# Decadal variations in wave heights off Cape Kelba, Saaremaa Island, and their relationships with changes in wind climate*

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## Abstract

Based on wind data from the Vilsandi meteorological station and a 5-month calibration measurement with a bottom-mounted Recording Doppler Current Profiler (RDCP), a semi-empirical hindcast of wave parameters near the quickly developing accumulative Kelba Spit is presented for the period 1966–2006. The significant wave heights with a gross mean value of 0.56 m exhibited some quasiperiodic cycles, with the last high stage in 1980–95 and a decreasing overall trend of −0.001 m per year. At the same time, both the frequency and intensity of high wave events showed rising trends, and the mean wave heights during winter (December to February) increased as well. As the study area has the longest fetches in westerly directions, the discussed tendencies in wave conditions are sensitive to regional changes in the wind climate and can be related to a decrease in the local average wind speed on the one hand, but an intensification of westerly winds, storm events and the wintertime NAO index on the other. The roughest wave

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storms on record were associated with prominent W-storms on 2 November 1969 and 9 January 2005; a few other extreme wind events (e.g. in 1967, 1999, 2001), however, did not yield equally prominent waves.

## 1. Introduction

An accurate understanding of wave climate is crucial, e.g. for shipping and port construction, but in the virtual absence of tides in the Baltic Sea, waves (together with storm surges) become the major hydrodynamic agents acting on seashores. The coastal sea near NW Saaremaa Island (Figure 1) has the roughest wave regime in Estonian coastal waters, where wave heights can reach 9–10 m (Soomere et al. 2008). Besides the new (inaugurated in June 2006), but actually not really important deep-sea harbour at Tamme, no noteworthy ports are located in the region. However, and interestingly from the geomorphic point of view, the quickly developing accumulative gravel spit at Cape Kelba and the leaning lighthouse tower on the transgressive coast at Cape Kiipsaare are located there.

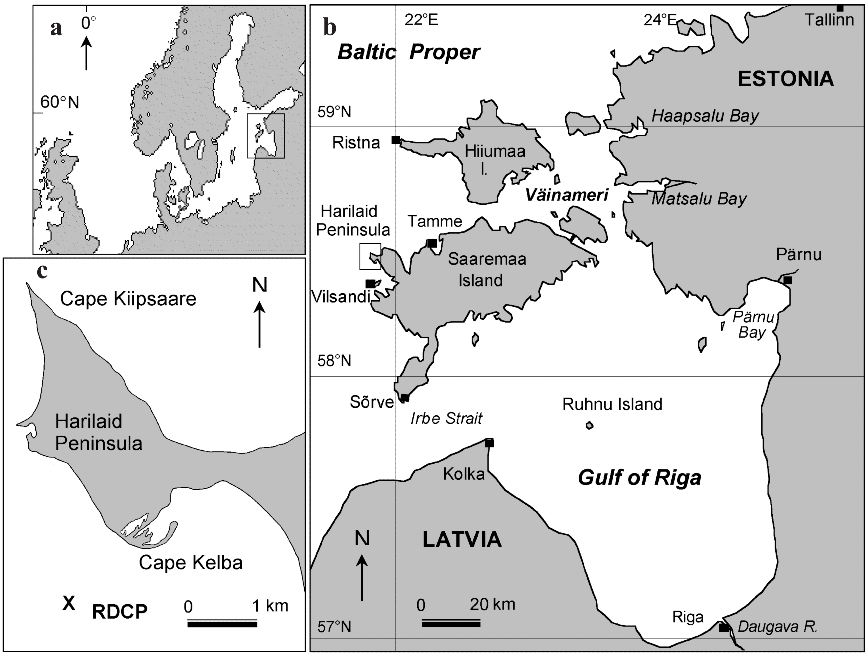

**Figure 1.** Study area (a), location of Saaremaa Island (b), the RDCP mooring off Cape Kelba (c)

The areas of the Harilaid Peninsula and the island of Vilsandi, together with their marine environs, belong to the Vilsandi National Park. The

Harilaid Peninsula region is hydrodynamically active, where changes in the wind and wave regime are probably reflected in the historical changes in shoreline position and contour (Orviku et al. 2003, Rivis 2004, Suursaar et al. 2008). Recently documented manifestations of climate change, which in the Baltic Sea region include warmer winters, higher mean and extreme sea levels, and more frequent high wind events (Alexandersson et al. 2000, Suursaar & Sooäär 2007, BACC 2008, Jaagus et al. 2008), are likely to intensify shore processes (Orviku et al. 2003, Suursaar & Kullas 2006, Tõnisson et al. 2008). The coastal formations of the Kelba Spit have been under investigation since the 1960s. The spit is comprised mainly of crystalline shingles and pebbles, and the beach ridges of different age reach 3.8 m above sea level (Rivis 2004). At the sandy Cape Kiipsaare, notable erosion and shoreline displacement during the last century caused the eastward migration of the whole northern part of the peninsula (Orviku et al. 2003, Tõnisson et al. 2008). However, there was a clear need for experimental measurements and modelling of the main hydrodynamic forcing factors. Most importantly, the lack of wave data, which could be attributed to the geomorphic development of that peninsula, initiated a hydrodynamic study by means of a Recording Doppler Current Profiler (RDCP). The instrument was placed 1.5 km off the Kelba Spit in December 2006. A 5-month long record of the multi-layer current regime, variations in sea level, wave parameters and other hydrological conditions was obtained, and parallel topographic surveys of beach formations and shoreline positions were carried out in 2006 and 2007. The results were summarised by Suursaar et al. (2008).

However, the existence of both wave measurements and high-quality wind measurements at the nearby Vilsandi meteorological station gives us an opportunity to continue here with the reconstruction of past wave conditions at the very spot where the RDCP was moored. Generally speaking, wave statistics can be obtained from either direct measurements or wave models. Wave recorders are still quite sparse in the Baltic Sea and are installed mostly near large ports or important lighthouses. In the northern Baltic Proper, a directional waverider has been operated by the Finnish Institute of Marine Research since September 1996 (see Kahma et al. 2003), and the echo sounder at Almagrundet supplied valuable data for the period 1978 –2003 (see e.g. Broman et al. 2006). In parallel, hindcast simulations have become a valuable tool to complement the limited (either in time or space) observational data. There are some studies on the wave climate of the adjoining open sea areas (Soomere 2001a, Jönsson et al. 2002, Broman et al. 2006, Soomere et al. 2008). However, to date, the time series obtained with contemporary spectral wave models are not long enough to determine the climatologic values and tendencies of wave properties. Our intention is to contribute some new insights into the wave climate of the northern Baltic Proper.

