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Spatial variations of wave loads and closure depths along the coast of the eastern Baltic Sea

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Abstract. The closure depth is a key parameter in coastal processes as it characterizes the overall wave intensity in the nearshore and indicates the water depth down to which storm waves are able to maintain a universal shape of equilibrium coastal profiles. The properties and alongshore variations of the closure depth for the eastern Baltic Sea coast are evaluated at a coarse resolution (5.5 km) and for the vicinity of Tallinn Bay at a higher resolution (0.5 km). The study is based on numerical simulations of wind-generated wave fields. It is shown that, due to the small contribution of remote swell in the Baltic Sea, the typical ratio of wave heights in strongest storms and average wave heights is about 5.5, which departs considerably from that of open ocean coasts. A modification of the formula for the approximate calculation of the closure depth from the average wave height is derived. The estimates are based on four methods: from the wave heights of the strongest storms, from average wave heights based on a linear approximation, and using two versions of a second-order approximation. The greatest closure depth of up to 7.25 m was found to occur along the coast of the Baltic Proper near Hiiumaa, Saaremaa and the Kurzeme Peninsula. These areas also experience the largest wave intensities. Along other parts of the Baltic Proper coast the closure depth is typically 5–6 m, whereas in the Gulf of Riga and along the southern coast of the Gulf of Finland it is usually in the range of 3–4 m.

Key words: equilibrium beach profile, closure depth, wave modelling, Baltic Sea, Gulf of Finland, Gulf of Riga.

1. INTRODUCTION

A fascinating property of sedimentary coasts lining ocean basins, marginal seas and large lakes is that the basic shapes of their cross-sections (called coastal profiles below) are essentially identical, in spite of the fact that they are exposed to extremely different wave conditions and may have different sediment properties [1]. This uniform shape is continuously maintained by ocean swells and wind-generated waves that give rise to persistent, so-called equilibrium beach profiles [2]. The existence of such a persistent shape was the core assumption of, for example, the Bruun's Rule [3]. This rule explains the relatively large changes in the location of the shoreline produced even by small changes in the mean sea level. Originally it predicted shoreline retreat, resulting from chronic sea level rise by applying the equilibrium profile concept. The Bruun's rule was subsequently extended to more complex cases such as variable heights of the berm [4], landward migration of barrier beaches [5], and the presence of offshore bars [6].

A breakthrough in the understanding of the appearance of such profiles was achieved about three decades ago when it became evident that equilibrium profiles could be described in terms of a simple power law

$$h(y) = Ay^b, \tag{1}$$

that expresses the water depth $h(y)$ along such profiles in terms of the distance y from the waterline whereas the profile scale factor A depends on the grain size of the bottom sediments. The exponent b can vary over quite a large range. The most widely used version of Eq. (1) is the Dean's equilibrium beach profile (EBP) with $b = 2/3$ that corresponds to the uniform wave energy dissipation per unit water volume in the surf zone [1]. For Dutch dune profiles, for example, $b = 0.78$ provides a better fit [7], and a range of $b = 0.73 - 1.1$ appears to be more suitable for Israeli beaches [8]. Values of the exponent b larger than 1 correspond to convex profiles and are relatively rare. For example, for Pikakari Beach in Tallinn Bay, the Baltic Sea, "non-reflecting" beach profiles with $b = 4/3$ may exist under the combined effect of irregular wind-wave fields and regular groups of longer-period waves, generated by high-speed ferries [9]. Although the power laws, characterizing coastal profiles, are not able to replicate many details of realistic nearshore profiles such as the presence of sand bars, the techniques that rely on this concept are extremely useful for solving a number of practical and theoretical problems of beach evolution and coastal zone management [1].

Another basic parameter of an EBP is the closure depth h_c, which is defined as the maximum depth at which breaking waves effectively adjust the nearshore profile [10,11]. Seawards of the closure depth, storm waves may occasionally move bottom sediments but are not able to maintain a specific profile.

Most applications of profiles, described by Eq. (1), assume that $b = 2/3$. The width W and the mean slope $\tan\theta = h_c/W$ of the profile are used as additional parameters [12] for applications of the Bruun's Rule along any particular coastal section to characterize the potential effects of sea-level change as well as for the application of the inverse Bruun's Rule to determine the amount of sediment, eroded or accreted in the course of the shoreline changes [13,14]. The parameters can be easily determined if two other fundamental quantities are known: the typical grain size (that determines parameter A) and the closure depth h_c. The mean slope of an EBP is simply the ratio of the closure depth h_c to the width W

of the profile. The width is usually treated as the distance from the coast to the point at which the water depth corresponds to the closure depth. It does not include the subaerial part of the beach profile. For the profile, described by Eq. (1), the width and the mean slope of the beach can be expressed as

$$W = (h_c / A)^{3/2}, \qquad \tan\theta = h_c / W = \frac{A^{3/2}}{h_c^{1/2}}. \tag{2}$$

All the listed parameters may vary along a beach and should therefore be treated as functions $A(x)$, $h_c(x)$ and $W(x)$ of the distance x along the shoreline.

A basic simplification, provided by the theory of EBPs, is that the parameter A and the closure depth are considered to be almost independent of each other and that they can be derived from completely different arguments. While parameter A depends on the typical grain size of the sediment, the closure depth is mostly a function of the local wave climate. The determination of the former is thus possible via granulometric analysis of bottom sediment, whereas the latter can be estimated either from repeated profiling or approximated from numerical modelling.

