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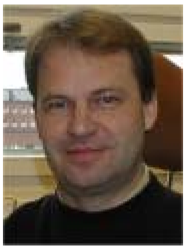

Implications of extreme waves and water levels in the southern Baltic Sea

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ABSTRACT

Several coastal areas in the south of Sweden are subjected to flooding and erosion. Such events depend on the magnitude and frequency of water levels and wave heights as well as their joint occurrence. Long time series of climate data from the south coast of Sweden were employed to investigate the statistical properties of extreme events in terms of the waves and water level changes. Through the combined analyses of waves and water levels the probability of extreme events occurring in the southern Baltic Sea was assessed. The study also established relevant probability distributions to characterize such extreme events as a basis of various risk assessments related to the impact on the coastal areas of large storms. Furthermore, an attempt was made to estimate the conditions after climate change. Based on available forecasts and scenarios of future climate change the corresponding probability distributions were determined. The study suggests that a run-up level, with a 100-year return period from today, in the year 2100 may occur up to thirteen times more frequently.

Keywords: Baltic Sea, Climate change, Erosion, Extreme waves, Flooding, Statistical analysis, Storm surge

1 Introduction

The coastline of northern Sweden is largely characterized by rocky shores with a marked glacial rebound (Lambeck 2004). In the south of Sweden, however, the landscape is low-laying and the coastline is typically made up of sandy beaches. In addition, a relative sea-level rise makes the coastal areas here generally subject to flooding and erosion (Larson and Hanson 1993). As an example, the municipality of Ystad, located along the south coast of the province Scania (see Fig. 1), has been subjected to coastal erosion for at least 150 years (Larson and Hanson 1992). Winds over the Baltic Sea generate waves which cause runup and direct erosion of the sand dunes on the beach. One of the most exposed areas is Ystad Sandskog, located to the east of the city of Ystad. Here, the beach profiles are characterized by a relatively, narrow and dry beach (foreshore) with sand dunes protecting low-lying areas shoreward of the dunes. In the case of future climate change, with increasing wave heights and water levels, the exposed coastline will suffer from greater impact in terms of erosion and flooding. This implies that popular areas, for tourism and recreation may partly or entirely disappear.

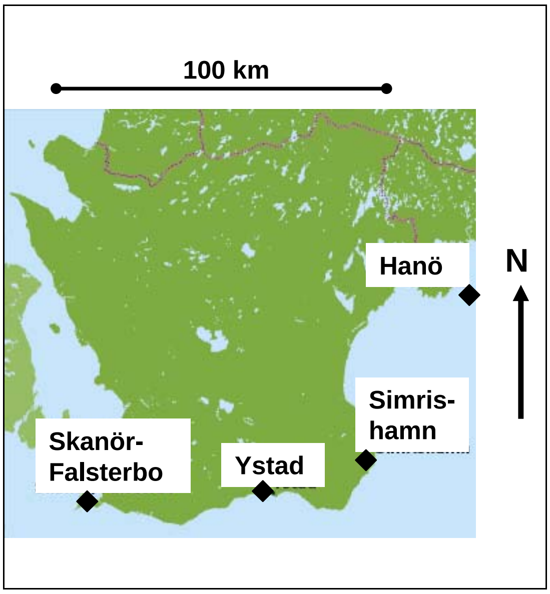


Figure 1 Map of Scania, the southern-most province in Sweden showing the location of the data sites (Ystad is the representative study site)

Another example of an area subject to serious flooding and erosion is the Skanör-Falsterbo Peninsula located on the western side of Scania (see Fig. 1). This peninsula resembles a trumpet in shape, extending about 7.5 km both in the east-west and north-south directions, covering an area of approximately 23 km^2 (Hanson and Larson 1993; Pakkan 2006). Because the peninsula constitutes a low-laying area, it is vulnerable to a future rise in sea level as well as any changes to the prevailing wave conditions. High water levels and large waves causing extreme run-up heights are already a problem, regularly damaging the area through flooding and erosion.

The main objective of this study is to jointly analyze waves and water levels, based on existing climate data, in order to assess the risk of extreme events occurring in the southern Baltic Sea with large consequences regarding flooding and erosion.

The analysis also focuses on establishing relevant distributions for assigning probabilities to such extreme events as a basis for various risk assessments related to impact on the coastal areas of large storms. Furthermore, an attempt was made to estimate the conditions after climate change based on available forecasts and scenarios.

Long time series of climate data from the south coast of Sweden were employed to investigate the statistical properties of storms in terms of the waves and water level changes. The primary sources for the analysis were wind and water level data, whereas the wave conditions and the run-up levels were derived based on mathematical relationships. Long-term measurements of waves and run-up heights were not available for the south coast of Sweden. The physical conditions along this part of the Swedish coast vary according to the hydrography, topography, morphology, and sedimentology. In most of the analysis, the conditions in the central part of the coast around Ystad were selected as being typical for this portion of the Baltic Sea. The wave conditions will be affected by the fetch length, which varies along the coast, whereas the run-up height primarily depends on the local waves and the beach slope.

The majority of the meteorological activities take place during the autumn and winter periods. If the analysis is based on calendar years there is a risk that extreme events that occur during the same winter season (December to February) will be referred to different years. Also events occurring during January-February in one year will belong to the same year as an event occurring in December the same year. Thus, the division of the data series into calendar years is not justified. Instead, the series were divided into what is referred to as climatic years. A climatic starts on July 1st of a particular year and ends on June 30th the following year. As an example, year 1983 in this report refers to the period from July 1st, 1982 to June 30th, 1983.

The statistical analysis of waves and water levels was performed in a large number of previous studies to estimate coastal flooding as well as overtopping of dunes and barrier islands. Less emphasis has been put to using statistical information on waves and water level for determining coastal erosion, although several studies were performed on dune erosion where a data base containing storm properties has been employed to derive the statistics of morphological impact on beaches. Soares (2003) provided an overview of stochastic models of waves at deep and finite water depths, including the joint probability of wave height and period. van Gelder (1996) analyzed a long time series of sea level measurements from the Netherlands in order to derive design water levels for the dikes. A Gumbel statistical model was employed to describe the annual maximum water level from which design levels were obtained. van Gelder et al. (2004) reviewed the statistical procedure to model joint probability distributions of wave height and wind speed or wind setup (surge) to analyze extreme situations. Four different approaches were compared using combinations of statistical analysis and physically based model simulations.