The main objectives of the study are (i) to present the results of in situ measurements of waves near the geomorphically active coastal section of the Harilaid Peninsula over the period December 2006–May 2007, (ii) on the basis of existing digitised wind data from the nearby Vilsandi station, to reconstruct time series of wave parameters for the period of 1966–2006 using a fetch-based first-generation wave model, which is calibrated by the wave measurements, and (iii) to discuss decadal changes in the wave climate of our study site and to analyse the relationships between the wave and wind conditions.

## 2. Material and methods

### 2.1. In situ wave measurements

An oceanographic measuring complex (RDCP-600; AADI Aanderaa Instruments, Norway) was deployed by divers to the seabed at the location of 58.46°N, 21.82°E, about 1.5 km offshore (Figure 1c). The mooring depth was about 14 m but the instantaneous water depth varied somewhat with meteorologically driven sea level changes. The chosen mooring location is on a gentle slope with the main gradients to the W and SW. To the SW and S, the water depth increases up to 25 m, but then decreases towards the island of Vilsandi (Figure 1b). To the W, the 50 m isobath lies about 7 km from the RDCP, and the 80 m isobath is about 20 km away.

The self-contained, upward-facing instrument was set to record from 1600 hrs GMT on 20 December 2006 to 1200 hrs GMT on 23 May 2007. The measuring interval was set at 1 hour and the instrument provided 3691 hours of data. The RDCP is equipped with a temperature, turbidity and conductivity (salinity) sensor, as well as a high accuracy quartz-based pressure sensor. The latter sensor enables it to measure relative sea level variations (as the depth of the instrument) and a set of wave parameters, such as significant and maximum wave height, peak wave period, mean wave period, energy wave period (a parameter which describes the most energetic part of the waves, used in calculations of the wave power of wave fronts), wave steepness and wave spectrum.

The model 3187 pressure sensor has a resolution of 0.001% of full scale, but with deep moorings the determination of wave periods has some limitations. In principle, the RDCP-600 is applicable to studies of waves with periods as short as 1 second. Since the dynamic pressure caused by waves with a short wave period decreases rapidly with depth, a cut-off frequency is calculated on the basis of deployment depth. For a depth of 14 m, a cut-off period of 4 seconds is imposed by the instrument software.

### 2.2. Fetch-based wave model

The calculation of wave parameters was based on the fetch-limited formulae of the Sverdrup, Munk and Bretschneider (SMB) type. This class of semi-empirical equations, also called the significant wave method, has been widely used since the 1970s for local wave forecasts and engineering purposes (e.g. Seymour 1977). For other versions and developments (such as the methods by Krylov, Wilson and CEM), see the overviews by e.g. Massel (1996) and USACE (2002).

Originally, the significant wave height ($H_S$) was defined as the average height of the 1/3 highest waves in a spectrum and is roughly equal to the 'wave height' visually estimated by a skilled observer. In both RDCP and numerical wave models, $H_S$ is estimated directly from the wave energy spectrum. Since the 1980s, second- and third-generation wave models have been introduced (e.g. Komen et al. 1994). Unlike the first-generation models (e.g. the SMB method), they describe waves in terms of the complete spectrum of period and energies. According to Hasselmann (1962), the evolution of the spectrum can apply the energy balance equation to demonstrate sea state condition. Third-generation spectral wave models (e.g. WAM) work with the full two-dimensional wave spectrum and reasonably estimate non-linear energy exchange between wave harmonics. In the northern Baltic Proper, the second-generation HYPAS has been applied, e.g. by Jönsson et al. (2002), and the WAM by Soomere (2001a, 2008). However, even the application of such wave models to the Baltic Sea is not straightforward since they cannot resolve interactions between steep waves, do not take into account interaction with currents, and may yield a relatively large error for shallow waters (e.g. Soomere 2001a).

Thus, when it comes to specific nearshore areas with a complex shoreline geometry and bottom topography, long-term hindcast simulations with more up-to-date wave models may be time-consuming and complicated. The size of the wave model grid is usually around 5–11 km, and for shallow nearshore wave conditions downscaling and nested calculations are needed (e.g. Gaslikova & Weisse 2006). Though neither scientifically novel nor sophisticated, the point models using SMB method can nevertheless deliver reasonably good results in certain conditions (Luettich et al. 1990, Huttula 1994, Samad & Yanful 2005, Özger & Sen 2007). The main drawback of the model is probably not its simplicity, but that it is a point-model and therefore only suitable for local hindcasts. Although it is possible to obtain 2D coverage of separate point-estimates, it is inefficient and inadequate in areal cases. However, as opposed to third-generation wave models, which require forcing with 2D wind field data, single-point high-quality marine wind data are conveniently sufficient for the first-generation models. As winds (especially strong winds) are usually highly homogeneous in the Baltic Proper and both the reaction and memory time of a large part of the wave fields in the relatively small basin of the Baltic Sea are short (Soomere 2001b), the use of such simple models can be justified in local applications. Hence, so long as we are interested in long-term changes in wave forcing conditions at the specific location off the Kelba Spit, some 1–1.5 km from the coast, a simple fetch-limited wave model functioning as a virtual extension of the RDCP recorder, may offer a simple alternative. Bearing in mind the limited availability of spatial (gridded) wind data for longer periods, this might even be the only possibility at present.

As given in the Shore Protection Manual of the US Army Coastal Engineering Research Center (CERC 1984), as well as in some newer manuals (e.g. USACE 2002), the inputs for the SMB equations for shallow- and intermediate-water waves are wind speed (U), effective fetch (F) and water depth (h) and they provide the significant wave height ($H_S$), wave period ($T_S$) and significant wave length ($L_S$):

$$H_S = 0.283\frac{U^2}{g}\tanh\left[0.53\left(\frac{gh}{U^2}\right)^{0.75}\right]\times\tanh\left\{\frac{0.0125\left(\frac{gF}{U^2}\right)^{0.42}}{\tanh\left[0.53\left(\frac{gh}{U^2}\right)^{0.75}\right]}\right\}, \quad (1)$$

$$T_S = 2.4\pi\frac{U}{g}\tanh\left[0.833\left(\frac{gh}{U^2}\right)^{0.375}\right]\times\tanh\left\{\frac{0.077\left(\frac{gF}{U^2}\right)^{0.25}}{\tanh\left[0.833\left(\frac{gh}{U^2}\right)^{0.375}\right]}\right\}, \quad (2)$$

$$L_S = \frac{gT_S^2}{2\pi}\tanh\left(\frac{2\pi h}{L_S}\right), \quad (3)$$

where g is the acceleration due to gravity (in m $s^{-2}$), U is in m $s^{-1}$, $T_S$ is in s, and F, $L_S$ and h are in m.

