$

The phase velocity at the breaker line was calculated in the long-wave approximation $c_f = \sqrt{gh}$. The angle α_b at the breaker line was determined from Snell's law: $\sin\theta/c_f$ = const, where θ is the angle between the wave crests and the isobaths. Given the uncertainties in the entire data set, the shoaling of waves propagating from the observation area was accounted for

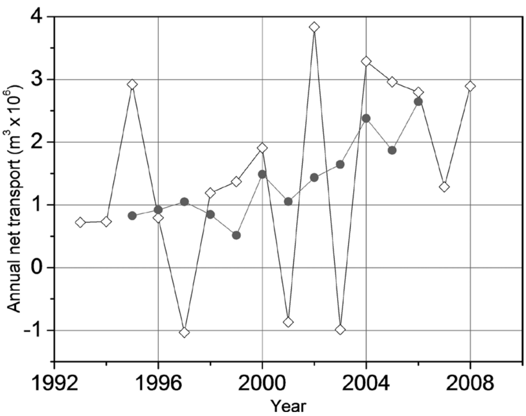

Fig. 9. Annual potential immersed weight transport rates (diamonds) and their 5-year running means (circles) at Palanga.

indirectly, by choosing the breaking index $\kappa = 1$. In this approximation, $d_b = H_b$ and the breaking wave height is simply equal to the observed wave height (cf. Soomere *et al*. 2008). The values of α_b and breaking depth d_b were used together with the mean grain size $d_{50} = 0.1$ and the difference $\rho_s - \rho$ to specify the CERC coefficient K. The experience with this method in the Baltic Sea conditions (Soomere *et al*. 2008) shows that the results are almost insensitive with respect to the particular choice of the mean grain size. For this reason, the characteristic value $d_{50} = 0.1$ was used. The porosity coefficient was set to 0.4 and the specific weights of sea water and sand to 1015 kg m^{-3} and 2650 kg m^{-3}, respectively. The potential transport rate for the given wave conditions within each day was calculated with Eqs. 1 and 3 using the observed wave properties at Palanga at 06:00 GMT. This data set contains the largest number of consistent wave data and the wave observation conditions are quite good at this site (Kelpšaitė *et al*. 2008). It was assumed that each set of wave parameters characterises wave conditions during the entire calendar day. At this location, especially to the south from Palanga, the coastline and isobaths make angle of about 4° counterclockwards from the direction to the north.

The temporal course of the annual transport (Fig. 9) has almost no similarity with that of the annual mean wave heights (Fig. 4). This feature indicates that the wave direction plays a very important role in the transport processes on the Lithuanian coast. Both the magnitude and direction of this transport show large interannual fluctuations, a part of which apparently is connected with the low temporal resolution of observed wave data. The transport to the north (in the positive direction in Fig. 9) was more or less in the same order of magnitude during the 1990s but increased considerably (by a factor of two) after the turn of the millennium. This increase correlates well with the decrease in the length of accumulative sectors of the Lithuanian marine coast (Fig. 2). A feasible interpretation of this correlation is that the magnitude of sediment sources, especially in the area to the north from Klaipėda, has not increased during the study period. It is very likely that the deficit in beach sediment owing to the described increase in the alongshore sediment transport to the north is compensated by coastal erosion. Interestingly, a decrease in the transport rate in 2007 to the level of the 1990s may be interpreted as one of potential reasons for the short-term relaxation of the accumulation areas in 2006–2007.

Conclusions

Although extreme and typical wave heights and periods in the Baltic Sea remain well below similar values observed in the open ocean (Soomere 2008), wave activity still is the major driver of coastal processes along the eastern coast of the Baltic Sea and in many sections of its sub-basins. The Lithuanian sea coast is almost straight and exposed to the wind and wave impacts. The above has shown that the majority of high waves approach the coast almost perpendicularly. Therefore, changes in any parameters of the wave regime, incl. the wave approach direction, may cause considerable changes in the coastal processes. While changes to wave heights that usually lead only to changes in the magnitude of littoral flow, even short-term changes in the wave approach direction may lead to significant changes both in the intensity and the direction of sediment transport.

The above analysis of the changes in the visually observed local wave regime and the previous analyses of the changes in the wind regime

(Pryor and Barthelmie 2003) in the south-eastern part of the Baltic Proper show that a part of these changes may be responsible for certain observed changes in the sedimentation regime on the Lithuanian coast in 1993–2008.