The closure depth h_c is generally defined as the depth where repeated survey profiles pinch out to a common line [15]. The instantaneous coastal profiles along macrotidal open ocean coasts frequently differ from the theoretical power law because the location of the surf zone may vary substantially over a tidal cycle and the width of the EBP is not always uniquely defined. Also, very severe storms tend to extend the EBP towards the offshore [16]. Additional problems arise in the case of subsiding coasts where the EBP may be masked by flooded coastal features, and in the case of Arctic coasts where the presence of ice may modify the evolution of a coast [17]. For these reasons several authors have suggested to evaluate the closure depth on the basis of certain properties of the local wave climate. The underlying assumption is that the closure depth basically depends on the roughest wave conditions that persist for a reasonable time [11]. Another frequently used assumption is that the ratio of certain measures, characterizing the roughest waves, and the mean wave height varies insignificantly [16], which is correct, for example, for wave systems having a Pierson–Moskowitz spectrum.

The simplest but still widely used (essentially linear) approximation for the closure depth, based on these assumptions, is [16,18,19]

$$h_c \cong q_1 H_{0.137\%} \cong q_2 H_{\text{mean}}, \tag{3}$$

where H_{mean} is the annual mean significant wave height, $H_{0.137\%}$ is the threshold of the significant wave height that occurs for 12 h a year (that is, the wave height that is exceeded with a probability of 0.137%; originally it was meant to represent a storm in which such wave heights persisted for 12 subsequent hours), $q_1 = 1.5$ [16] (often a value of $q_1 = 1.57$ is used [11,12]) and $q_2 = 6.75$.

Equation (3) assumes a specific constant ratio of the annual mean H_{mean} and a higher percentile of the significant wave height, namely $H_{0.137\%} \cong 4.5 H_{\text{mean}}$ [19].

This ratio is established for wave fields with a Pierson–Moskowitz spectrum. It matches the observed wave statistics along the US coasts [19] but does not necessarily hold for semi-enclosed seas where remote swell is almost absent and the wave height is mainly governed by local storms. A specific feature of the wave climate in the Baltic Sea is that the average wave conditions are relatively mild but very rough seas may occur episodically in long-lasting severe storms [20–22]. Waves generated by such storms are much higher than one would expect from the mean wave conditions. The main reason for this feature is that the complicated geometry of the Baltic Sea and its subbasins rarely matches perfectly with the wind field in terms of favourable wave generation. Moreover, the strongest storms in the Baltic Proper and in the Gulf of Finland approach from directions from which winds in general are rather infrequent [23,24]. As a result, simplified estimates, based on the annual mean wave parameters, may lead to considerable errors in estimations of the closure depth [25,26].

The purpose of the present paper is twofold. Firstly, the ratio of extreme and average wave properties along the eastern Baltic Sea coast are analysed with the aim of establishing the extension of spatial variations of this ratio and to explore the possibilities of using simplified methods for the evaluation of the closure depth along this coast. For the eastern Baltic Sea coast as a whole this analysis is performed at a relatively coarse resolution (about 5.5 km). A much finer resolution (about 500 m) is applied for the analysis of the situation in the vicinity of Tallinn Bay, which is a typical example of the deeply indented bays, characterizing the southern coast of the Gulf of Finland. Secondly, typical values for the closure depths of the sections of the eastern Baltic Sea coast, exposed to the predominant waves, are determined to establish the range of variation of the relevant wave loads. This depth not only serves as a key property of the beach profile but also directly characterizes the overall intensity of wave impact for a particular coastal section (and thus the potential of coastal erosion) and implicitly indicates the relative level of wave energy resources for the different coastal stretches. For this purpose, adequate values of the parameter q_2 in Eq. (3) are estimated for the Baltic Sea conditions and the closure depth is calculated from second-order approximations, in this way expanding the observations, previously described in [26], to the entire coastline of Estonia. This analysis is also performed at a higher resolution for an urban area around Tallinn which is characterized by a complex coastal geometry.

2. PHYSICAL SETTING AND COMPUTATIONAL METHODS

Starting at the Sambian Peninsula in the southeast (20°E, 55°N), the study area covers the entire nearshore of Lithuania, Latvia and Estonia with about 5.5 km long coastal sections. The study area extends to the eastern part of the Gulf of Finland, to Kurgolovo in Russia (28°E, 59°51′N). The coastline of the Baltic Proper and the Gulf of Finland (about 950 km) is divided into 154 sections and the nearshore of the Gulf of Riga (about 450 km) into 68 sections. Wave statistics and closure depths were calculated for each of these 222 sections (Fig. 1). In order to avoid the potential distortion of wave fields in nearshore areas with complex geometry, the grid cells of the wave model (see below) were chosen at water depths ranging from 7 to 48 m, with an average of 18 m. This restriction means that several grid cells used in this study differ from the cells used in a previous analysis [[14,26]]. The differences are minor along the coast of Lithuania and the Baltic Proper coast of Latvia but substantial in the eastern part of the Gulf of Riga where Pärnu Bay was omitted in our analysis.

The dataset, generated for these nearshore cells, adequately characterizes the wave loads along relatively straight coastlines such as the coast of Lithuania and Latvia, and part of Estonian coast in the Gulf of Riga as well as Narva Bay. Along the rest of the Estonian coast the situation, regarding wave properties, is essentially different. Straight shoreline sections typically occur here at spatial scales of about 1 km and less and can therefore not be resolved by the 5.5 km spatial resolution. As an example, the variability of wave loads and closure