In the following, the measured (primary) data employed are first discussed and some of their statistical properties are revealed. Different distributions are fitted to the data and used for extrapolation to longer return periods. Then, the calculated data, including wave height and period, and run-up height are presented together with a brief background to the mathematical relationships used to compute these quantities. The probability of extreme events in terms of joint occurrence of high water levels and large waves is investigated, as well as the run-up levels derived from simultaneous time series of waves and water levels. Finally, the effect of the expected future climate conditions on primarily the run-up levels is determined based on published scenarios.

2 Measured data employed

2.1 *Wind data*

In order to analyze the wind climate, data from the Swedish Meteorological and Hydrological Institute (SMHI) stations at Falsterbo, Ystad, and Hanö were used (Fig. 1). Detailed analysis of these data indicated to what extent the different stations may be used to represent the conditions along the south Swedish coast, as well as the particular conditions in Ystad (Dahlerus and Egermayer 2005) and the Skanör/Falsterbo Peninsula (Pakkan 2006). The overall statistics for the three stations were similar, both regarding wind speed and direction. Correlation analysis of the wind speed between the stations gave the following result: Falsterbo versus Ystad 0.68, Falsterbo versus Hanö 0.63, and Ystad versus Hanö 0.68.

In total, the measured time series encompassed a period of 44 years (1961-2004). From 1961 to 1972 measurements were made every three hours starting at 3.00 and ending at 18.00, and from 1973 to 2004 measurements were also made at 21.00 and 24.00. The wind speed resolution is 1 m/s and the resolution in direction is 10 deg, although the present analysis was made with respect to the 16 compass directions. At Falsterbo, the recorded average wind speed for the entire period was 6.8 m/s and the maximum wind speed was 28 m/s. Since this data series was complete (Ystad and Hanö had some gaps) it was used in the subsequent analysis.

In order to detect whether there are any trends in the storms appearing in the southern Baltic Sea, the number of days per year with gale winds (> 18 m/s) was calculated as presented in Fig. 2 (data from Falsterbo 1961-2004). A distinct increase in such events may be observed in the period 1965-1985, but there is no evidence of a long-term trend in the wind data. An extensive analysis of the temporal variation with respect to wind directions was also performed and this analysis displayed no temporal trend either. Figure 3 shows the frequency distribution of the wind directions (data from Falsterbo 1961-2004), indicating dominance for winds coming from a sector W to S. Since the longest fetches appear in this sector, the largest waves will also arrive from these directions. The winds were used for calculating wave conditions off the central part of the coast using a model developed by Larson and Hanson (1992) based on SPM (1984), where the modification introduced by Dahlerus and Egermayer (2005) to take into account wave growth and wave decay was employed (see below).

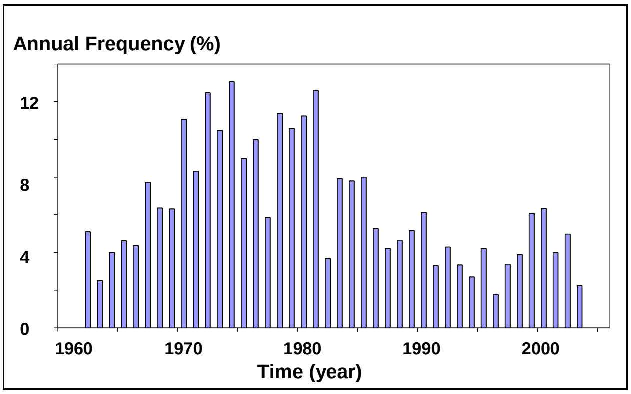


Figure 2 Annual frequency of gale winds exceeding18 m/s in Falsterbo 1961-2004

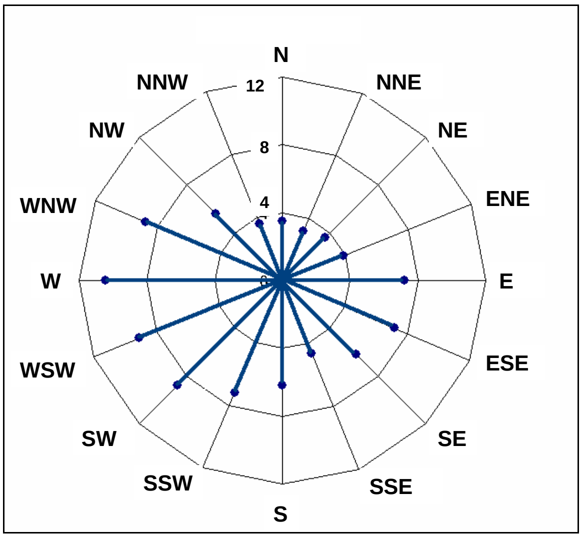


Figure 3 Frequency distribution of wind directions in Falsterbo 1961-2004

2.2 *Water level data*

Two time series of water level data were available from Ystad. The longest time series measured in Ystad extends from 1887 to 1986 and holds daily maximum, minimum, and mean water levels, whereas another shorter series (1996-2004) consists of hourly values. For the analysis of run-up levels, a detailed series of water levels is required with duration as long as possible. For this reason the short time series from Ystad was therefore supplemented by one series from Skanör (1992-2004) and another one from Simrishamn (1982-2004), both with hourly observations, to generate a time series consisting of 23 years of hourly water level observations (1982-2004). A correlation analysis between the three stations gave a basis for extending the time series of hourly water levels from Ystad.

The long time series from Ystad is shown in Fig. 4, including the annual mean water level varies over the period 1887-1986 with respect to the overall mean water level (annual mean values calculated as means of mean daily values). If a linear trend line is fitted to the data, an increase of 0.55 mm/yr in the mean water level is obtained, in agreement with the accepted rate of sea level rise along the south Swedish coast. However, the variance explained by a linear regression model is only about 15%. A singular spectrum analysis (SSA) of the annual mean water level (Vautard et al. 1992, Southgate et al. 2003), resulting in an improved description of the long-term trend, indicated that the rate of sea level rise is significantly lower during the second half of the time series compared to the first half. The lowest reconstructed component from the SSA is also plotted in Fig. 4 to illustrate the long-term trend obtained with this type of analysis.

