Climate change related increase of storminess near Hel Peninsula, Gulf of Gdańsk, Poland
Grzegorz R. Cerkowniak, Rafał Ostrowski and Piotr Szmytkiewicz

ABSTRACT

The paper deals with the growing threat of erosion to the south Baltic coast, caused by the intensification of a wind-induced wave climate and sea level rise, which is expected to continue until 2100 as a result of climate change. In the analysis, a deep-water wave prognostic point is located about 13 km north-east of the Hel Peninsula, situated in the NW part of the Gulf of Gdańsk. The study comprises the analyses of wind velocity, storm surge, wave height, wave set-up and wave run-up. A significant predicted increase in wave heights during extreme storms, compared with the wave climate reconstructed for 1958–2001, combined with anticipated higher storm surges, is expected to result in a lower resilience of the sea shore to erosion and flooding. Although nourishment operations conducted along the open sea shore of the Hel Peninsula have proved efficient and successful, nourishment needs will have to be adequately recalculated in future to ensure sufficient protection of this coastal segment.

Key words | climate change, Gulf of Gdańsk, storm surge, wave climate, wind, wind climate

INTRODUCTION

South Baltic sandy shores are subject to erosion at many locations and require protection, similarly to a number of other European coastal segments (e.g., European Commission 2004). For the Hel Peninsula (see Figure 1), this protection is extremely important and absolutely necessary. Inhabited permanently by about 10,000 people, the peninsula is visited by more than 1 million tourists every year. With an area of about 32 km², the peninsula has a population density of c. 313 inhabitants per km², which is about 2.5 times more than the average in Poland. The communications between the towns and villages of the Hel Peninsula and Władysławowo, located at its root, are provided by one road and one railway line, which not only serve tourists and local inhabitants, but are also the only supply lines for numerous institutions and companies situated on the peninsula. Coastal erosive phenomena, which have been observed since the 1940s, constitute a serious threat to these supply lines and other facilities located in the vicinity of the shoreline (Różyński et al. 1999).

On the strength of the Act of Parliament of the Republic of Poland (28 March 2003) on the establishment of a long-term ‘Coastal Protection Programme’, the safe maintenance of the shores of the Hel Peninsula is provided by a system of sediment bypassing at the harbour of Władysławowo and by artificial beach nourishment along the shore segment stretching 23.5 km south-eastwards from Władysławowo. In addition to shore protection measures, the above-mentioned parliamentary act and a governmental directive (29 April 2003) concerning the width of the coastal technical/protective belt recommend coastal monitoring and research aimed at identifying the most threatened shore segments. These activities are carried out by the Maritime Office in Gdynia (a governmental agency whose responsibilities include coastal management) with important support from scientific institutions, including the Institute of Hydro-Engineering of the Polish Academy of Sciences (IBW PAN).

Coastal research provides a basis for nourishment interventions along specific shore segments identified as the most vulnerable to erosion. So far, extensive nourishment
operations have proved to be efficient and successful in protecting the coast of the Hel Peninsula against erosion and flooding.

Extreme wave parameters play a key role in erosion and flooding processes. The future scenarios for these processes on the Hel Peninsula depend on extreme conditions that may result in the erosion of its shore and the breach of the dune system. Created by shore nourishment, the artificial beaches and dunes of the Hel Peninsula have been designed to satisfy the safety standard of resisting a storm with a return period of 100 years. The same standard ought to be applied to the forcing anticipated in the next decades.

The Baltic Sea has been increasingly stormy in winter in recent decades. This phenomenon has been particularly pronounced in January, but notable also in February and October. In November and December, it has been
discernible, but barely significant (see Różyński & Pruszak 2010). The wave impact coincides with an accelerated rise in sea level, particularly dangerous to some segments of the Polish coast, including its eastern part with the Gulf of Gdansk and the Hel Peninsula (Pruszak & Zawadzka 2008). Future wave and sea level scenarios, developed by Miętus (2011) on the basis of global climatic scenarios, suggest that hydrodynamic conditions in the south Baltic will become more severe in the 21st century, particularly in the period 2081–2100.