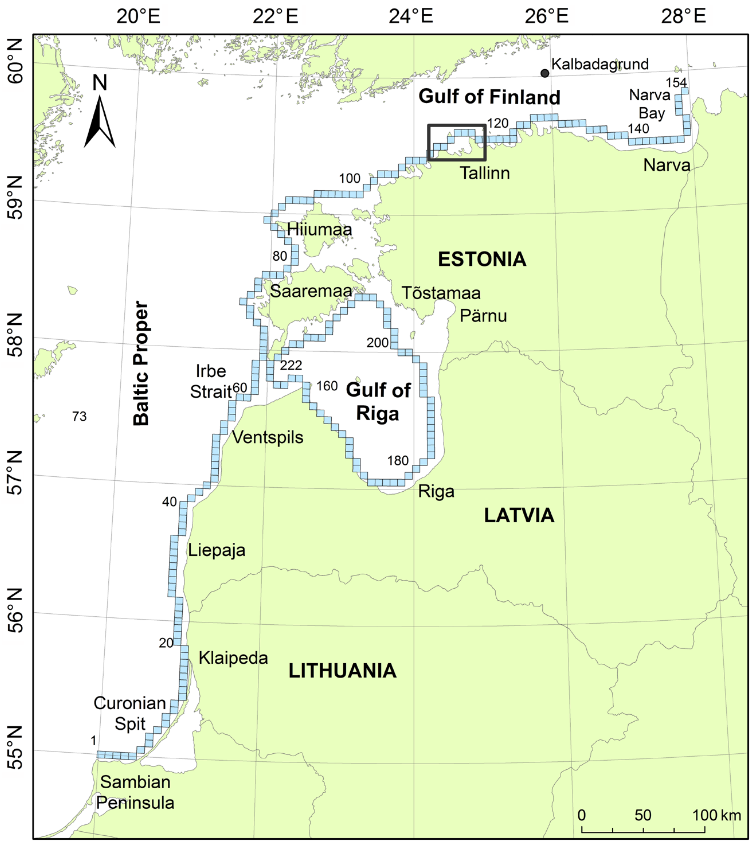


Fig. 1. Grid cells of the wave model used to evaluate nearshore wave statistics and closure depths for relatively straight coastal sections and at locations open to the offshore. The box indicates the detailed study area in the vicinity of Tallinn Bay.

depths were calculated at a higher resolution for the wave-dominated micro-tidal coastline of Tallinn Bay and adjacent small bays (Fig. 2), where straight coastal stretches extend for only a few hundreds of metres and up to a kilometre or two, but at larger scales are interrupted by peninsulas and headlands, separating individual bays that are deeply indented into the mainland. This is a relatively young coast, which is still actively in the process of straightening [27]. In addition, the bays open into a variety of directions so that they are individually impacted by storms approaching from different angles.

To match the difference in resolution of the regional eastern Baltic Sea coast and the Tallinn Bay area, two sets of numerically simulated wave data were generated. For the analysis of wave loads and closure depths along the former coastline, hourly time series were extracted from numerical simulations of the Baltic Sea wave fields, performed for 1970–2007, using the third-generation spectral wave model WAM [28]. The model was run for a regular rectangular grid that covers the entire Baltic Sea with a spatial resolution of 3′ along latitude and 6′ along longitude (about 3×3 nm) [29]. The bathymetry of the model was based on data from [30], which has a resolution of 1′ along latitude and 2′ along longitude.

The wave model was forced with wind data corresponding to an elevation of 10 m above the sea surface, constructed from the Swedish Meteorological and Hydrological Institute (SMHI) geostrophic wind database. This data set has a spatial and temporal resolution of $1° \times 1°$ and 3 h, respectively (6 h before

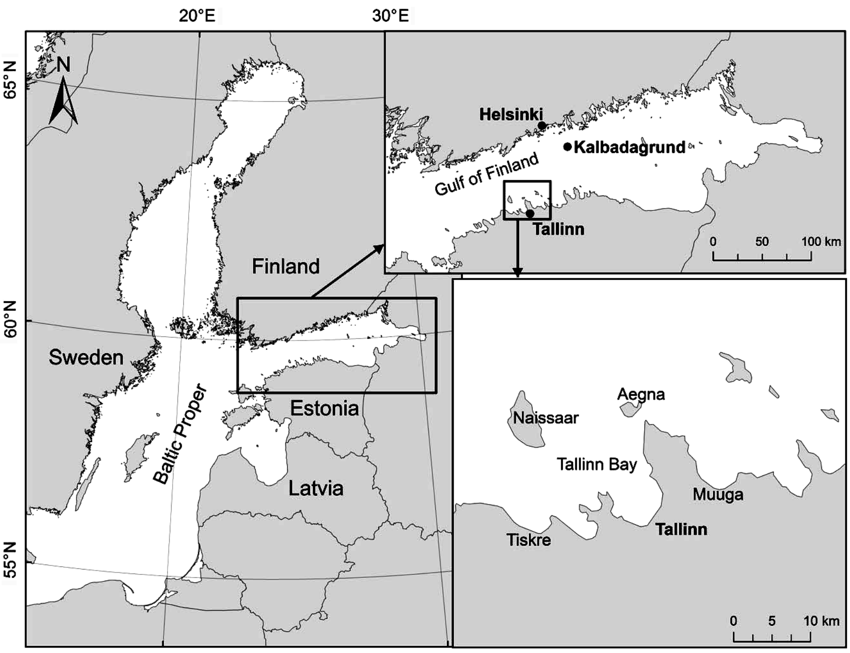


Fig. 2. Computational areas of the triple-nested wave model, applied to the Tallinn Bay area and the location of the wind measurement site at Kalbådagrund.

September 1977). The geostrophic wind speed was multiplied by 0.6 and the wind direction was turned counter-clockwise by 15° [31]. This approximation of the vertical structure of wind properties is frequently used in the Baltic Sea region. Although it completely ignores stability aspects of the atmospheric stratification, it leads to an acceptable reproduction of circulation patterns [32]. The use of an extended frequency range of wave harmonics (42 frequency bins with an increment of 1.1) down to wave periods of about 0.5 s ensures realistic wave growth rates under weak winds after calm periods and an adequate reproduction of high-frequency part of the wave fields [20,22]. Thus, at each grid cell, 600 spectrum components were calculated (24 evenly spaced directions with a directional resolution of 15° and 42 frequencies ranging from 0.042 to 2.08 Hz).