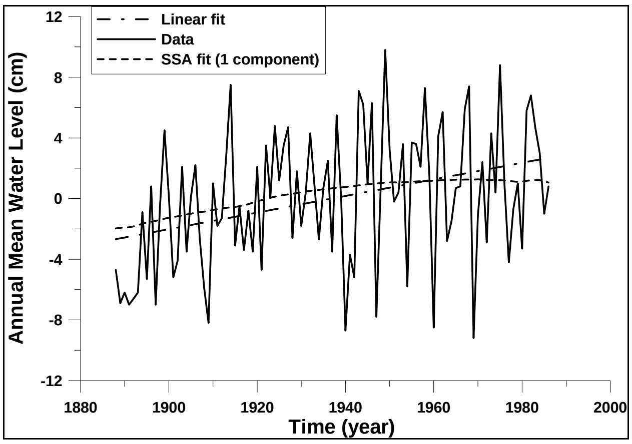


Figure 4 Annual mean water level in Ystad 1887 – 1986 together with a linear fit, resulting in an annual increase of 0.55 mm/yr, and a fit using the lowest reconstructed component from SSA

Since the measurement period is relatively short in a sea level rise perspective it is interesting to compare the present data with those of other relevant climatic variables. Fig. 5 illustrates the annual mean temperature for Sweden between 1860 and 2006 based on 37 stations together with a Gaussian-filtered signal (SMHI 2007). The three lowest reconstructed components from an SSA are also plotted as an alternative to the trend obtained with the Gaussian filtering. Three components were included from the SSA to describe the long-term trend based on the variance explained by the individual components and their general behavior. The temperature exhibits a similar variation as the mean sea level in Fig. 4 for the period 1887-1986. Thus, it is interesting to note that the mean temperature increased markedly after 1986. Similar increases in the annual mean sea level are also observed in the other shorter measurement time series of water level from Ystad and Simrishamn that extended to year 2004.

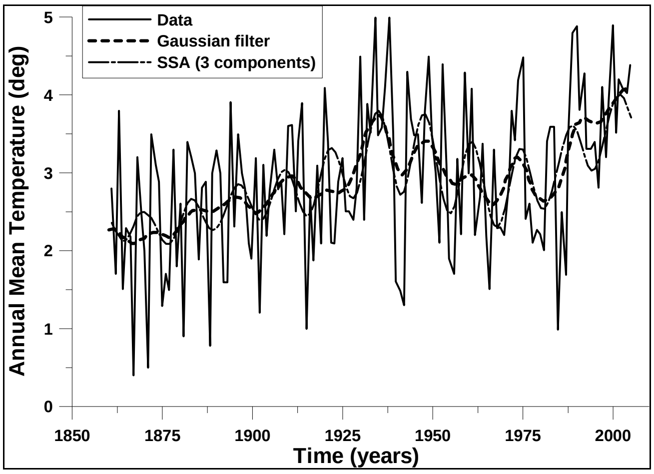


Figure 5 Annual mean temperature for Sweden 1860-2006 based on 37 stations together with a Gauss-filtered curve with three standard deviations and a curve based on the four lowest reconstructed components from SSA (partly after SMHI 2007).

Figure 6 illustrates the annual maximum water level in Ystad (1887-1986) derived from the daily observed maximum levels. As opposed to the annual mean water level (Fig. 4), the annual maximum water level does not seem to display any trend in time, with the two largest water levels observed in the early part of the 1900's. To investigate the probability of a certain water level being exceeded annually, the data were plotted with the Gringorten (1963) plotting position formula and a Gumbel distribution was fitted to the data. This distribution function is given by

$$G(z) = \exp\left(-\exp\left(-\left(\frac{z-\mu}{\sigma}\right)\right)\right) \tag{1}$$

where z is the annual maximum water level, μ a location parameter, and σ a scale parameter. The Gringorten formula estimates the return period T_R for a specific event in a time series of annual values being exceeded as

$$T_R = \frac{N+0.12}{n-0.44} \tag{2}$$

where N is the number of events recorded and n is the order of the event with return period T_R, where the events are ordered from the largest (number one) to the smallest. Thus, plotting the value associated with a certain event against the reduced value $y = -\ln(-\ln(1-1/T_R))$ yields a straight line, if the Gumbel distribution is adequate to the data (Yevjevich 1972).

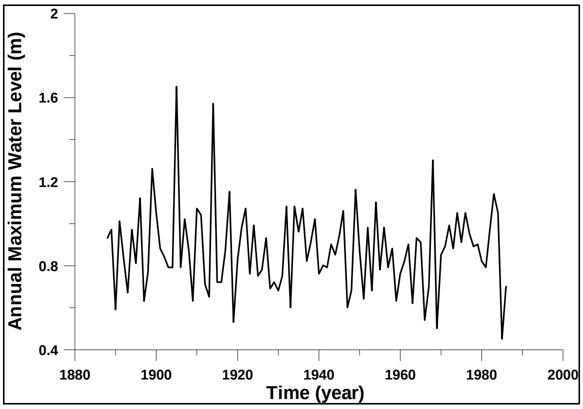


Figure 6 Annual maximum water level in Ystad 1887 - 1986

Figure 7 displays the annual maximum water level plotted against the reduced value together with a fitted straight line. The correlation coefficient of the fit is r^2 = 0.97 indicating good agreement, although the upper range of the data is less well reproduced. The two highest water levels are somewhat underestimated, whereas a group of values just below these two values are overestimated. Optimal parameter values for the fit were $\mu = 0.78$ m and $\sigma = 0.16$ m.