The formulae resemble the classical surface-wave dispersion relation for finite depth, which is written in terms of wave period and length. Equations (1)–(2) can be solved on the basis of wind speed and fetch data at once, while $L_S$ (equation (3)) is calculated iteratively. Figure 2a shows a nomogram for significant wave height, calculated for our mooring location with a depth of 14 m.

Basically, wave growth can be limited mainly by wind speed and duration (e.g. in oceans), fetch length, or by depth (in very shallow areas). The Baltic Sea is largely fetch-limited, and our study site (Figures 1, 2) belongs to the so-called restricted fetch areas. Wind fetch is defined as the unobstructed distance that wind can travel over water in a constant direction. As a first approximation, it can be calculated from the wind direction as the headwind distance from the nearest shore point for that direction. Usually, a specific method (e.g. effective fetch method, Saville's method, etc.) is applied in order to take into account basin proportions (e.g. Massel 1996, Samad & Yanful 2005). We used a weighted average process of the fetch over a wind sector ± 40° from the wind direction. As a result, the calculated fetches varied between 2 km (30°–50°) and 250 km (270°–290°), roughly permitting waves over 2 m only with very strong winds blowing from 220°–320° (Figure 2). However, it is rather difficult to take into account islands and shoals that fall into sectors radiating from the point where the wave characteristics are to be calculated, and to determine the 'best' combination of input settings (i.e. angular distribution of fetches, depth and possible corrections for wind speed data). Finally, extensive empirical data can help out. In our case, 5-month measurements were used in the final calibration of the model.

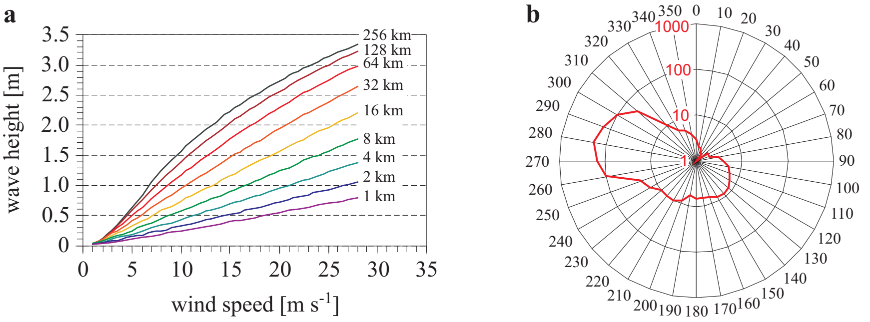

**Figure 2.** Modelled dependence between significant wave height, wind speed and fetch distance (a), directional distribution of fetches used in the model (b – the values in km are expressed on a log scale)

Ice conditions were not taken into account in the model. During the calibration period, the maximum extent of Baltic Sea ice cover was 139 000 km$^2$ (according to the website of the Finnish Institute of Marine Research, http://www.fimr.fi/fi/tietoa/jaa/jaatalvi/fi_FI/2007), but the mooring site remained ice-free. However, when the extent of the ice exceeds roughly 200 000 km$^2$, the study site may be covered by ice for a short period. Historically, this has happened roughly once in two-three years (Seinä et al. 1994), but recently just about once per decade.

### 2.3. Input wind data

For supplying the wave model with wind speed and direction, we acquired data from the Vilsandi meteorological station (58°22′59″N, 21°48′55″E), which is operated by the Estonian Meteorological and Hydrological Institute (EMHI). This is the closest station to our measurement site, just 7 km south of the Harilaid Peninsula (Figure 1). The station is on the western coast of the island and has the most open location of all the Estonian weather stations. The only sheltering obstacles that might slightly impair wind readings are a few low trees among the scrub to the east and a lighthouse to the west. According to Soomere (2001b), Vilsandi wind data satisfactorily represent both the scalar and the directional properties of the wind regimes in the northern Baltic Proper. Extensive periods in which wind directions are uniform over large areas frequently occur in the Baltic Proper, especially in high wind situations. Although both wind speed and direction may change significantly during such events, the changes occur quite synchronously at remote sites.

The wind data consisted primarily of hourly measurements from December 2006 until May 2007, which were used for the model calibration. Since September 2003 meteorological stations in Estonia have been equipped with MILOS-520 automatic weather complexes. They include the Väisälä wind instruments WAA151 and WAV151, which provide hourly average wind speed, gust wind speed and prevailing wind direction. In this study, both the wave measurements and wind data had an interval of 1 hour, but wind gust data were not used. Then, all the historical wind data since 1966, available in digital form, were used for the long-term hindcast; for this, a time interval of 3 hours was applied to the period from from January 1966 to August 2003.

Data homogeneity is an important issue in long-term wind recordings. In addition to the latest change in measuring equipment in 2003, which did not introduce any substantial discrepancies into the data sets (Keevallik et al. 2007), an important change from wind vanes (weathercocks) to automatic anemorhumbometers took place in November 1976. During a few years of parallel measurements, it turned out that anemorhumbometers were systematically underestimating strong ($> 10$ m s$^{-1}$) winds in comparison with previous visual readings from weathercocks, mostly because the traditional 3-hour samples of visual readings during a 2-minute period were replaced by hourly samples of 10-minute (or 1 h) average wind speeds. Thus, during data pre-treatment, we adjusted the older data with corrections provided by certain professional handbooks (Scientific-practical Handbook of the Climate of the USSR 1990). For example, a 15 m $s^{-1}$ mean wind speed corresponds to the previous 17 m $s^{-1}$, and 26 m $s^{-1}$ is equivalent to the previous 30 m $s^{-1}$. The value step for wind speed is 1 m $s^{-1}$ from 1966 until September 2003. Wind directions for 1966–76 are given in the 16-rhumb system. An anemorhumbometer provides the wind direction readings with a resolution of 10°. Since 9 September 2003, the value step for wind speed has been as small as 0.1 m $s^{-1}$ and 1 for direction. Although several different integration periods are available, an hourly 10 min averaging procedure is traditionally used for wind speeds.