The accuracy and reliability of wave calculations, using this approach, are discussed in a number of recent papers [31,33]. They demonstrate that the simulated wave properties satisfactorily replicate the time series of measured wave data [33] and also reproduce the statistical properties of the wave fields at several observation sites quite well [31]. The presence of sea ice is ignored in the calculations. Although this is generally acceptable for the southern part of the Baltic Proper, it may substantially overestimate the wave load in the northern Baltic, especially in the Gulf of Riga and the Gulf of Finland. However, as the strongest storms usually occur before the ice cover is formed, this approximation is evidently still adequate for the estimation of the closure depth and extreme wave loads.

Wave properties in the vicinity of Tallinn Bay were calculated with a spatial resolution of about 470 m using a triple-nested version of the WAM model for the years of 1981–2012. Additionally to the coarse model (with a spatial step of about 5.5 km) run for the entire Baltic Sea (Fig. 2), a medium-resolution model was run for the Gulf of Finland with a grid step of about 1.8 km. The bathymetry of the models is based on data from [30]. Finally, a high-resolution model with a grid step of about 470 m (1/4′ along latitude and 1/2′ along longitude), which resolves the major local topographic and bathymetric features, was run for the Tallinn Bay area (Fig. 3). The standard frequency range of the WAM model (from 0.042 to 0.41 Hz, 25 frequencies) was employed for stronger winds. It was extended to 2.08 Hz (42 frequencies) for wind speeds ≤10 m/s to better represent the wave growth under weak wind and short fetch conditions.

All three models in the hierarchy were forced with a spatially homogeneous wind field that matches the wind, measured in fully marine conditions not affected by the land. Such a wind measurement site is located at Kalbådagrund, a caisson lighthouse in the central part of the Gulf of Finland (Fig. 2, 59°59′N, 25°36′E). Here, wind speed and direction are recorded at a height of 32 m above mean sea level. To reduce the recorded wind speed to the reference height of 10 m, height correction factors of 0.91 for neutral, 0.94 for unstable and 0.71 for stable stratifications have been employed in earlier studies [34]. As a first approximation, a factor 0.85 was used in the present case, which is similar to that used in [20].

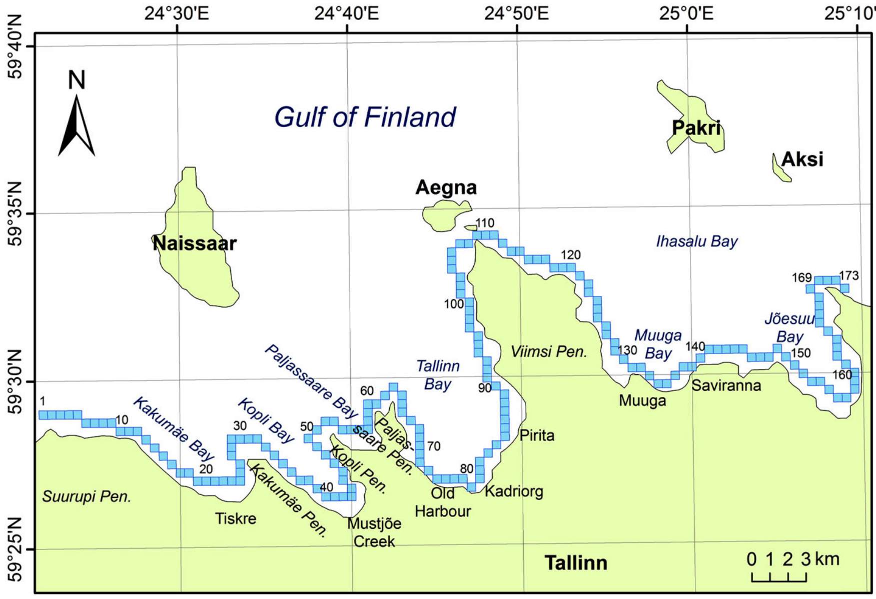


Fig. 3. Grid cells of the fine model used for the evaluation of wave properties in the nearshore of Tallinn Bay. Graphics by K. Pindsoo.

The nearshore wave time series along this coastal stretch in the vicinity of Tallinn Bay were estimated using a simplified scheme for long-term wave hindcasting, in which calculations of the sea state were reduced to an analysis of a cluster of wave field maps, precomputed from single-point wind data. This method produces adequate results in the study area where wave fields rapidly become saturated and have a relatively short memory (normally no longer than 12 h) of wind history [20]. This feature makes it possible to split the wave calculations into a number of short independent sections of 3–12 h. As a first approximation, it was assumed that an instant wave field in Tallinn Bay is a function of a short section of the wind dynamics and that the contribution of remote wind conditions in the open Baltic Sea to the local wave field in Tallinn Bay is insignificant. For Tallinn Bay, these assumptions are correct for about 99.5% of all cases [20]. As waves are relatively short in the Baltic Sea [21] and usually even shorter in its semi-enclosed sub-basins [22], the wave model using the innermost grid allows a satisfactory description of wave properties in the coastal zone down to depths of about 5 m and as close to the coast as about 200–300 m [20].