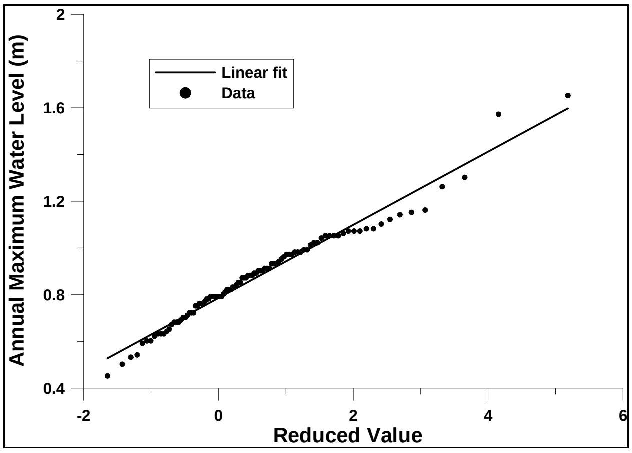


Figure 7 Annual maximum water level in Ystad 1887 – 1986 plotted against the reduced value from the Gumbel distribution using the Gringorten plotting position formula together with a linear fit

A comparison was performed relative to the annual maximum water levels with respect to climatic or calendar years. As previously stated, all analysis presented in this paper was carried out using climatic years to avoid an incorrect description of the storm characteristics at the study site. The storms typically occur during the winter season, which stretches over two calendar years. Figure 8 illustrates the annual maximum water level plotted against the reduced value from the Gumbel distribution using the Gringorten plotting position formula, where the analysis was done with respect to climatic or calendar year. As expected, the latter approach generally leads to an overestimation of the water level for a certain return period. Thus, fitting a straight line through the data points produces a line for the calendar-year data that is consistently above the line through the climatic-year data.

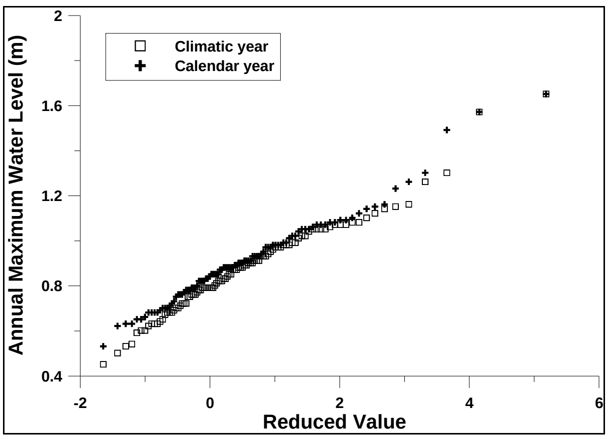


Figure 8 Annual maximum water level in Ystad 1887 – 1986 plotted against the reduced value from the Gumbel distribution using the Gringorten plotting position formula for climatic and calendar year

As a more general alternative to the Gumbel distribution, a Generalized Extreme Value (GEV) distribution was fitted to the data using a maximum likelihood approach. The GEV distribution is given by (Coles 2001)

$$G(z) = \exp\left(-\left(1+\xi\left(\frac{z-\mu}{\sigma}\right)^{-1/\xi}\right)\right) \quad (3)$$

where ξ is a shape parameter. In fact, if $\xi \rightarrow 0$ the GEV distribution results in a Gumbel distribution. Fig. 9 shows the fitted GEV distribution together with the 95% confidence limits for the estimated distribution. The parameter values for the best fit were $\mu = 0.79$ m, $\sigma = 0.18$ m, and $\xi = -0.091$. Thus, the value on the shape parameter, being less than zero, would indicate that a Weibull distribution is a better description of the annual maximum values (Coles 2001). However, the 95% confidence limits for the estimate of ξ are [–0.18, 0.03], implying that a Gumbel is still possible as a valid distribution for the data.

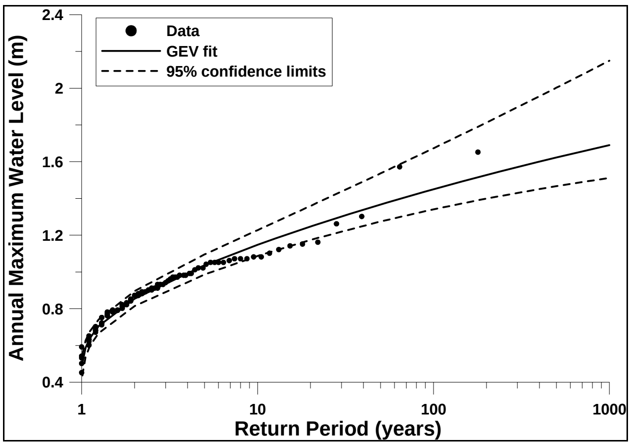


Figure 9 Annual maximum water level in Ystad 1887 – 1986 plotted against the return period using the Gringorten plotting position formula together with a GEV distribution fit including 95% confidence limits

Individually measured water levels in the 1982-2004 time series are more or less normally distributed. Water levels above +50 cm occur about 3% of the time and above +70 cm about 0.5% of the time. This time series will be used in the analysis of run-up levels where simultaneous data on water levels and waves are required at high resolution, as previously pointed out.

3 Calculated data employed

3.1 *Wave data*

The wave conditions were computed from the wind observations in about 20 m water depth outside the central part of the south Swedish coast close to the city of Ystad. For most of the calculated waves this depth corresponds to deep water conditions, although for the longer period waves some effects from the bottom are expected. The equations for wave prediction recommended in SPM (1984) were employed with a constant representative depth along each fetch length (Larson and Hanson 1992). Fetch lengths were estimated at an angular resolution corresponding to the measurements of the wind direction (*i.e.*, for the studied compass directions). Results from more sophisticated wave hindcasting carried out by Blomgren et al. (2001), validated with wave measurements from the southern part of the Baltic Sea, were compared with the SPM approach in a previous study showing good agreement. Thus, for the purpose of the present study the simplified SPM method was deemed sufficiently accurate.