The authors of the present study have carried out computations and analyses to find out whether and to what degree the predicted climate changes will affect hydrodynamic processes that directly influence coastal morphodynamics. The lithodynamic equilibrium of the open sea shores of the Hel Peninsula definitely depends on artificial beach nourishment. The question arises whether the increasing storminess, represented by future growth of parameters of wave-related phenomena, will be quantitatively high enough to endanger the Hel Peninsula shores. The present paper is an attempt to answer this question.

**DATA AND METHODS**

**Reconstructed wind and wave climate**

The offshore wave climate was determined on the basis of the numerical prognostic wave model WAM4 (WAMDI Group 1988), in which the input is determined from meteorological (wind and air pressure) fields. Several years ago, the spectral wave model WAM4 was used under the HIPO-CAS project (coordinated by HZG, former GKSS, Germany), aimed at reconstructing the long-term European wave climate from 1958 to 2001. The reconstruction procedure is described in detail by Weisse et al. (2009). In brief, a global reanalysis by the National Centers for Environmental Prediction-National Center for Atmospheric Research (NCEP-NCAR) (Kalnay et al. 1996) was applied in combination with the spectral nudging technique (von Storch et al. 2000) as the forcing to the REgional Climate MOdel (REMO), which is based on the numerical weather prediction model EM of the German Weather Forecast Service (Feser et al. 2001). In this way, wind parameters (velocity and direction) at a height of 10 m above the sea and pressure fields were obtained. The results from the REMO model were subsequently used in the WAM4 model.

The WAM4 model is based on a so-called wave action balance equation and takes into account the energy transfer from wind to the sea, ‘white-capping’ wave breaking, bottom friction and resonance interactions of wave components. For the reconstruction of Baltic waves, the model resolution of the spatial grid was 5′ × 5′ (angular minutes). The model time step of the input wind data was set to 1 hour. This input was then interpolated, which yielded a computational resolution of 300 s. At each grid point for every hour of the 44-year-long reconstruction period, the computational results comprised the following representative wave parameters: significant wave height, wave period and wave ray direction.

The results of the wave climate reconstruction (1958–2001) described above were used to determine offshore wave parameters for the Hel Peninsula. A deep-water wave prognostic point was chosen to represent waves coming from a direction favourable for the largest wind fetch, namely the NE sector. Such a representative wave prognostic point is located 13 km north-east of the central part of the Hel Peninsula (see Figure 1). The coordinates of this point and the corresponding approximate local water depth are 54.8° N, 18.8° E, h ≈ 90 m.

**Forecasted extreme wind conditions**

The modelling of wave motion was based on wind parameters determined by the climatic simulation A1B_1 (the first run of the global IPCC scenario A1B). The analysis dealt with values with a probability of exceedance of 1% (i.e., those with a 100-year return period) and 10% (corresponding to a return period of 10 years).

It should be noted that more climatic scenarios and simulations were considered in the first steps of the current study. The analysis of the wind climate anticipated by the other scenarios/simulations, namely A1B_2, B1_1 and B1_2, revealed fairly similar wind velocity patterns to be expected in future at the study site. In the core phase of the study, the research was based on the simulation...
most extreme waves in the Gulf of Gdansk offshore from which produce the longest fetch and thus generate the dimensional spectral predictive method by Krylov speed, direction and fetch. The model is based on a two-dimensional spectral predictive method by Krylov

Forecasted extreme wave conditions

The extreme wind parameters calculated in the way described above were used to obtain extreme wave parameters with PROGNOZA model. The PROGNOZA model, developed at IBW PAN, is routinely used for predicting deep-water wind wave parameters on the basis of wind speed, direction and fetch. The model is based on a two-dimensional spectral predictive method by Krylov et al. (1976), which involves semi-empirical equations of the following form:

\[
g_H = 0.16(1 - A_x^2) \tanh \left[ 0.625 \left( \frac{gH}{W^2} \right)^{0.8} (1 - A_x^2)^{-1} \right]
\]

with \( A_x = 1 + 0.006 \left( \frac{gX}{W^2} \right)^{0.5} \)

\[
g_T = 6.2\pi \left( \frac{gH}{W^2} \right)^{0.625}
\]

where \( g \) [ms^{-2}] is the acceleration due to gravity, \( H \) [m] is mean wave height, \( W \) [m/s] is wind speed, \( X \) [m] is wave fetch and \( T \) [s] is mean wave period.