The overall completeness of the Vilsandi wind data is very good. Over the period 1966–2006, measurements failed to be made for one reason or another in just 1.9% of cases. The percentage of missing data was high in the politically turbulent years of 1991 (52% of mostly summer data are missing) and 1990 (22%). The missing data in 2003 (2%) were related to the above-mentioned changes in the measuring equipment. The data sets of other years were practically 100% complete. Some short-term equipment malfunctioning occurred during extreme storms (e.g. in 9 January 2005). For long-term trend analysis, the missing data were made good using averages from the seasonal cycle.

## 3. Results and discussion

### 3.1. Results of wave measurements and calibration (correction) of the model output

During the measuring period, the significant wave height reached 3.16 m on 15 January, and was > 2 m on six further occasions (Figure 3d). These events were well correlated with the variations both in the modula and the W–E components of wind speed (Figure 3a,b). The maximum wind speed of 23 m $s^{-1}$ (gusts up to 33 m $s^{-1}$) was measured on 15 January at the Vilsandi station (Figure 3a). The prevalence of SW winds in December and January caused above-average sea levels (Figure 3c), including the maximum according to the Ristna tide gauge (Figure 1b; 171 cm above the average), which occurred on the evening of 14 January, a few hours before the maximum in the wave storm. Starting from February, when easterlies and northerlies prevailed, the sea level dropped below the long-term average (roughly equal to 13.8 m as expressed by the instrument depth; Figure 3c).

The significant wave height averaged 0.56 m and the standard deviation was 0.49 m. The recorded maximum wave height (4.59 m on 15 January) was 1.45 times higher than the corresponding $H_S$ and the ratio remained

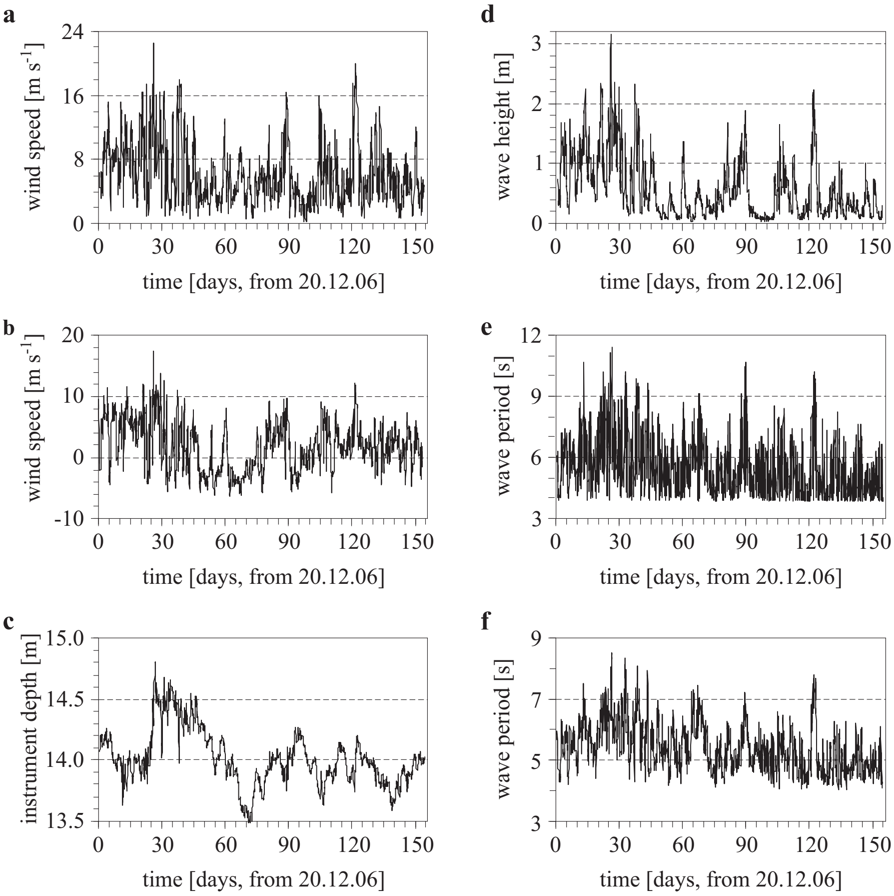

**Figure 3.** Variations in wind speed (a) and WE wind component (b – a W wind has a positive direction) at Vilsandi station; sea level variations as RDCP 'instrument depth' (c), variations in measured significant wave height (d), peak wave period (e) and energy wave period (f) between 20 December 2006 and 23 May 2007

around 1.5 during the rest of the study period. It is also expected that the height of every hundredth wave could have been as much as 1.67 $H_S$ (e.g. Massel 1996). In general, the series of maximum wave heights do not provide much additional information, since they behave synchronously with $H_S$.

Peak wave periods reached 11 seconds (Figure 3e). The corresponding maximum and average values for the mean wave period were 7.8 and 5.2 s, and for the energy wave period 8.5 and 5.4 s respectively. However, when interpreting these values we must bear in mind that the cut-off period of 4 s probably does not allow the wave statistics to be reproduced correctly.

Although the influence of smaller waves is partly eliminated in the case of significant and maximum wave height estimations, the information about wave periods is probably distorted at deeper moorings. On the other hand, as the larger periods occur with higher waves, the record still more or less adequately represents the dominant part of the wave energy.

Based on the Vilsandi wind (Figure 3) and the corresponding fetch data (Figure 2b), we calculated the basic wave parameters for the same period and location as in the RDCP mooring.

It appears that the model slightly underestimated the wave properties. The initial output of the model may have been underestimated for several reasons. Firstly, the coastal wind speed may have been smaller than the wind speed over the open sea (e.g. Soomere 2001b, CERC 2002). However, as such semi-empirical models ought to perform well with normally available forcing data, we decided not to manipulate the wind input data. Secondly, the model assumes a constant (average) depth of the basin, and although only about 17% (60°) of the fetch directions radiate from sea areas with depths $>15$ m, this figure may have been underestimated. An increase in model depth probably yields higher maxima, but also changes the whole output structure somewhat. Then, there is the possibility that the influence of homogeneous winds along the axis of the Baltic Proper combined with topographic refraction of certain wave components may correspond to much longer effective fetches for SW winds at Kelba. Although the incremental influence of larger fetches is very small above distances of about 100–200 km (see Figure 2a), it may cause some errors. Moreover, additional growth of the highest waves may occur as a result of shoaling as well as in the case of convergent wind fields (as occurred during the January 2005