However, a difficulty with the SPM method is to take into account wave growth and decay in a proper way. In the present study, the modification developed in Dahlerus and Egermayer (2005) was employed, where it is assumed that the waves evolve from the existing wave conditions based on a simple exponential response function. For the wave height the evolution equation is written,

$$\frac{\mathrm{d}H}{\mathrm{d}t} = k\left(H_{eq} - H\right) \tag{4}$$

where H is the wave height generated by the wind, H_{eq} the wave height at equilibrium conditions (determined by the fetch length or wind speed from SPM), t time, and k a response coefficient. The solution to Eq. (4) is

$$H = H_{eq} - \left(H_{eq} - H_{in}\right)\exp\left(-\lambda \frac{t}{t_{eq}}\right) \tag{5}$$

where H_{in} is the wave height at $t = 0$ when a new set of wind conditions start to apply and $\lambda = kt_{eq}$ was introduced in which t_{eq} is the time needed for fetch-limited (equilibrium) conditions to be attained according to SPM. The wind conditions are assumed to be constant for the time period during which Eq. (5) is employed. Also, the direction between consecutive wind measurements should change relatively smoothly so that the simple approach of combining the old and new wave conditions is applicable.

Equation (5) is valid both for $H_{in} > H_{eq}$ and $H_{in} < H_{eq}$, which would correspond to decay and growth of the waves, respectively, in response to changes in wind conditions. In the present study, when calculating wave heights from a time series of wind data, Eq. (5) was employed taking into account the initial wave height at each time step. The empirical response coefficient was determined by fitting Eq. (5) towards the wave growth obtained from SPM corresponding to $H_{in} = 0$. For a specific fetch length, the SPM equations yield a wave growth of $H/H_{eq} \propto (t_d/t_{eq})^{3/4}$ up to $t_d = t_{eq}$, where t_d is the duration of the wind, after which $H = H_{eq}$. Fitting Eq. (5) to this function gives an optimum value of $\lambda = 2.17$ for a least-squares fit. A similar evolution equation as Eq. (5) was developed for the wave period.

To compute the wave conditions, wind data from Falsterbo (Fig. 1) were used, because these were considered most representative for the south Baltic Sea. These data series covers the period 1961-2004 with values every three hours, including in total more than 106,000 data points. The calculated mean significant wave height (based only on wave-generating wind directions) was 0.87 m. Winds from S to WSW generate the largest waves and the maximum calculated significant wave height was 4.8 m.

Gringorten's plotting position formula was used to empirically estimate return periods for the annual maximum significant wave height and a Gumbel distribution was fitted to the data. Fig. 10 shows a plot of the non-exceedance significant wave height versus the reduced value. The optimum parameters in the fitted Gumbel distribution were $\mu = 3.4$ m and $\sigma = 0.45$ m with $r^2 = 0.95$. Based on this analysis, the annual maximum significant wave height with a return period of 100 years is estimated to be about 5.5 m.

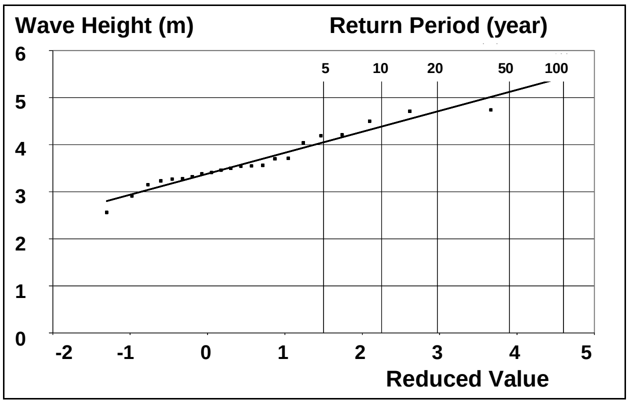


Figure 10 Annual maximum wave height in Ystad (period 1983-2004) plotted against the reduced value from the Gumbel distribution using the Gringorten plotting position formula together with a linear fit

3.2 *Run-up height*

Run-up height is a critical quantity to estimate when assessing the probability of flooding since it defines the highest elevation to which the waves might reach. The run-up height is normally referenced to the still water level and it includes the wave setup. The earliest formula for wave run-up height (*R*) was developed by Hunt (1959) as

$$\frac{R}{H_o} = \frac{\tan\beta}{\sqrt{H_o / L_o}} \tag{6}$$

where β is the beach slope, *L* wavelength, and subscript *o* denotes deepwater conditions. More recent run-up formulas are mainly variations of Eq. (6), where the selections of representative input wave parameters and slope are the major issues

(Mayer and Kriebel 1994, Stockdon *et al*. 2006). After evaluating several different formulas (e.g., Mase 1989, Mayer and Kriebel 1994), Eq. (6) was employed herein to compute the run-up height. Larson and Kraus (1989) (see also Wise *et al.* 1996) employed this formula to simulate the overtopping and impact on dunes and other morphological features, and it was demonstrated that it produces reliable estimates when compared to field data. Larson *et al.* (2004) developed a more physically based model of dune impact than Larson and Kraus (1989), also using Eq. (6) to estimate the run-up height.

Different approaches to obtain a representative slope for the run-up height computations were investigated, including a weighted value on the slope between the foreshore and the underwater profile (Mayer and Kriebel 1994). Employed values of these slopes were obtained from measured beach profiles in the Ystad area representative for the south Swedish coast (Hanson 2004). A comparison with the observed impact during storms and field visits indicated that the classical estimate of the slope in the Hunt formula, i.e. when using the foreshore slope as the characteristic slope, yielded the best predictions. Using a weighted slope between the foreshore and the underwater profile tended to underestimate the run-up height.

To account for the large angles of incidence with respect to the shoreline, a simple correction was applied to the input wave height according to $H_o' = H_o (\cos\theta_o)^{1/2}$, where H_o' is the modified wave height to be used in Eq. (6) and θ_o the incident wave angle in deep water with respect to the shoreline. Such a correction results if run-up height is assumed to be related to the onshore component of the wave energy flux. Most run-up formulas were derived based on data from normally incident waves or waves measured in the nearshore, subsequently backed out to deep water neglecting refraction. Thus, the proposed correction of the deepwater wave height yields an input wave height compatible with the run-up formulas, where large offshore angles of incidence are taken into account. The run-up height was computed for every value in the calculated wave time series and added to the applicable still-water level given by the water level time series. These generated data may constitute a base for determining the risk of flooding including overtopping of dunes at various alongshore locations in the study area.