It is unlikely that relatively small (and statistically not significant), long-term variations in the wave heights (Kelpšaitė *et al*. 2008, Räämet 2010) could cause drastic variations in the length of accumulative and eroding sections (Fig. 2). The performed qualitative analysis of long-term variations in the alongshore transport rate suggests that changes in the approach directions, albeit they show somewhat diverse nature at different observation sites, may be responsible for these variations. Only a weak prevalence of waves from SW and W was observed in the beginning of the time interval in question (1993–1994) and a wide directional distribution with a slight prevalence of waves from the easterly directions occurred in 1996–1997 and around 2000. The relevant distributions became much narrower in the recent past, from about 2002, and concentrated into the south-western direction. Although there were single years with similar narrow distributions before, by the end of the 2000s, the narrowness is the dominant feature at Palanga. As the data from this site apparently are the most representative for the Lithuanian coastline (Klimienė 1999, Kelpšaitė *et al*. 2008), this narrowness likely represents certain rearrangement of the wind regime in the recent past.

An obvious consequence of this narrowness, with almost all observed waves approaching from SW, is that Sambian Peninsula receives very little wave energy. The magnitude of supply of sediments to the Curonian Spit, to a first approximation, is determined by the wave energy flux approaching from W and NW to Sambian Peninsula and thus may have considerably decreased. As discussed above, this change may lead to an overall decrease in sediment availability along the Lithuanian coast. This decrease apparently becomes at places evident as an increase in the length of eroding coastal sections. Unfortunately, the temporal and directional resolution of the available wave data set does not allow for more concise analysis of the changes. Given the inability of the contemporary wave models and wind forcing to capture similar observed changes in the Gulf of Finland (Räämet *et al*. 2010), more measured data are necessary to further rationalize the presented mechanism.

The described changes evidently are related to similar changes in the directional structure of winds and the prevailing wind direction, in particular with the evidence about the increase in frequency of SW winds (Kull 2005, Dailidienė *et al*. 2006). The W and SW directions correspond to the longest fetches for the entire south-eastern section of the Baltic Sea. The established changes in the wave regime, therefore, may serve as a feasible (albeit not exclusive and at this stage to some extent hypothetical) explanation for the changes in the abrasion processes at the Lithuanian coast. Further studies into the practical and economical consequences of such changes in the local wave regime are necessary in order to reveal the magnitude of the reaction of the coast.

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References

Alenius P., Myrberg K. & Nekrasov A. 1998. Physical oceanography of the Gulf of Finland: a review. *Boreal Env. Res*. 3: 97–125.

Broman B., Hammarklint T., Rannat K., Soomere T. & Valdmann A. 2006. Trends and extremes of wave fields in the north-eastern part of the Baltic Proper. *Oceanologia* 48(S): 165–184.

U.S. Army Corps of Engineers 2002. *Coastal engineering manual 1110-2-1100*. *Engineer manual*. U.S. Army Corps of Engineers, Washington, D.C.

Dailidienė I., Davulienė L., Tilickis B., Stankevičius A. & Myrberg K. 2006. Sea level variability at the Lithuanian coast of the Baltic Sea. *Boreal Env. Res*. 11: 109–121.

Dean R.G. & Dalrymple R.A. 2002. *Coastal processes with engineering applications*. Cambridge University Press.

Gailiušis B., Kriaučiūniene J. & Kriaučiūnas R. 2004. Klaipėdos uosto įplaukos kanalo tėkmės hidrodinaminio režimo pokyčiai dėl molų pertvarkymo. *Energetika* 1: 57–61.

Gudelis V. 1998. *Lietuvos ijūris ir pajūris*. Lietuvos Mokslas, Vilnius.

Gulev S.K. & Hasse L. 1998. North Atlantic wind waves and wind stress fields from voluntary observing ship data. *J. Phys. Oceanogr.* 28: 1107–1130.

IAHR [IAHR working group on wave generation and analysis] 1989. List of sea-state parameters. *J. Waterw. Port Coast. Ocean Eng.* 115: 793–808.

Kachel M.J. 2008. *Particularly sensitive sea areas*. Hamburg Studies on Maritime Affairs 13, Springer-Verlag, Berlin, Heidelberg.