3. RESULTS

3.1. Longshore variations of wave properties

Basic wave properties (mean wave height and various quantiles of wave heights) vary substantially along the eastern Baltic Sea coast (Fig. 4). The overall

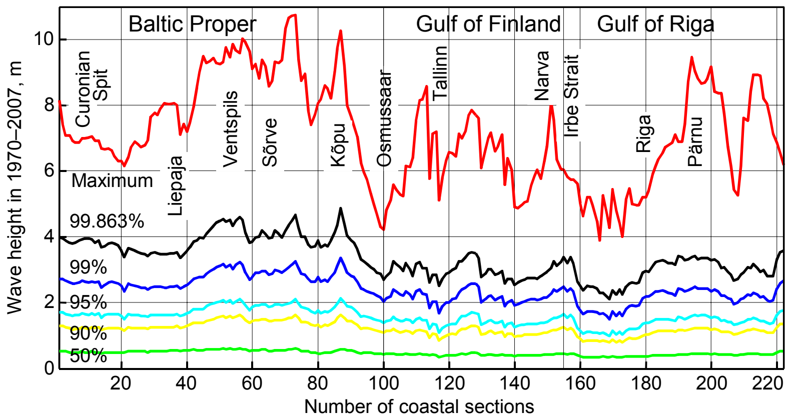


Fig. 4. Modelled significant wave height (overall maximum over the years of simulation and thresholds for various quantiles) in the nearshore of the eastern Baltic Proper, the Gulf of Finland and the Gulf of Riga for the period 1970–2007. The numbers of grid points are given in Fig. 1.

wave height maximum for the entire study area was computed as 10.7 m, which exceeds the maxima of 9.6–9.7 m estimated for offshore conditions in the open Baltic Sea under extreme storms [[35,36]] by about 10%. Nevertheless, the individual maxima for selected nearshore locations may still be realistic due to wave energy focusing, caused by refraction in certain domains [[37,38]]. The maximum significant wave heights of >8 m, computed for the Gulf of Finland and for the Gulf of Riga, appear to be overestimates, even though single waves with a height of around 10 m have been reported in older literature from the southern part of the Gulf of Riga during extreme north-northwesterly storms. The number of such wave conditions, however, is very small; for example, in the eastern Gulf of Riga such wave heights have been recorded during a single storm only. The threshold for wave heights, occurring with a frequency of 0.1%, is well below 4 m for the Gulf of Riga, varies between 4 and 5 m in the nearshore of the Baltic Proper, and is around 3 m in the Gulf of Finland.

The ratio of the maximum and mean wave height (interpreted as either the arithmetic mean of all hourly values of the wave height or, alternatively, as the median wave height $H_{50\%}$) also varies substantially along the coastline. The minimum and maximum values differ by a factor of 2 (Fig. 5). The ratio of the 99.863th percentile, $H_{0.137\%}$, and the mean wave height, H_{mean} (Fig. 5), however, varies much less. Almost its values lie in a relatively narrow range from 5 to 6, with an overall mean of 5.54. Although the maximum value of $H_{0.137\%}/H_{\text{mean}}$ is 6.38, it exceeds 6 in only 13 out of the 222 coastal sections. The minimum value is 4.84 with only 5 values lying below 5. This result suggests that the use of Eq. (3) for the calculation of the closure depth, based on the annual mean wave height, is definitely not justified in the Baltic Sea conditions. This equation, on average, underestimates the closure depth by about 20%. However, as demonstrated below, the use of the 99.863th percentile for this purpose is still adequate.

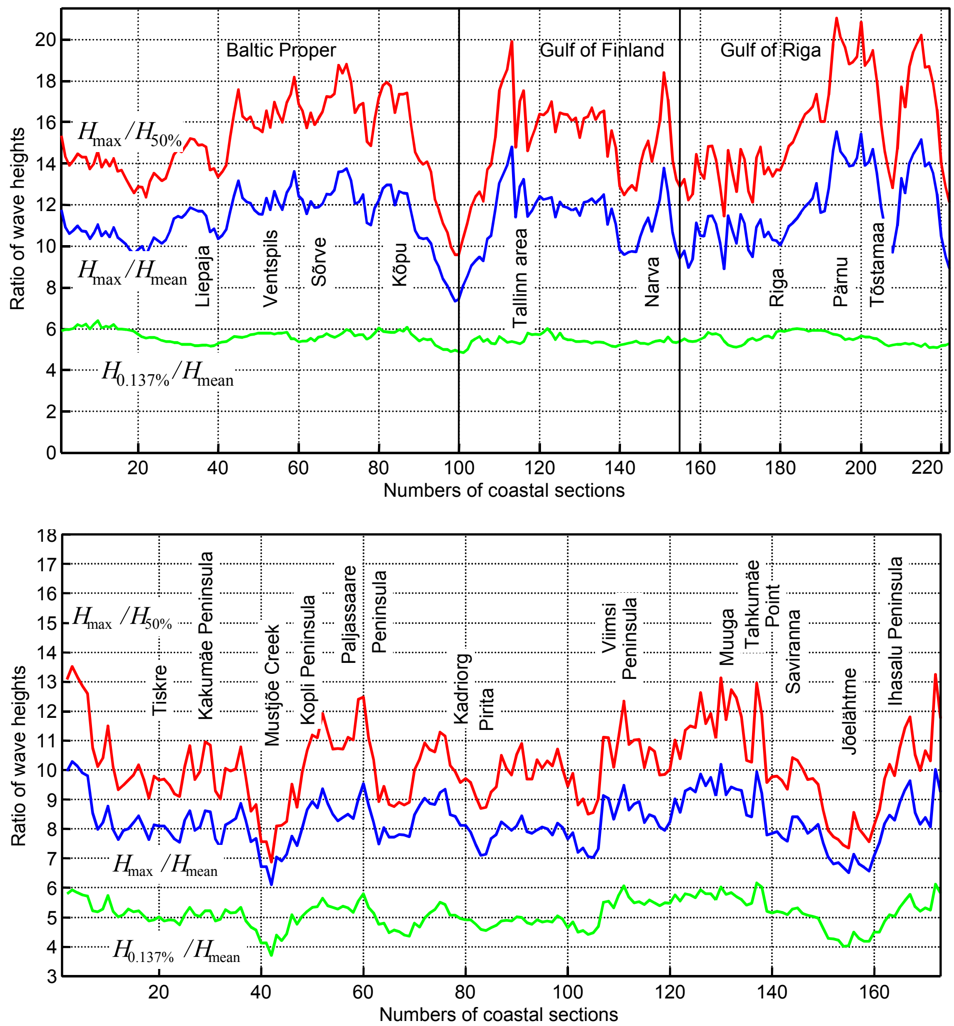


Fig. 5. The ratio of maximum and average significant wave height along the eastern Baltic Sea coast and the Gulf of Riga in the period 1970–2007 (upper panel; numbers of grid points in Fig. 1) and for the Tallinn Bay area in the period 1981–2012 (lower panel, numbers of grid points in Fig. 3). Here $H_{50\%}$ stands for the median wave height.