4 Probability of extreme events

4.1 *Background*

The water level variations in the Baltic Sea are mainly a function of the distribution of the wind field over the sea surface although differences in air pressure may have some influences (Larson and Hanson 1992). Winds coming from the N to the E sector tend to move the water down into the southern part of the Baltic Sea causing high water levels in this area. Contrary, for winds from a sector S to W the water is moved to the northern part of the Baltic Sea with low water levels in the southern portion as a result. Thus, since the largest waves along the south Swedish coast occur for winds from S to W, the water level tends to be lower than normal, which in general reduces the risk of flooding. However, even though this simplified reasoning holds in most cases, a more detailed analysis is required to identify the events that may induce flooding and to determine the associated probability. Since the water levels may change appreciable over a time scale of hours, simultaneous records of water level and waves at this scale are required for a reliable assessment of the probability of flooding. It should be stressed that the conditions on the German and Polish Baltic Sea coasts are different from the Swedish coast as high waves occur in conjunction with high water levels along the former coastal stretches since they are exposed to large waves coming out of the sector N to E.

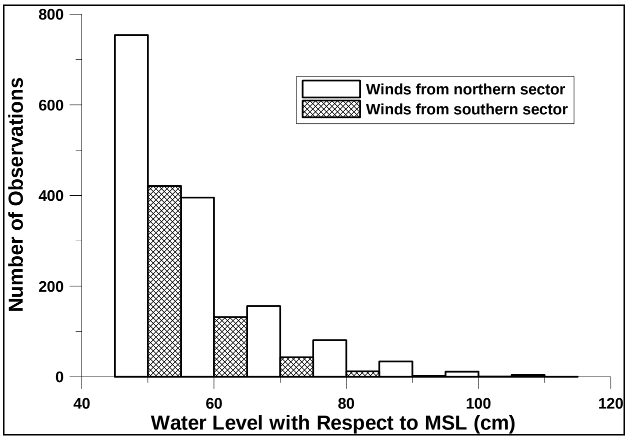
A first approach to determine the probability of extreme events and their implication for flooding would be to analyze the joint probability of strong winds and high water levels, or large waves and high water levels. However, since flooding often is a result of the combined effect of the mean water level and the wave properties through the run-up, it is also worthwhile to analyze the run-up level, which is the sum of the mean water level and the run-up height, as previously discussed. In the following selected results of the analysis pertaining to these different aspects of the probability of flooding are presented.

4.2 *Wind and water level*

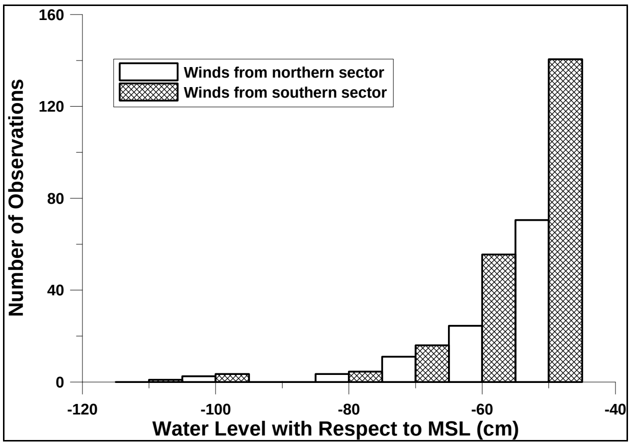
The analysis of the joint occurrence of strong wind and high water level utilized wind data from Falsterbo in combination with water levels derived from the series measured at Ystad and Simrishamn. The combined time series of wind and water level covered the period 1982 to 2004, with values every three hours, encompassing in total 66,481 values. As previously pointed out, most of the water level variations in the Baltic Sea are associated with the distribution of the wind over the sea surface area. An analysis of water levels versus wind direction demonstrated that low water levels are generated for winds from SW to W, whereas high water levels occur for winds from N to NE. This is a result of the shifting water masses in the Baltic Sea, which is as a more or less enclosed basin. Under conditions of strong uni-directional wind followed by calm conditions seiching may be induced in parts of the Baltic Sea because of the release of piled-up water (Jönsson et al. 2005). The period of the seiching is typically in the range of 23-27 hr for the areas experiencing this phenomenon.

Figures 11(a) and (b) display the distribution of high and low water levels, respectively, on the south Swedish coast depending on the wind direction. High water levels are consistently associated with winds coming from the northern sector (WNE), whereas the opposite prevails for low water levels, which tend to occur for winds from the southern sector (ESW). Overall, high water levels seem to occur more frequently than low water levels do.

A special analysis was made regarding gale and storm winds with focus on the water levels they typically are associated with. Winds arriving from the E to W have a potential for generating large waves, so it is of interest to see how often high water levels are associated with strong winds from these directions. The number of data points with wave-generating winds was in total 42,469 (64% of the cases). The analysis showed that the strongest winds are not necessarily associated with the highest water levels (due to their directional properties). For gale winds the water level varies between −110 cm and +80 cm, whereas for storm winds the fluctuations are typically between −40 cm and +40 cm.



(a)



(b)

Figure 11 Distribution of (a) high and (b) low water levels on the south Swedish coast with respect to wind direction

4.3 *Waves and water levels*

Due to the general orientation of the coastline on the south Swedish coast, wave-generating winds only arrive from the lower part of the compass, *i.e.*, within the sector ESW. The largest calculated deep water significant wave height was 4.8 m occurring at a measured water level of +20 cm. At a water level of about +100 cm the highest calculated waves were about 0.8 m. This demonstrates that high waves do not appear in combination with high water levels. Thus, in order to accurately assess the probability of flooding a detailed analysis of combined waves and water levels is required, as discussed below.

4.4 *Run-up levels*

A schematic of a typical profile was used for calculating representative run-up levels (i.e., run-up height added to the current water level; Hanson 2004). The foreshore was described by a linear profile with a slope tan $\beta = 0.20$, whereas the underwater profile was modeled by an equilibrium profile with $A = 0.16$ (Dean 1977), corresponding to a grain size of 0.40 to 0.45 mm. As previously discussed, using the foreshore slope only provided the best description of the run-up height, and this slope was used in all calculations.