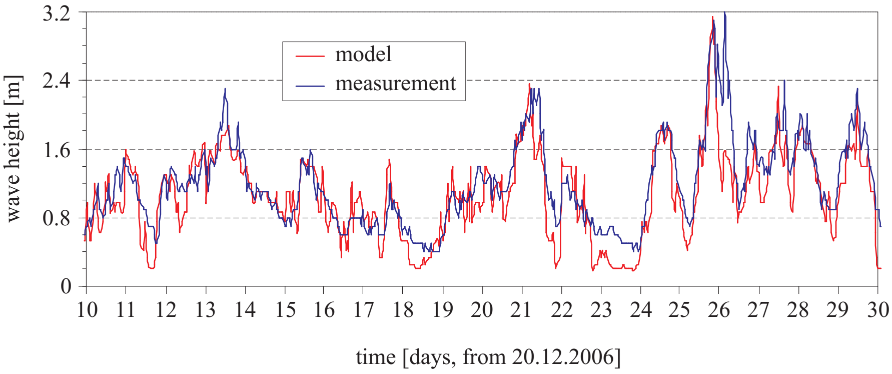

**Figure 4.** Comparison between measured and modelled (corrected with a 4th-order polynomial) wave series. Excerpt for the period 30 December 2006–18 January 2007, which includes the storm of 15 January

storm; Soomere et al. 2008). The model also lacks a wave growth feature and treats both short and continuous wind events equally. In reality, only small waves are saturated quickly (i.e. $< 3$ hours, which is the step for the majority of the wind data), whereas waves in strong winds continue to increase in height for up to about 5–7 hours in the Baltic Sea (Soomere 2001a). One more shortcoming concerns the failure in reproduce remotely generated wave fields, i.e. the absence of swell. After the end of the wind event, the modelled waves dropped quickly, whereas in reality the wave heights decreased slowly over a period of about one day (Figure 4). Finally, owing to the frequency cut-off in the measured wave periods, no attempt was made to apply corrections to the modelled wave periods and lengths. As a result, the variations in the modelled wave periods may be synchronous with the actual ones, but the values will not be directly comparable with the measured ones (Figure 5).

Despite all the critical issues pointed out above, the result of comparison was surprisingly promising. In order to achieve the best fit of statistical parameters between the measured and modelled data sets during the 5-month calibration period, the model output was corrected slightly. A linear regression in the form $\mathrm{H_{SC}} = 1.004\,\mathrm{H_{SM}} + 0.062$, where $\mathrm{H_{SC}}$ is the corrected significant wave height and $\mathrm{H_{SM}}$ is the modelled significant wave height (both in metres), was enough to yield practically the same average value (0.57 m), a root-mean-square (RMS) of differences as low as 0.237 m and a correlation coefficient $r = 0.875$, although the maxima were still slightly underestimated. As can be concluded from both the regression coefficients and the statistical comparison, the correction was in fact quite mild. Still, a small proportion (about 1%) of the larger wave data had to be slightly larger still. As the second-order polynomial was growing too aggressively and the shape of the third-order did not fit, a fourth-order polynomial was finally found, which produced a high $r$ (0.880), a low RMS error (0.233) between the measured and modelled data, as well as nearly equal average and maximum values (Figure 4).

This comparison (Figure 4) showed that the model results were in good agreement with those measured by the RDCP and that the calibration settings for significant wave height can be used to a reasonable degree of approximation in the hindcast for the entire period between 1966 and 2006. The fact that the model results were slightly over- or underestimated, or that they included some systematic biases, is really not important here, since we were studying mainly the long-term and seasonal variations in a specific (actually arbitrary) location.

### 3.2. Results of the 1966–2006 wave hindcast

The hindcast results for the period 1966–2006 had a gross average value of 0.54 m. It should be stressed that the statistics are given in terms of $H_S$ (roughly equal to 'visual average wave height'). The mean standard deviation was 0.42 m with a positively skewed empirical frequency distribution (Figure 5b), which can be approximated either by a lognormal distribution or, as is usually done for wave studies (e.g. Soomere 2008), by Rayleigh's distribution. The histograms (Figure 5b, d) were based on 136 864 entries; however, since only the hourly intervals since September 2003 were taken into account, just 117 543 data equivalent to 3-hour intervals were used. The first three and the most popular bins $\leq 0.75$ m included 72.1% of the RDCP data (Figure 5a) and 75.8% of the 41-year hindcast. The main difference – the lack of very high but infrequent values (which is visually enhanced by the use of the log scale on the y-axis) – can be explained by the different length of the samples: the longer period contains

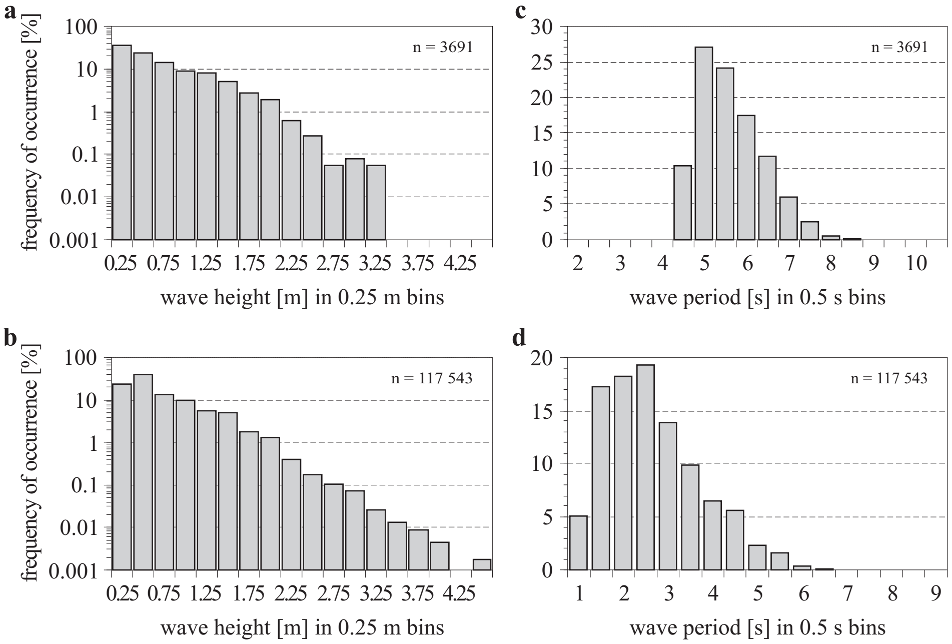

**Figure 5.** Frequency distributions of significant wave heights (a) and energy wave periods (c) measured from 20 December 2006 to 23 May 2007; frequency distributions of modelled (and corrected) significant wave heights (b) and significant (uncorrected) wave periods (d) in 1966–2006. Note that due to severe damping of measured wave periods of < 4 seconds, the distribution in (c) is rather distorted and appears just as an example of the RDCP output for the given depth

some extreme storm events, the occurrence of which is unlikely during a 5-month period.