Figure 5 also demonstrates that there is no obvious relationship between the geometry or orientation of the coastline and the values of the ratio $H_{0.137\%}/H_{\text{mean}}$. This ratio is close to 6 along almost straight coastal stretches such as the entire Curonian Spit or the vicinity of Ventspils, and also to the east of Tallinn in the Gulf of Finland or near Riga. This ratio exhibits minimum values at the entrance to the Gulf of Finland and near Liepaja, the two areas having radically different orientations, besides being exposed to greatly different wave conditions. This observation suggests that a first approximation to the closure depth in the Baltic Sea conditions can be found by using the relationship

$$h_c^B \cong 1.5 H_{0.137\%} \cong 8.25 H_{\text{mean}}. \qquad (3')$$

The alongshore variation of the ratio $H_{0.137\%}/H_{\text{mean}}$ is even larger along the coastal stretch around Tallinn with its complicated geometry (Fig. 5). The ratio of the maximum wave height and the 99.9th percentile (not shown) varies by about 20% in the study area (1.42–1.78). This level of variation signals that, in this region, the distributions of occurrence of different very large wave heights may have quite different properties for different sections. This conjecture is further supported by the behaviour of the ratio $H_{0.137\%}/H_{\text{mean}}$. It varies from about 3.7 to 6.1 whereas its average over the entire coastal stretch around Tallinn is about 5. Somewhat surprisingly, this value is by about 10% smaller than the one for the entire eastern Baltic Sea coast calculated using the wave data from grid points located slightly farther offshore. A potential reason for this difference may be a relatively larger influence of remote swell in the nearshore of the deeply indented bays. Because such swells are almost totally absent in the Baltic Proper, even these comparatively low levels may increase the annual mean wave height and thereby adjust the rate in question.

3.2. Closure depth

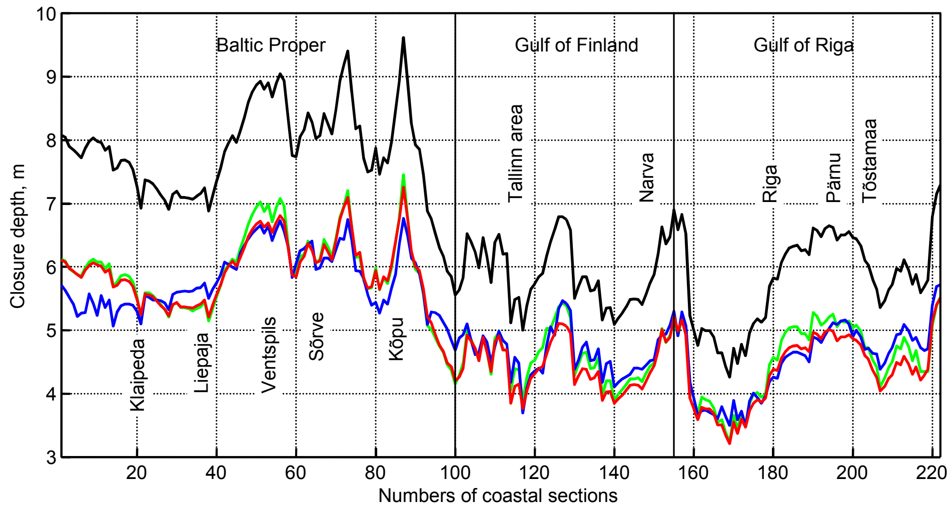
The estimates of the closure depth were calculated from the modified Eq. (3′) with $q_2 = 8.25$ and from the second-order (so-called parabolic) approximations that describe the closure depth as a quadratic function of the wave height and that also involve the wave period [11,12]:

$$h_c = p_1 H_{0.137\%} - p_2 \frac{H_{0.137\%}^2}{g T_s^2}. \qquad (4)$$

In Eq. (4), g is the gravity acceleration. In the original version of this approximation [11,12], $p_1 = 2.28$, $p_2 = 68.5$ and T_s is the typical peak period that corresponds to the largest significant wave height that occurs for 12 h a year. This expression is known to somewhat overestimate the closure depth but is still often used in coastal engineering as a conservative estimate in the design of beach refill. Another version of parameters in Eq. (4) with values of $p_1 = 1.75$ and $p_2 = 57.9$ [16,19] matches the average values of closure depth quite well and also the estimates derived using Eq. (3). These expressions give more realistic results for semi-sheltered domains of the Baltic Sea [14,25]. The use of even higher-order approximations is evidently not justified as the concept of closure depth is an approximation in itself.

The calculations were performed using two different approaches. Firstly, the values of $H_{0.137\%}$ and the corresponding typical periods and the closure depth for each section were evaluated separately for every year in the period 1970–2007. The closure depth was then estimated as an average of the annual values. Secondly, all these quantities were evaluated directly from the entire dataset comprising 333 096 hourly values of wave time series. Consistently with the concept of gradual increase in the width of the EBP [16], the results based on the sequence of annual values were slightly smaller than those obtained directly from the entire time series. The difference between the results for individual coastal sections was surprisingly small, being less than 4% for single sections and about 2.5% on average. This suggests that the overall storminess level remained fairly constant during the entire simulation period.