A comparative review of wave prediction models carried out by Massel (1996) showed that Krylov’s model yielded as good results as a number of other models. The explanation of Krylov’s approach for deep water, as well as its extension for finite water depths (water basins of small and moderate depths, like the Baltic Sea), can be found in Massel (1996).

This approach takes into account an arbitrary shoreline layout and bathymetric variability along each directional spectral component. It assumes a directional wave energy distribution, proportional to \( \cos^2 \alpha \) in a range of \( \pm 90^\circ \) from the wind direction (where \( \alpha \) are angles between the wind direction and individual directional components). Each directional sector covers 22.5°, and the rays in all directions are divided into segments of constant depth, maximum 40 NM long. For each segment, the depth is averaged for a 20-NM wide strip. The agreement between the measured and modelled deep-water wind wave parameters is good for the conditions of open sites, undisturbed by headlands, harbour breakwaters, etc. The model yields wave parameters at the offshore deep water boundary of a coastal zone.

Before predictive simulations were run, the wave model had been calibrated with wind and wave data reconstructed for the period 1958–2001. During the calibration, the wave prediction model was tuned in such a way that for extreme wind conditions it yielded the same wave height values as the ones resulting from the wind/wave climate reconstruction.
Two-dimensional analysis of extreme storm surges and waves in a changing climate

The prediction of extreme water levels (storm surges) which may occur simultaneously with extreme waves is important both for the safety of inhabitants of coastal regions and in the formulation of engineering requirements (design parameters, e.g., hydrodynamic forces on coastal structures). In the present case, the extreme value distributions of storm surges and wind velocities are used to define extreme storm surges occurring simultaneously with extreme wind-driven offshore (deep-water) waves. These wave and sea level scenarios are based on a long-term climatic forecast.

The CERA database does not contain water levels. Therefore, the data comprising the monthly 99th percentiles of the water level (basing also on the long-term global climatic scenario A1B_1) anticipated in the nearby Władyśląwowo harbour (see Figure 1) for the period 2001–2100 were obtained from the Institute of Meteorology and Water Management (IMGW) in Gdynia. Because both wind-wave and sea level (storm surge) scenarios are based on the same long-term global climatic scenario, they have the same physical background and can be assumed to be mutually consistent.

First, in order to carry out a consistent analysis of the 99th percentiles of both water level and wind velocity, the monthly values of the 99th percentile of wind velocity were calculated. Then the maximum annual values of the monthly 99th percentiles of both water level and wind velocity were selected. In this database, three representative time slices were distinguished: 2001–2020, 2001–2050 and 2040–2100. For all these time slices, joint probability analyses were carried out.

Joint probability analysis refers to joint occurrences of two parameters (wind velocity and water level) and yields extreme pair values. In all calculations, the annual maximum values of the monthly 99th percentiles of wind velocity and water level were considered. First, parameters of the generalised extreme value (GEV) analysis were determined separately for wind velocity data and water level data. The GEV parameters are essential for the joint probability analysis. Different models of the joint probability distribution are available (e.g., logistic model, and bilogistic model). Several studies have shown that all these models describe the distribution of two-dimensional data equally well, and the final estimate of return levels is not sensitive to the choice of the model (Tawn 1988; Yue 2001; Yue & Wang 2004). Here, the logistic model, which is relatively simple in form, was applied to calculate joint extreme value distributions for wind velocity and water level. The distributions were approximated by the least-square fitting.