The wave height averages, as well as their higher percentiles and variability, displayed clear seasonal cycles (Figure 6b, f). The minimum average was in May (0.39 m) and the maximum in December (0.69 m). The

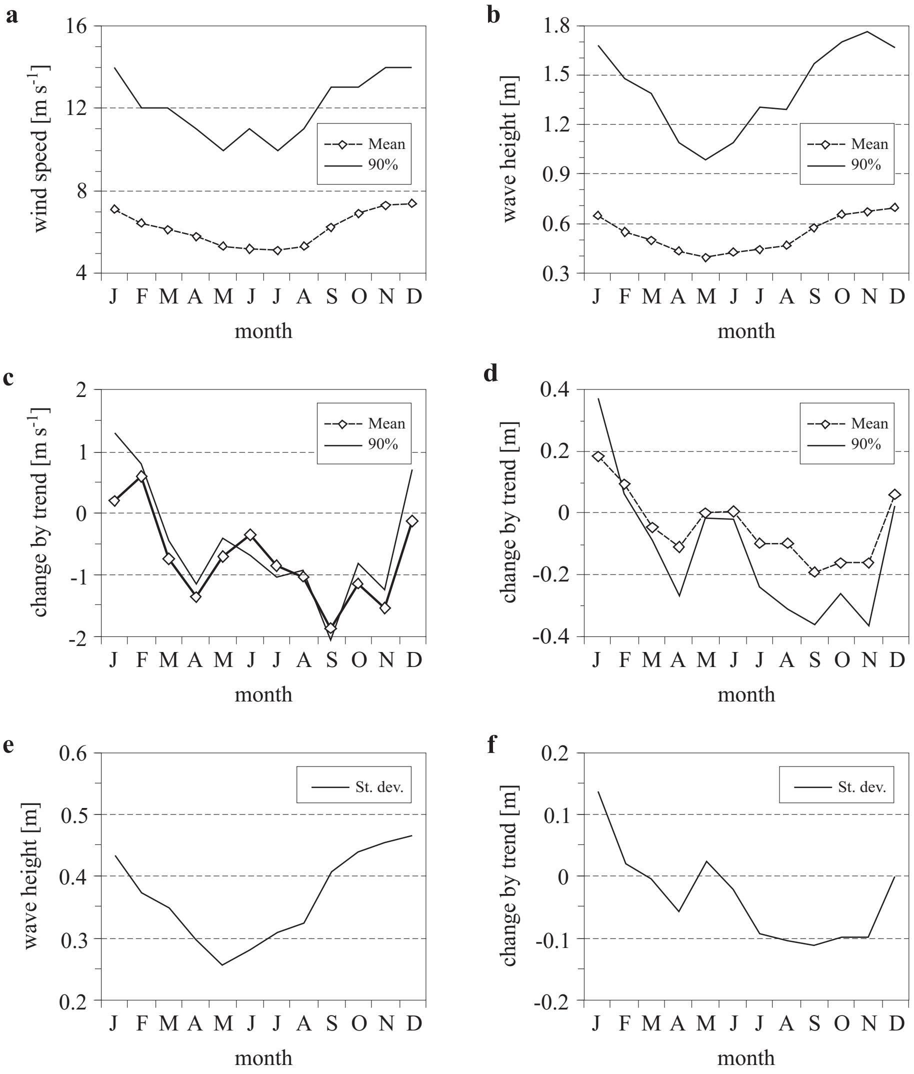

**Figure 6.** The annual cycles of the monthly average Vilsandi wind speed and 90%-ile (a), corresponding hindcast wave heights (b) and standard deviations (e). The annual cycles of changes by linear trend on the basis of monthly datasets of wind speeds (c), wave heights (d), and wave height standard deviations (f) over a 41-year period

seasonal curves resembled the Vilsandi wind statistics for the same period (Figure 6a, c), although June and July winds had slightly lower average values in comparison with May, but a somewhat larger share of westerlies. The April and May wind data contain more easterlies, with implications for the wave climate (Mietus 1998).

The results of decadal variations of averages and standard deviations (Figure 7g) showed some quasi-periodic 30–40 year cycles with above-average values in 1980–95, and lower values in 1970–80 and since 1995. However, the overall trend of averages was negative with an average slope of $-0.001$ m per annum (or $-4.2$ cm over the 41-year period). It should be stressed here that due to the limited length of the series and the presence of some cyclic variability, the concrete trend estimates should be treated with caution. The series on wave periods (Figure 7h) seem to follow the same pattern, while the higher percentiles and maxima show positive trends (Figure 7e, f). The increase in the 90%-ile of the annual samples shows that extreme wave events have been more frequent, and the even steeper increase in the 99%-iles and maxima (Figure 7e) show that these events have become more extreme. The series of maxima are less reliable, however. In many cases, the annual maximum values represent extrapolations beyond the calibration range (i.e. 3.2 m) and their exact magnitudes should be treated with caution.

The highest wave storm ($H_S$ about 4.5 m) probably occurred on 2 November 1969 with 24 m $s^{-1}$ sustained wind speeds from 290°. The second highest event occurred on 9 January 2005 during the infamous hurricane Gudrun ($H_S = 4.2$ m, wind speed 23 m $s^{-1}$, 270°), and the third one on 29 November 1999 ($H_S = 4$ m, 22 m $s^{-1}$, 250°). However, the wind-measuring equipment at Vilsandi malfunctioned during the January 2005 storm (Suursaar et al. 2006b). While the maximum modelled open-sea wind was close to 29 m $s^{-1}$ during this storm (Soomere et al. 2008), the existing wind data (and therefore also the wave hindcast) may have been underestimated slightly. During windstorm Gudrun in January 2005, the roughest ever wave conditions in the Baltic Sea were estimated to have been 10–30 km off the coast of NW Saaremaa, where $H_S$ probably reached 9.5 m and the peak wave period exceeded 12 s (Soomere et al. 2008). Wave heights are strongly depth-dependent until water depths of about 50–100 m. According to the model estimations (Soomere 2001a), the significant wave height can be as much as 10 m at deeper sections off the Harilaiu Bank, which is about 15 km from our measuring site.