The calculations with three of the four applied methods produced almost the same results (Fig. 6), whereas Eq. (4) with $p_1 = 2.28$ and $p_2 = 68.5$ gave some-



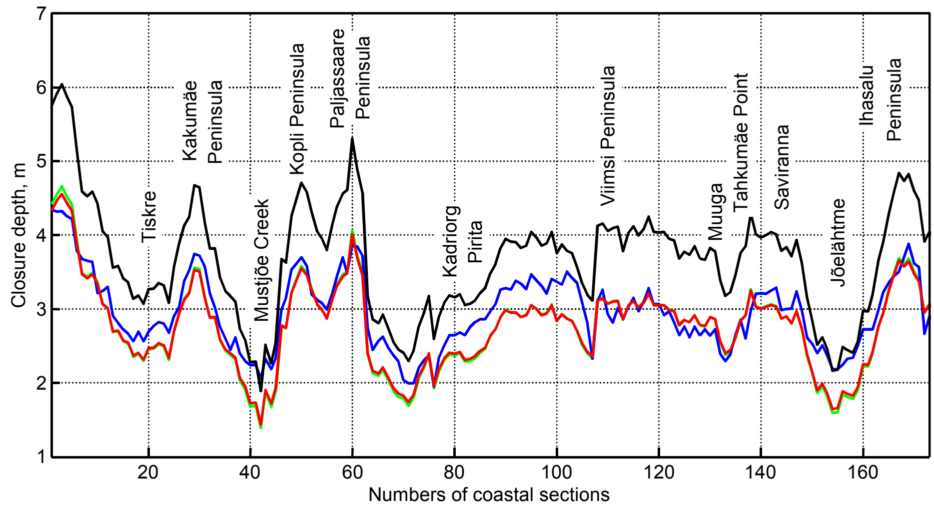


Fig. 6. Closure depths along the coasts of the Baltic Proper, the Gulf of Finland and the Gulf of Riga (upper panel), and in the Tallinn Bay area (lower panel) calculated using Eq. (3′) with $q_1 = 1.5$ (green) and $q_2 = 8.25$ (red), and Eq. (4) with $p_1 = 1.75$ and $p_2 = 57.9$ (blue), and $p_1 = 2.28$ and $p_2 = 68.5$ (black). The quantity $H_{0.137\%}$ was calculated over the entire time interval of wave simulations for 1970–2007 (upper panel) and for 1981–2012 (lower panel).

what larger values. As expected, the closure depth is largest (up to 7.25 m) in regions that are fully open to the predominant south-westerly winds in the Baltic Proper and where the overall wave intensity is the largest in the entire Baltic Proper. These areas are the west coasts of the islands of Hiiumaa and Saaremaa, and north-northwest coast of the Kurzeme Peninsula. The coasts of the Baltic Proper all have a closure depth >5 m, whereas almost the entire coastline of the Gulf of Finland and the Gulf of Riga (except for a very few locations) has a closure depth well below 5 m (Fig. 7). This difference is consistent with the well-known difference in the properties of wave climate in these three domains.

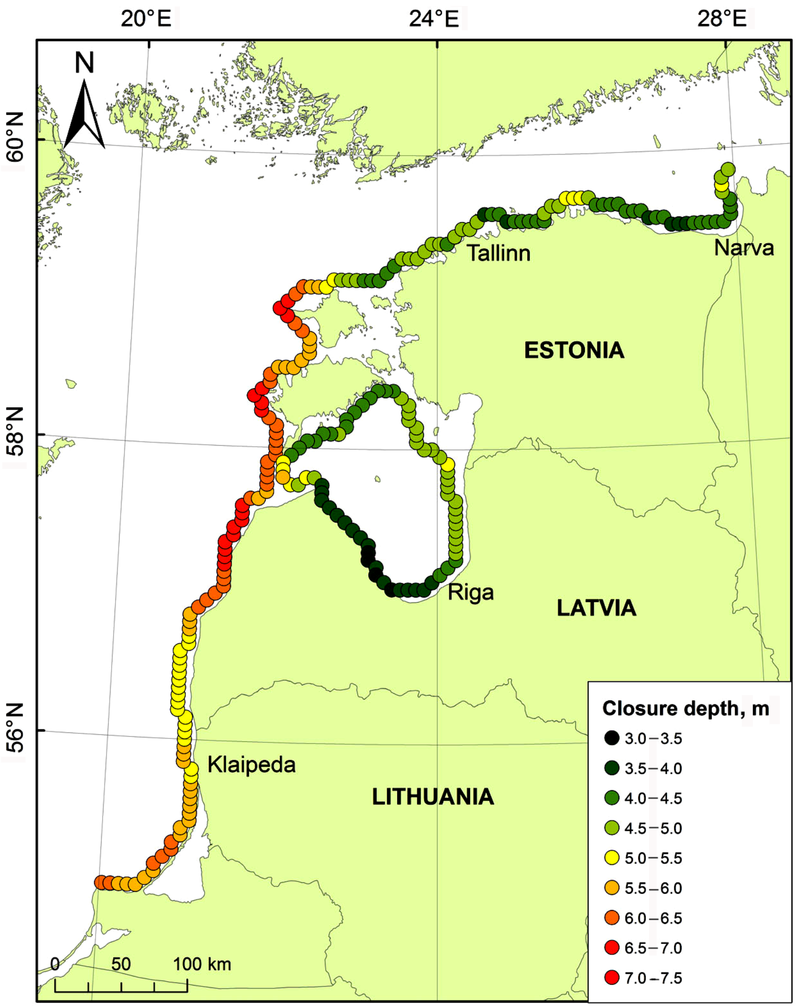


Fig. 7. Comparison of closure depths at the coasts of the Baltic Proper, Gulf of Finland and Gulf of Riga calculated using Eq. (4) with $p_1 = 1.75$ and $p_2 = 57.9$. The quantity $H_{0.137\%}$ has been calculated over the entire time interval 1970–2007.