Wave set-up scenario for the Hel Peninsula

Extreme sea water levels in the direct vicinity of the shoreline depend on storm surge and wave set-up effects. The latter results from the wave transformation process on the cross-shore profile, including the wave radiation stress phenomenon.

Wave set-up quantities were calculated as part of the modelling of wave transformation by the Battjes & Janssen (1978) approach, adapted by the IBW PAN research team to a multi-bar coastal zone and multiple wave breaking (e.g., Szmytkiewicz 2002). Computations were carried out for the following three cross-shore profiles selected along the coast of the Hel Peninsula:
- at the root of the Hel Peninsula (0.0);
- 10 km from the root (10.0);
- 20 km from the root (20.0).

The input deep-water (offshore) wave parameters were assumed in accordance with the previously determined wave scenario.

RESULTS AND DISCUSSION

The results of computations of the cumulative probability distributions of the maximum annual values of the wind velocity for the periods 1960–2020, 1990–2050 and 2040–2100 are given in Figure 2, whereas the values corresponding to 1 and 10% probabilities of exceedance are given in Table 1.

It can be seen that the anticipated representative extreme wind velocities (mean values) increase systematically in the consecutive periods 1960–2020, 1990–2050 and 2040–2100. It should be noted that the wind speed with a return period of 100 years reconstructed at the considered location for 1958–2001 is only 19.85 m/s.
The extreme wind with the parameters derived above was assumed uniform over the entire Baltic Sea. Such an assumption for the Baltic Sea during a heavy storm is realistic - the experience (e.g., the most intensive storm ever recorded of 14–16 October 2009) shows that extreme storm impacts (and loads on coastal structures) are caused by waves generated by persistent wind fields, which are homogeneous over the entire basin. The assumption that extreme wind conditions last several hours and are uniform over the (relatively small) Baltic Sea represents the worst

![Figure 2](https://iwaponline.com/jwcc/article-pdf/6/2/300/375724/jwc0060300.pdf)

Cumulative probabilities: 'empirical' maximum annual wind velocity values and approximations by the Gumbel distribution for the periods: (a) 1960–2020 (goodness of fit $R^2 = 0.9840$); (b) 1990–2050 (goodness of fit $R^2 = 0.9840$); (c) 2040–2100 (goodness of fit $R^2 = 0.9943$).
meteorological, hydrological and hydrodynamic situation and can therefore be applied in formulating the critical erosive scenario.

The results of the numerical prediction of wave heights with the two selected probabilities of exceedance for the periods 1960–2020, 1990–2050, 2040–2100 and reconstructed for the period 1958–2001 are given in Table 1. The bolded quantities denote wave heights to be used in future for determining the values of design parameters applied in the planning of coastal protection against erosion and flooding on the Hel Peninsula.

The increase in the 100-year wind speed from 19.85 m/s in the period 1958–2001 (reconstruction) to 26.13 m/s in the period 1960–2020 (reconstruction until 2001 + prediction after 2001, see Table 1) results in a considerable increase in the 100-year wave height to 10.54 m (from 8.12 m reconstructed for the period 1958–2001). Further notable increases in the 100-year wave height are seen in the next periods of prediction, up to 11.63 m in the period 2040–2100.

The 100-year wave height is a contemporary offshore design input value for coastal structures on the Hel Peninsula. Since it is the parameters of waves in the vicinity of a structure that should be considered in its design, the deep-water wave height needs to be recalculated taking into account wave transformation along a representative cross-shore profile.

The role of long waves can be regarded as relatively small. In the Baltic Sea, the periods of swell and wind waves typically last 4–7 s and never exceed 10–12 seconds, so all wind-driven waves are short waves. Field measurements carried out by IBW PAN have shown that other types of waves (e.g., infragravity waves) appear sporadically, and their heights very rarely attain 0.1–0.15 m. Seiches in the Baltic are most often related to storm surges, which are taken into account in the present study. Baric waves are another type of Baltic seiches, but these are much smaller than wind-induced storm surges. Owing to the specificity of baric fields over the Baltic Sea, it is unlikely that baric-type seiches overlap with storm surges. Thus, the critical water level is related to storm surge and wave set-up.