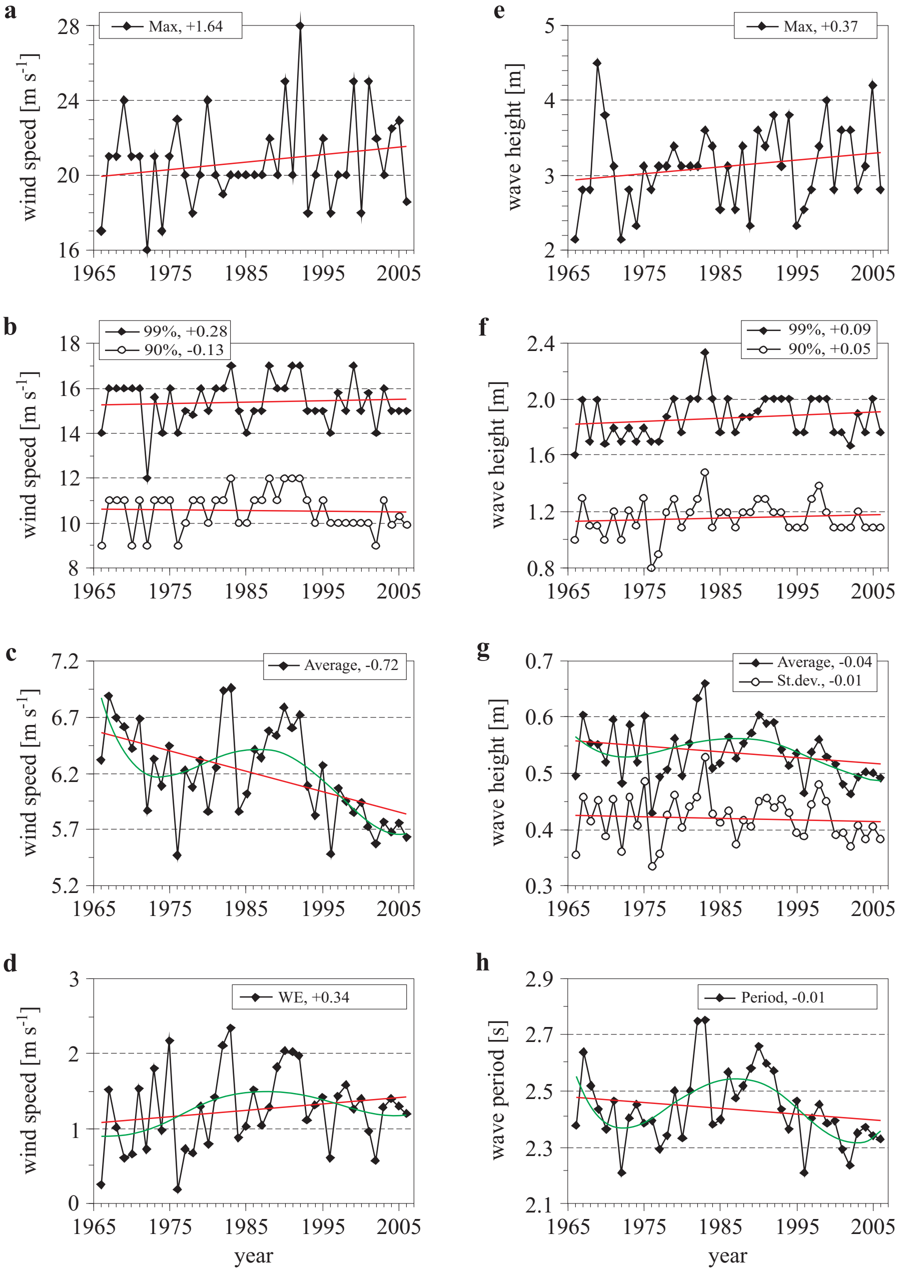

**Figure 7.** Decadal variations in the annual statistics of the Vilsandi wind speed: maxima (a), 90- and 99-percentiles (b), averages (c) and zonal wind component (d); variations in maximum wave heights (e), 90- and 99-percentiles (f), standard deviations (St. dev.) and averages (g), and wave periods (h) in 1996–2006. the values in the legend mark the changes by linear trendlines over the study period

### 3.3. Discussion on decadal variations in wave parameters and their relationships with forcing conditions

Interestingly enough, although the annual trend of wave heights was negative (Figure 7g), the analysis of monthly data yielded positive trends in mean wave heights in December, January and February (Figure 6d; see also Figure 8a). A similar seasonal structure of trend estimates also occurred in sea level series (Suursaar et al. 2006a). There were no particular trends in March, May or June, and the trend was negative in the remaining months (Figure 6). However, it must be borne in mind that secondary statistical procedures with percentiles and standard deviations should be interpreted with caution. For example, although the 90%-iles of monthly samples showed decreasing trends in most of the months (Figure 6c, d) and the 'annual average monthly trend' appeared to be negative, the same percentiles for annual samples actually show rising trends (Figure 7b, f). Similarly, the monthly trends of standard deviations (Figure 6f) are not simply additive to yield one single annual trend (Figure 7g).

The correlation coefficients between wave and wind statistics were rather high (Table 1) and the trends in wave parameters were very similar to those in the wind statistics (Figures 7a–d). This is quite natural, as the wave model is forced primarily by the corresponding wind data. Nonetheless, the connection is not always straightforward owing to the fetch-limited study area. For example, there were a number of strong windstorms in the record, which, due to their unfavourable direction, did not yield equally prominent wave storms: the legendary storm of 18 October 1967 yielded a significant wave height of just 1.9 m; a 28 m $s^{-1}$ sustained wind speed during the southerly storm on 12–13 March 1992, probably the strongest ever recorded at Vilsandi, brought about 3.8 m waves; the 25 m $s^{-1}$ SW storm on 27 February 1990 gave rise to 3.6 m waves, and the 25 m $s^{-1}$ S-storm on 17 December 1999 produced 1.7 m waves. The impact of easterlies is even more efficiently suppressed by the fetch-limited wave model, but in any case easterly storms are never as powerful as westerly storms in this part of Estonia (Soomere 2001b, Keevallik et al. 2007).