As expected, the closure depth is clearly smaller in the Tallinn Bay area. Because the wave properties for this area were calculated not only with a much finer resolution but also at grid points located relatively close to the coast, the wave model was able to account for most of the wave transformation and decay in the nearshore. For this reason the closure depth even for the most open sections in this domain is smaller than the corresponding values estimated using the coarse model. Typical values of the closure depth in this region are in the range of 2.5–3.5 m, which is about 1 m smaller than the estimates using the coarse model. In several bayheads the closure depth drops to 1.5 m, whereas it reaches over 4 m along a number of headlands.

Apart from the very strong alongshore variability of the closure depths in this region, an interesting feature is that the values calculated using Eq. (4) with $p_1 = 1.75$, $p_2 = 57.9$ deviate in some places from the estimates derived using the simpler expressions (3) and (3′), but match the values obtained using Eq. (4) with $p_1 = 2.28$, $p_2 = 68.5$. Such areas are characterized by exceptionally low $H_{0.137\%}/H_{\text{mean}}$ ratios (cf. Fig. 5). These values, however, are in the range of 4–4.5 and thus only slightly smaller than the typical values for the open ocean coasts. This feature once more highlights the intrinsic difference of the Baltic Sea wave climate from that in many other parts of the world oceans and stresses the point that the generic approximations and relationships derived from the wave properties along open ocean coasts may fail in the Baltic Sea conditions.

4. DISCUSSION AND CONCLUSIONS

The results reveal a substantial difference in the wave statistics for open ocean coasts and for the coasts of semi-sheltered basins. While in both coastal settings the ratio between certain higher quantiles of wave heights and the average wave height varies insignificantly, this ratio ($H_{0.137\%}/H_{\text{mean}} \cong 4.5$ for open ocean coasts) is much larger (approximately 5.5) along the eastern Baltic Sea coasts. This difference is evidently related to the proportion of remote swell in the particular coastal stretch. Along ocean coasts, relatively low-amplitude swell is known to substantially contribute to the total wave energy and its flux [39], whereas extreme wave heights are mostly governed by severe local storms. The absence of this remote component of wave energy is the most plausible explanation for the observation that the mean wave energy levels along the coasts of sheltered seas are much lower in comparison to those associated with extremely large wave heights of open ocean coasts. This observation is implicitly supported by a clearly lower ratio of the extreme and average wave heights in the Tallinn Bay area. This area is sheltered from the predominant south-westerly winds but is frequently affected by low swells generated in the Baltic Proper. This component to the wave activity increases the mean wave height and leads to a certain decrease in the ratio in question; particularly in bays that are even more sheltered.

An important consequence of the analysis is that the simple equations for the evaluation of the closure depth, based on the average wave height and derived for open ocean conditions, have to be modified for the use in semi-sheltered regions. In areas where remote swell is virtually absent (such as the Baltic Proper), a suitable expression for the closure depth is $h_c^B \cong 1.5H_{0.137\%} \cong 8.25H_{\text{mean}}$. This expression may need further modification for certain sub-basins that experience an appreciable level of remote swells such as the Gulf of Finland that is widely open to the Baltic Proper. This peculiarity, however, does not modify the role of the highest waves in shaping the coastal profile and Eq. (3) in terms of $H_{0.137\%}$ is evidently applicable to all coastal regions, even if it reflects extreme wave properties for several shorter storms.

The alongshore distribution of closure depths in the three basins, considered here, basically corresponds to similar variations in extreme wave heights. The largest closure depths of up to 7.25 m along the Baltic Proper occur in areas experiencing the largest wave intensities, whereas much smaller closure depths (usually well below 5 m) are found in the Gulf of Riga and along the southern coast of the Gulf of Finland. In more sheltered bays the closure depth may be even smaller (about 2 m).

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Lainekoormuste ja sulgemissügavuste muutlikkus Läänemere idarannikul

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Sulgemissügavus iseloomustab lainetuse intensiivsust rannikuvööndis ja kirjeldab, millise sügavuseni kujundavad tormilained tasakaalulise rannaprofiili. Selle parameetri väärtused on leitud aastaiks 1970–2007 rekonstrueeritud tormilainete omaduste alusel lahutusvõimega 5,5 km piki kogu Läänemere idarannikut Sambia poolsaarest Soome lahe idaosani ja Liivi lahes nelja erineva metoodika abil. Sulgemissügavused Tallinna lahe ümbruses on leitud aastaiks 1981–2012 rekonstrueeritud lainetuse omaduste alusel lahutusvõimega 500 m. On näidatud, et kõrgeimate lainete (mida iseloomustab aastas keskmiselt 12 tunni jooksul esinev oluline lainekõrgus) ja keskmiste lainekõrguste suhe nimetatud rannikualadel on ligikaudu 5,5, mis ületab selle suhte väärtuse avaookeani rannikutel enam kui 20% võrra. Erinevus on tingitud ummiklainete väikesest osakaalust Läänemere lainetuses. On tuletatud sulgemissügavuse arvutusvalemi Läänemere tingimuste jaoks sobiv modifikatsioon. Suurimad sulgemissügavused (kuni 7,25 m) paiknevad Läänemere avaosa põhjapoolses sektoris Hiiumaa, Saaremaa ja Kuramaa rannikualal. Läänemere avaosa teistes rannikulõikudes on sulgemissügavus üldiselt vahemikus 5–6 m, Soome ja Liivi lahes 3–4 m.