Kahma K., Pettersson H. & Tuomi L. 2003. Scatter diagram wave statistics from the northern Baltic Sea. *MERI — Report Series of the Finnish Institute of Marine Research* 49: 15–32.

Kaplin P.A. [Каплин П.А.] 1973. [*Contemporary history of shores of the World Ocean*]. Moscow University Publishers, Moscow. [In Russian].

Kelpšaitė L., Herrmann H. & Soomere T. 2008. Wave regime differences along the eastern coast of the Baltic Proper. *Proc. Estonian Acad. Sci.* 57: 225–231.

Klimienė V. 1999. *Meteorologijos stotys Lietuvoje 1777–1997m*. Lietuvos hidrometeorologijos tarnyba.

Kriaučiūniene J., Gailiušis B. & Kovalenkoviene M. 2006a. Peculiarities of sea wave propagation in the Klaipėda Strait, Lithuania. *Baltica* 19: 20–29.

Kriaučiūniene J., Gailiušis B. & Rimavičiūte E. 2006b. Modelling of shoreface nourishment in the Lithuanian nearshore of the Baltic Sea. *Geologija* 53: 28–37.

Kull A. 2005. Relationship between interannual variation of wind direction and wind speed. *Publicationes Instituti Geographici Universitatis Tartuensis* 97: 62–73.

Leppäranta M. & Myrberg K. 2009. *The physical oceanography of the Baltic Sea*. Springer Praxis, Berlin–Heidelberg–New York.

Orviku K., Jaagus J., Kont A., Ratas U. & Rivis R. 2003. Increasing activity of coastal processes associated with climate change in Estonia. *J. Coastal Res.* 19: 364–375.

Pryor S.C. & Barthelmie R.J. 2003. Long-term trends in near-surface flow over the Baltic. *Int. J. Climatol.* 23: 271–289.

Räämet A. 2010. *Spatio-temporal variability in the Baltic Sea wave fields*. Ph.D. thesis, Tallinn University of Technology.

Räämet A. & Soomere T. 2010. The wave climate and its seasonal variability in the northeastern Baltic Sea. *Estonian J. Earth Sci.* 59: 100–113.

Räämet A., Suursaar Ü., Kullas T. & Soomere T. 2009. Reconsidering uncertainties of wave conditions in the coastal areas of the northern Baltic Sea. *J. Coastal Res.* Special Issue 56: 257–261.

Räämet A., Soomere T. & Zaitseva-Pärnaste I. 2010. Variations in extreme wave heights and wave directions in the north-eastern Baltic Sea. *Proc. Estonian Acad. Sci.* 59: 182–192.

Soomere T. 2005. Wind wave statistics in Tallinn Bay. *Boreal Env. Res.* 10: 103–118.

Soomere T. 2008. Extremes and decadal variations of the northern Baltic Sea wave conditions. In: Pelinovsky E. & Kharif C. (eds.), *Extreme ocean waves*, Springer Verlag, pp. 139–157.

Soomere T. & Zaitseva I. 2007. Estimates of wave climate in the northern Baltic Proper derived from visual wave observations at Vilsandi. *Proc. Estonian Acad. Sci. Eng.* 13: 48–64.

Soomere T., Kask A., Kask J. & Nerman R. 2007. Transport and distribution of bottom sediments at Pirita Beach. *Estonian J. Earth Sci.* 56: 233–254.

Soomere T., Kask A., Kask J. & Healy T. 2008. Modelling of wave climate and sediment transport patterns at a tideless embayed beach, Pirita Beach, Estonia. *J. Marine Syst.* 74: S133–S146.

Valdmann A., Käärd A., Kelpšaitė L., Kurennoy D. & Soomere T. 2008. Marine coastal hazards for the eastern coasts of the Baltic Sea. *Baltica* 21: 3–12.

Zaitseva-Pärnaste I., Suursaar Ü., Kullas T., Lapimaa S. & Soomere T. 2009. Seasonal and long-term variations of wave conditions in the northern Baltic Sea. *J. Coastal Res.* Special Issue 56: 277–281.

Žilinskas G. 2005. Trends in dynamic processes along the Lithuanian Baltic coast. *Acta Zoologica Lituanica* 15: 2004–2007.

Žilinskas G. 2008. Distinguishing priority sectors for the Lithuanian Baltic Sea coastal management. *Baltica* 21: 85–94.