The maximum annual values of the monthly 99th percentiles of water level and wind velocity are presented in Figure 3. It can be seen in Figure 3 that coincidences of

![Figure 3](https://iwaponline.com/jwcc/article-pdf/6/2/300/375724/jwc0060300.pdf)

**Figure 3** | Maximum annual values of the monthly 99th percentiles of water level and wind velocity on the Hel Peninsula predicted for the 21st century.

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**Table 1** Mean wind velocities \( W \) and significant wave heights \( H_s \) for a return period of 100 years (exceedance probability of 1%) and 10 years (exceedance probability of 10%) calculated from the Gumbel distribution approximations of annual maxima reconstructed for the period 1958–2001 and predicted for the periods 1960–2020, 1990–2050 and 2040–2100

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<tbody>
<tr>
<td>( W ) [m/s]</td>
<td>( H_s ) [m]</td>
<td>( W ) [m/s]</td>
<td>( H_s ) [m]</td>
<td>( W ) [m/s]</td>
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<tr>
<td>100/1</td>
<td>19.85</td>
<td>8.12</td>
<td>26.13</td>
<td>10.54</td>
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<tr>
<td>10/10</td>
<td>16.78</td>
<td>6.27</td>
<td>20.37</td>
<td>8.51</td>
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peak values of water level and peak velocity are rare which suggest that these variables can be assumed statistically independent. On the basis of the analysis of archival data, the long-term mean sea level in the south Baltic (on the Polish coast) used to be set to 500 cm. Recently, owing to sea level rise, slightly higher values have been suggested for use, namely 504–505 cm.

Figure 4 shows the histograms and the cumulative probability distributions of the maximum annual values of the monthly 99th percentiles of water level and wind velocity for the period 2001–2100. The cumulative probability distributions were approximated by the GEV distribution, commonly applied to predict the probability of future extreme events (Huang et al. 2008; Warner & Tissot 2012). The GEV distribution is a generalised form of the Gumbel approach and frequently yields very similar results (Li et al. 2008). These approximations, carried out by means of GEV, appeared to be slightly more accurate than the approximations obtained by the Gumbel distribution. The calculation results for GEV are therefore presented in Figure 4.

Figure 5(a) displays two isolines of the joint extreme cumulative probability for the period 2001–2100. These isolines correspond to cumulative probabilities of 0.9 and 0.99, that is, exceedance probabilities of 10% and 1% (return periods of 10 and 100 years, respectively).

Figures 5(b)–5(d) show the isolines of the joint extreme cumulative probability of wind velocity and water level for the years 2001–2020, 2001–2050 and 2040–2100, respectively.

The goodness of fit values ($R^2$), also given in the caption of Figure 5, can be regarded as good for all the time slices (except for 2001–2050, Figure 5(c)).

The correlation coefficient values shown in the caption of Figure 5 indicate that the variables are practically independent. This is not surprising in view of Figure 3. The lack of correlation between extreme water levels and wind velocities may result from the fact that the local water level depends not only on wind conditions in the adjacent area, but also on other factors (e.g., baric and wind fields over the entire Baltic). In particular, the layout of depressions and high pressure areas implies various wind velocities and directions at the individual marine locations. For instance, a very strong wind can be accompanied by high or low water level if it blows landwards or seawards, respectively.

Shown in Figures 5(b) and 5(d), the isolines resulting from the two-dimensional analysis of extreme storm surges and wind velocities anticipated in the years 2001–2020, 2001–2050 and 2040–2100 reveal a considerable increase in maximum values in the consecutive time slices. This increase is evident for cumulative probabilities of both 0.9 and 0.99, that is, exceedance probabilities of both 10% and 1% (return periods of 10 and 100 years, respectively).

It can be seen from Figures 5(b)–5(d) that the extreme pair values may occur for various water levels and wind velocities. Particular extreme situations take place for the maximum water level and the corresponding wind velocity, as well as for the maximum wind velocity and the corresponding water level. Such pairs of parameters, defining extreme events (in the context of either water level or wind velocity) with a 10-year return period and a 100-year return period are presented in Table 2.