Equation (6) was employed to determine run-up heights for the period 1982-2004, from which the run-up levels were derived by taking into account the water levels. The calculated results showed a maximum run-up level of 4.6 m and a minimum level of −1.0 m relative to mean sea level (MSL). In addition, the calculations indicated that high run-up levels are typically caused by high waves in combination with modest water levels. Fig. 12 shows the number of hours per year the run-up level exceeds a certain elevation. Based on these results, it is possible to make risk estimates of the flooding and overtopping of dunes. For low-laying areas such as the Skanör/Falsterbo Peninsula the duration of an extreme event is crucial for assessing the extent and magnitude of the flooding.

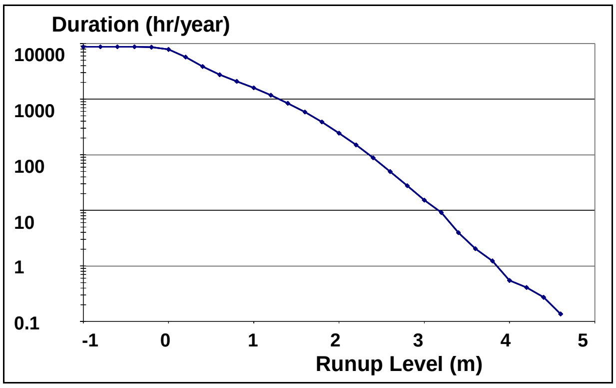


Figure 12 Hours per year of exceedence of run-up levels simulated for Ystad 1983-2004

Figure 13 shows the empirical distribution function for the annual maximum run-up level plotted with Gringorten's formula together with a fitted Gumbel distribution. The optimum parameters in the fitted Gumbel distribution were $\mu = 3.0$ m and $\sigma = 0.42$ m with $r^2 = 0.97$. The annual maximum run-up level with a return period of 100 year was estimated to 4.9 m.

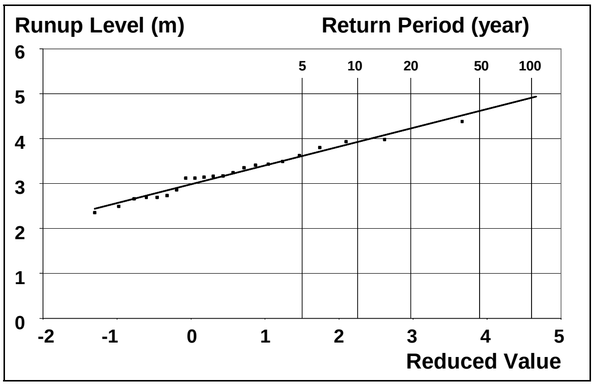


Figure 13 Annual maximum run-up level in Ystad (period 1983-2004) plotted against the reduced value from the Gumbel distribution using the Gringorten plotting position formula together with a linear fit

5 Future climate conditions

5.1 *Scenarios*

The future climate scenarios utilized in this study are derived partly from global climate models (Meier et al. 2004, Karoly et al. 2003, Hudson and Jones 2002) with coarse spatial resolution, and partly from regional models (Meier et al. 2004) that were used for making more detailed predictions for the Scandinavian region. The global models were developed by the IPCC (2001) and the regional models were developed within SWECLIM, a Swedish research project sponsored by SMHI (2007) and the Foundation for Strategic Environmental Research (MISTRA), 1997-2003. The scenarios for conditions up to the year 2100 used in this study, are the so-called A2 and B2 scenarios, where A2 assumes a larger increase of greenhouse gas concentration resulting in a mean temperature increase of 3.7°C relative to conditions in 2000 (Bernes, 2003), whereas B2 is more optimistic with lower concentration of greenhouse gas (Nakićenović et al, 2000) with a temperature increase of 2.6°C. The regional SWECLIM simulations originate from a British model (HadAM3H; regional scenarios denoted as HA2 and HB2) and a German model (ECHAM4/OPYC3; regional scenarios denoted as EA2 and EB2).

Wind climate

According to the SWECLIM simulations, which were available at a monthly basis, the wind speed will increase mainly during the winter period from December through February. Wind speeds during these months will increase 5-10 % according to scenario EB2, but twice as much according to EA2. The results from scenarios HB2 and HA2 show a more limited increase at around 1-5 %. Wind speeds may, thus, in the worst case increase as much as by 20 % (EA2) but may be limited to only 1 % (HB2). A mean change is estimated to 5 %. Calculations below are based on these three scenarios EA2, HB2, and the estimated mean value from the two. Table 1 provides a summary of the simulated changes in the wind climate for the various seasons and scenarios studied. In the calculations of run-up level for the different scenarios the wind time series was modified on a monthly basis with respect to the simulated changes. Thus, the calculated wave height and period would change for the different scenarios affecting the run-up height.

Table 1. Future change in seasonal wind speed for Ystad simulated by SWECLIM (change in % based on results for monthly simulations).

	German Model (E)				British Model (H)			
	A2		B2		A2		B2	
	max	min	max	min	max	min	max	min
Winter	20	10	10	5	5	3	2	1
Spring	10	5	3	2	1	0	–2	–3
Summer	–5	–10	–5	–10	–2	–3	1	0
Fall	3	2	5	3	–3	–5	2	1

Water level

Meier et al. (2004) presented results from SWECLIM simulations using the different scenarios with respect to annual mean water levels. As for wind speeds, the greatest changes are expected during the winter months. Three components are contributing to the changes, namely glacial rebound (−0.05 mm/yr in Ystad), changes in the wind regime, and the global sea level change, which depends on model and scenario. Simulations for 2100 show a best case (HB2) with a water level reduction by 0.05 m, whereas the worst case scenario (EA2) gives an increase by 0.85 m. The estimated mean scenario results in a water level increase of +0.38 m.

5.2 *Run-up levels*

Based on the schematized representative profile, the number of hours per year a specific elevation is reached was calculated for the different scenarios, as shown in Fig. 14. The calculations included changes in water level, wind, and wave climate. All the levels shown refer to the mean water level in 2004. As seen from the figure scenario HB2 implies less flooding compared to the present conditions, whereas the mean and EA2 scenarios cause a significant increase in the duration of the flooding for a certain elevation. For example, at many locations along the coast the dune crest is at an elevation of about 4 m. At present, this level is exceeded less than 1 hr/year, whereas in the mean scenario it will occur more than 2 hr/year and for EA2 almost 12 hr/year.

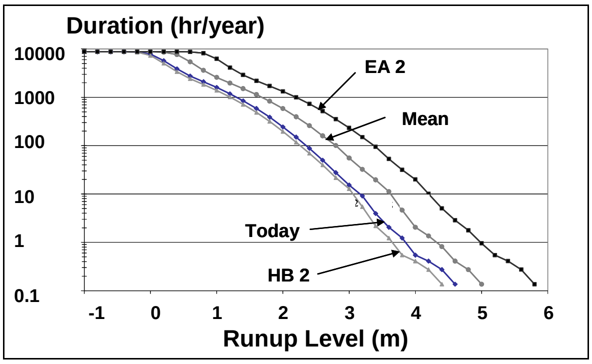


Figure 14 Hours per year of exceedence of run-up levels simulated for Ystad for different scenarios (levels are referenced to the mean sea level at present)

A comparison with respect to the return period for a certain annual maximum run-up level between the present conditions and the future scenarios is shown in Fig. 15, with the fitted Gumbel distributions for the different scenarios as well as for the present conditions. At present, a 100-year return period yields an annual maximum run-up level of about 4.9 m. The corresponding value for the EA2 scenario is 6.2 m. The future return period that corresponds to the present 100-year value is for the EA2 scenario only about 8 years, *i.e.*, flooding at this level will be about thirteen times more frequent in 2100 than what it is today (see Fig. 15).

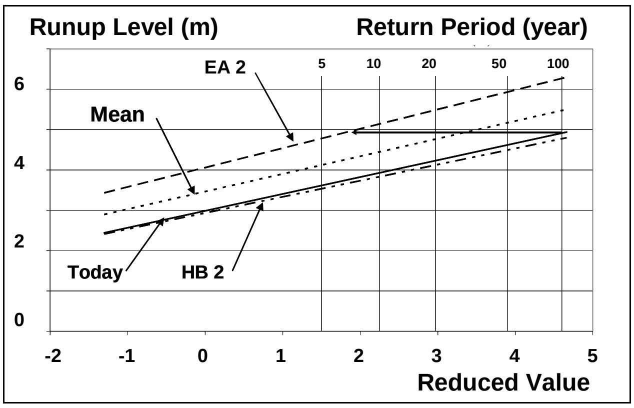


Figure 15 Comparison of return periods of run-up levels for the different scenarios

6 Conclusions

Long-term data series of wind speed and direction (1961-2004) as well as water levels (1887-1986 and 1982-2004) were analyzed with respect to the statistical properties of extreme events. By plotting annual maximum water level data using the Gringorten plotting position formula, it was shown that the Gumbel distribution is a good description of the probability that a certain maximum water level is exceeded annually. Furthermore, the wind data were used to calculate wave conditions along the Swedish south coast. A simplified method, based on the SPM (1984) approach was employed to calculate the wave conditions for which similar extreme value analyses were made.

With respect to coastal flooding and erosion the combined effect of water level and wave runup height are of particular interest. The run-up height is normally referred to the still water level, where slow changes caused by wind and pressure (surge) are taken into account, and it includes the wave setup. By adding the simultaneous water level to the run-up height the total run-up level may be determined. The annual maximum run-up level plotted with Gringorten's formula was used to fit a Gumbel distribution from which return periods could be determined.

Results from previous studies were employed to derive scenarios for conditions up to the year 2100 used in this study. Three different scenarios were formulated, including one pessimistic, one optimistic, and the mean of these two. For example, at many locations along the coast the dune crest is at an elevation of about 4 m. At present, this level is exceeded less than 1 hr/year, whereas in the mean scenario it will occur more than 2 hr/year and for the worst case scenario almost 12 hr/year. A comparison with respect to the return period for a certain annual maximum run-up level between present conditions and the future scenarios showed that the future return period that corresponds to the present 100-year value is for the worst case scenario only about 8 years, i.e., flooding at this level will be about thirteen times more frequent in 2100 than what it is today.

Although this study was undertaken at a particular site along the south Swedish coast, the approach and the experiences gained should be applicable to any coastal site where wave (or wind) and water level data are available. The impact on the coast during storm events in terms of flooding and erosion is the result of the combined action by waves and water level. Thus, the statistical properties of these two variables should be analyzed simultaneously, either by adding their effect in parameters that better reflect the impact such as the run-up level, or by a joint analysis of the two variables. This paper emphasized the former approach and demonstrated that the run-up level is a highly useful parameter to quantify the impact on the coast during storms. The run-up level is most sensitive to the run-up height estimate, where the assessment of a representative slope might require some experience employing run-up formulas and the availability of data from the site.

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Notation

G = Gumbel probability distribution function

H = wave height generated by the wind

H_o = deepwater wave height

$H_o^{'}$ = modified deepwater wave height to be used in run-up height formula taking into account incident wave angle in deep water

H_{eq} = wave height at equilibrium conditions (determined by fetch length or wind speed)

H_{in} = wave height at t = 0 when a new set of wind conditions start to apply

k = a response coefficient controlling wave growth/decay

L_o = deepwater wavelength

n = order of a specific event in the time series (from largest to smallest)

N = number of events recorded in a time series

r = correlation coefficient

R = run-up height

t = time

t_{eq} = time needed for fetch-limited (equilibrium) conditions to be attained

T_R = return period for a specific event being exceeded

y = reduced value in the Gumbel distribution

z = annual maximum water level

β = beach slope

ξ = shape parameter

$\lambda = kt_{eq}$ = coefficient in wave growth/decay relationship

μ = location parameter

σ = scale parameter

θ_o = incident wave angle in deep water with respect to the shoreline

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