Extreme wind conditions produce extreme wind-driven waves. Table 3 presents the numerical predictions (by PROGNOZA model) of the heights of waves generated by extreme wind velocities specified in Table 2, which define extreme events represented either by the maximum water level and the corresponding wave height or by the maximum wave height and the corresponding water level with return periods of 10 and 100 years, respectively.

The quantities given in Table 3 have been obtained for wind blowing from the azimuth $7^\circ$ (the direction for which the wind generates the highest offshore waves near the Hel Peninsula) and can be helpful in determining the design wave parameters in the nearshore zone. Nearshore wave parameters depend on conditions in which wave transformation takes place. Such processes as wave refraction and breaking are distinctly controlled by instantaneous depths on the cross-shore profile; they result directly from the water level in a given hydrological situation. Therefore, one can expect a situation in which the nearshore wave height resulting from higher offshore waves may be smaller than the nearshore wave height resulting from lower offshore waves. This may happen if the storm surge (represented by the extreme water level) corresponding to higher offshore waves is considerably smaller than the storm surge corresponding to lower offshore waves. Such
a case is possible, e.g., for the parameters given in the last row of Table 3 (a higher surge with a lower wave versus a smaller surge with a higher wave).

The mean water level in the model was raised by the storm surge value with a 1% probability of exceedance, namely by 1.74 m (resulting from the highest
Thus, the computational cross-shore profiles became deeper by the above quantity. The results of wave set-up prediction are given in Table 4.

The inclusion of wave set-up (attaining at least 0.4 m in extreme stormy conditions) in the analysis of coastal flooding threats seems necessary, as the wave set-up phenomenon constitutes boundary conditions for the

### Table 2 | Predicted particular cases of water level and wind velocity W for 10-year return period ($P = 0.9$) and 100-year return period ($P = 0.99$)

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<td>$P = 0.9$</td>
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<tr>
<td>2001–2020</td>
<td>607</td>
<td>22.3</td>
<td>592</td>
<td>26.5</td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>2001–2050</td>
<td>630</td>
<td>22.3</td>
<td>601</td>
<td>26.8</td>
<td></td>
<td></td>
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<tr>
<td>2040–2100</td>
<td>659</td>
<td>22.8</td>
<td>615</td>
<td>29.5</td>
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<tr>
<td>$P = 0.99$</td>
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<tr>
<td>2001–2020</td>
<td>610</td>
<td>24.5</td>
<td>603</td>
<td>27.0</td>
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<tr>
<td>2001–2050</td>
<td>638</td>
<td>25.4</td>
<td>621</td>
<td>28.6</td>
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<td></td>
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<tr>
<td>2040–2100</td>
<td>674</td>
<td>26.5</td>
<td>638</td>
<td>30.5</td>
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</table>
The above increase in wave height will intensify the wave impact on the sea shore. Although wave energy is subject to considerable dissipation along the multi-bar cross-shore profile of the Hel Peninsula, wave-induced currents may cause a severe erosion of the beach, the dune toe, and the dune itself, leading to dune breaching and the flooding of the hinterland. The direct threat of this phenomenon to the dune system is distinctly amplified by storm surge and wave set-up. As presented in Table 4, the latter, calculated for the root part of the Hel Peninsula, amounts under extreme conditions (100-year return period) to 0.39 m in 1960–2020, as well as in 1990–2050, and to 0.40 m in 2040–2100. For the locations 10 and 20 km away from the root, wave set-up values attain even higher values, up to 0.55 m. These quantities should be added to the corresponding extreme storm surge, which will increase to 1.74 m in 2040–2100. The long-term rise in the mean sea level has not been taken into consideration because of a wide scatter in various predictions, from about 0.21–0.35 m (Miętus 2011) to 0.28–0.97 m (Wong et al. 2014) in one century.

In sum, the sea level under extreme conditions may rise to 2.14–2.29 m in the long-term scenario. The height of wave run-up on the seaward slope of the dune during the extreme storm can be assumed as at least 0.5 m. Under such conditions, erosion of the dune foot is unavoidable. The situation of the extreme sea level rise on the cross-shore profile of the Hel Peninsula 1 km SE of its root is shown in Figure 6.

The relatively small run-up height results from the fact that the wave energy is gradually dissipated on the shoreface which generally has a very mild inclination (c. 1–1.5%) at this site. During transformation on this typically dissipative cross-shore profile, the wave height decreases considerably, and the ultimate erosive impact on the dune is limited. On the other hand, one ought to remember that the wave energy dissipation process mobilises sea bed grains and initiates bottom changes along the entire cross-shore profile, including the storm-driven erosion in the nearshore zone. This process is less dependent on the instantaneous water level and seems to be more destructive to the sea shore in the long term, whereas the wave run-up phenomenon, although directly affecting the dune, is a mechanism active only during high water levels. It can be concluded that the maximum wave set-up range delineates the area at the boundary of which one can encounter conditions favourable for dune erosion driven by wave run-up. In other words, the extreme water level indicates the level at which dune erosion, driven by run-up (swash) processes, becomes

### Table 4

<table>
<thead>
<tr>
<th>Time slice</th>
<th>$H_s$ [m]</th>
<th>$\tau$ (s)</th>
<th>$L$ [m]</th>
<th>$\eta_{0.0}$ [m]</th>
<th>$\eta_{10.0}$ [m]</th>
<th>$\eta_{20.0}$ [m]</th>
<th>$\eta_{\text{mean}}$ [m]</th>
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<tr>
<td>1960–2020</td>
<td>10.54</td>
<td>10.9</td>
<td>128.9</td>
<td>0.39</td>
<td>0.43</td>
<td>0.51</td>
<td>0.44</td>
</tr>
<tr>
<td>1990–2050</td>
<td>11.14</td>
<td>11.1</td>
<td>134.3</td>
<td>0.39</td>
<td>0.45</td>
<td>0.53</td>
<td>0.46</td>
</tr>
<tr>
<td>2040–2100</td>
<td>11.63</td>
<td>11.3</td>
<td>138.7</td>
<td>0.40</td>
<td>0.46</td>
<td>0.55</td>
<td>0.47</td>
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### CONCLUSIONS

Owing to the predicted considerable increase in wind speed, the deep-water significant wave height for storms with a 100-year return period may grow in the Hel Peninsula region from $H_s = 8.12$ m, reconstructed for 1958–2001, up to 11.63 m in 2040–2100.

The above increase in wave height will intensify the wave impact on the sea shore. Although wave energy is subject to considerable dissipation along the multi-bar cross-shore profile of the Hel Peninsula, wave-induced currents may cause a severe erosion of the beach, the dune toe, and the dune itself, leading to dune breaching and the flooding of the hinterland. The direct threat of this phenomenon to the dune system is distinctly amplified by storm surge and wave set-up. As presented in Table 4, the latter, calculated for the root part of the Hel Peninsula, amounts under extreme conditions (100-year return period) to 0.39 m in 1960–2020, as well as in 1990–2050, and to 0.40 m in 2040–2100. For the locations 10 and 20 km away from the root, wave set-up values attain even higher values, up to 0.55 m. These quantities should be added to the corresponding extreme storm surge, which will increase to 1.74 m in 2040–2100. The long-term rise in the mean sea level has not been taken into consideration because of a wide scatter in various predictions, from about 0.21–0.35 m (Miętus 2011) to 0.28–0.97 m (Wong et al. 2014) in one century.

In sum, the sea level under extreme conditions may rise to 2.14–2.29 m in the long-term scenario. The height of wave run-up on the seaward slope of the dune during the extreme storm can be assumed as at least 0.5 m. Under such conditions, erosion of the dune foot is unavoidable. The situation of the extreme sea level rise on the cross-shore profile of the Hel Peninsula 1 km SE of its root is shown in Figure 6.

The relatively small run-up height results from the fact that the wave energy is gradually dissipated on the shoreface which generally has a very mild inclination (c. 1–1.5%) at this site. During transformation on this typically dissipative cross-shore profile, the wave height decreases considerably, and the ultimate erosive impact on the dune is limited. On the other hand, one ought to remember that the wave energy dissipation process mobilises sea bed grains and initiates bottom changes along the entire cross-shore profile, including the storm-driven erosion in the nearshore zone. This process is less dependent on the instantaneous water level and seems to be more destructive to the sea shore in the long term, whereas the wave run-up phenomenon, although directly affecting the dune, is a mechanism active only during high water levels. It can be concluded that the maximum wave set-up range delineates the area at the boundary of which one can encounter conditions favourable for dune erosion driven by wave run-up. In other words, the extreme water level indicates the level at which dune erosion, driven by run-up (swash) processes, becomes...
significant. It should be pointed out that although the highest deep-water waves near the Hel Peninsula are generated by wind directed from the NW–NE sector, the most severe shore erosion is observed during storms with waves approaching the peninsula coast from N and NE directions. This obviously results from the location and exposure of the shores of the Hel Peninsula on its open sea side.

The dune system on the Hel Peninsula is a crucial element of its morphology, protecting important hinterland objects (buildings, railway, road) from flooding and degradation. Since the 1980s, this system has been developed by extensive artificial shore nourishment. It appears from field observations (including the monitoring of coastal morphology), expert opinions and social perception that the nourishment operations and their effects satisfy the standards formulated by the Maritime Office in Gdynia on the basis of the Polish parliamentary act of 2003 concerning a strategy of coastal protection until 2023. Thorough coastal monitoring and nourishment activities ensure the maintenance of a safe shore profile along the coast of the Hel Peninsula. Adequate safety standards are achieved by a sufficiently high ordinate of the dune toe (the landward edge of the beach emerged under normal hydrological conditions), which corresponds to an elevation of 1.8 m above the long-term mean sea level.

Artificial beaches and dunes created by shore nourishment have been designed to meet the safety standards for a storm with a return period of 100 years. The same standards ought to be applied with respect to the forcing anticipated in future. Therefore, future extreme hydrodynamic conditions will have to be taken into account in planning the maintenance of the coast. It should be pointed out that the root and central parts of the peninsula have been intensively nourished in the last decade. For instance, in the period 2003–2008, the beach/dune fill volume on a 4-km-long root part of the Hel Peninsula amounted to about 250–300 m$^3$/m. Despite this intervention, the cross-shore profiles still display erosive tendencies, and the nourishment activities can hardly maintain a ‘relative’ lithodynamic equilibrium. Thus, the currently used nourishment volumes (rates) can be regarded as the boundary values, the reduction of which is impermissible. According to studies carried out by the Maritime Institute in Gdańsk, the shoreline retreat on a few coastal segments of the Hel Peninsula, including its root part, will be about 0.6 m/year if the nourishment is abandoned. In view of the anticipated increase in hydrodynamic and hydrological loads, the nourishment needs will have to be adequately recalculated. The present study shows that the predicted storminess (waves and storm surges) will cause more severe erosive threats compared with the current situation. It can therefore be supposed that the current nourishment interventions will become insufficient under the anticipated changing climatic conditions.

ACKNOWLEDGEMENTS

The study was sponsored by the Ministry of Science and Higher Education, Poland, under mission-related programme no. 2 of IBW PAN. The authors also acknowledge support from the European Commission through FP7.2009-1, contract 244104 – THESEUS (‘Innovative technologies for safer European coasts in a changing climate’). The wind forecast data (CLM data) were downloaded from the CERA.
database, whereas the sea level rise scenarios (storm surges) were courtesy of the Institute of Meteorology and Water Management (IMGW) in Gdynia.

REFERENCES


First received 21 February 2014; accepted in revised form 31 August 2014. Available online 26 September 2014.