While the average wind speed (Figure 7c) has decreased, both WE (Figure 7d) and SN wind components have increased. That is to say, the increase in W and S winds, and the decrease in N and E winds, imply certain shifts in the air-pressure systems and cyclone trajectories above the Baltic Sea; this is also expressed by recent tendencies in the NAO index (Table 1, Figure 8a). Generally, the Iceland-Gibraltar version of the NAO index (Jones et al. 1997) is expected to best describe the variations in the Estonian climate (e.g. Jaagus et al. 2008). Also, wind speed, storminess,

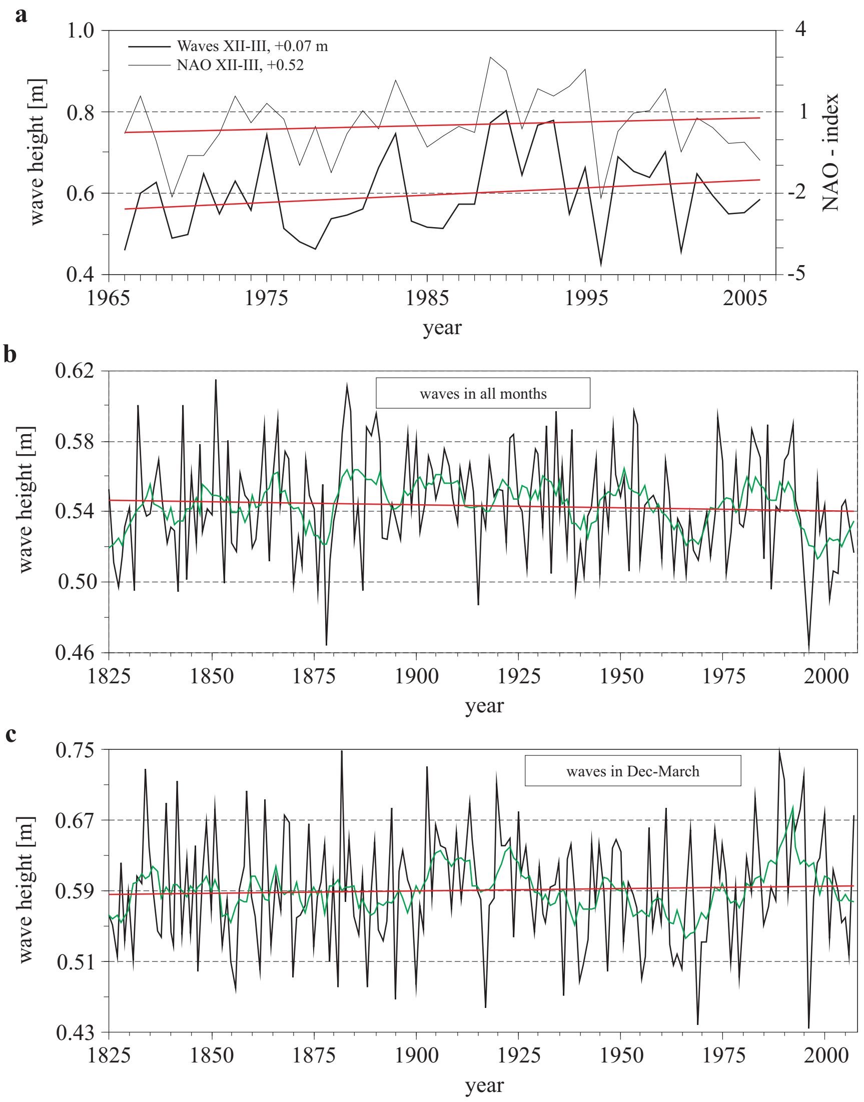

**Figure 8.** Variations in winter subsets of wave hindcast and the NAO index together with linear trendlines (a). Reconstruction of wave heights based on regression between the August-to-February NAO index and annual mean wave heights (b), and between the December-to-March NAO index and wave heights for the corresponding season (c – see also (a) and Table 1). Annual data, linear trendlines and 9-year running averages are shown in (b) and (c)

sea level variations and wave statistics are correlated to each other and to the NAO index on the windward coast of Estonia (Table 1, Suursaar & Sooäär 2007, Jaagus et al. 2008).

**Table 1.** Correlation coefficients between various forcing factors and wave statistics. For the NAO index, the Iceland-Gibraltar version is used (Jones et al. 1997); for a definition of storm days, see Orviku et al. (2003); for sea level, see Suursaar & Sooäär (2007). * indicates December to March wave statistics only. Some notable correlations are marked in bold; the coefficients are statistically significant ($p < 0.05$) mostly starting from 0.3

| Influencing factor | Wave statistics | | | | | |
|---|---|---|---|---|---|---|
| | Average | 90% | 99% | Max | Period | Standard deviation |
| wind speed modules | **0.87** | 0.52 | 0.38 | 0.11 | 0.82 | 0.57 |
| W–E wind component | **0.85** | **0.79** | **0.60** | 0.15 | 0.70 | **0.74** |
| S–N wind component | 0.11 | -0.02 | 0.07 | 0.04 | 0.24 | -0.06 |
| wind speed 90% | **0.76** | **0.65** | 0.56 | 0.17 | 0.73 | **0.65** |
| wind speed 99% | **0.67** | 0.56 | 0.57 | 0.52 | 0.61 | 0.63 |
| wind speed maximum | 0.12 | 0.02 | 0.16 | **0.62** | 0.15 | 0.12 |
| NAO-index all months | 0.48 | 0.35 | 0.41 | 0.24 | 0.56 | 0.36 |
| NAO-index Dec.-March* | **0.72** | | | | | |
| NAO-index Aug-Feb | **0.61** | 0.50 | 0.43 | 0.15 | 0.59 | 0.52 |
| count of storm days | **0.68** | 0.68 | 0.66 | 0.34 | 0.65 | **0.66** |
| count of storm hours | 0.56 | 0.55 | 0.61 | 0.39 | 0.59 | 0.54 |
| Ristna sea level average | **0.71** | 0.54 | 0.38 | 0.06 | 0.67 | 0.51 |
| Ristna sea level max | 0.06 | 0.19 | 0.34 | 0.45 | 0.07 | 0.19 |
| Pärnu sea level average | 0.26 | 0.33 | 0.43 | 0.43 | 0.27 | 0.32 |
| Pärnu sea level max | 0.28 | 0.29 | 0.50 | 0.51 | 0.22 | 0.37 |

Since monthly NAO data have been available since the 1820s (and, apparently, no similar historical wind data exist), we were tempted to find the best applicable relationships between the air circulation and the wave data. For 1966–2006, the highest correlation for the annual average wave height ($r = 0.61$) was obtained using the average annual NAO data from August to December. The highest correlation for partial data sets ($r = 0.72$) was found between the NAO data from December to March and the wave heights for the same period (Table 1, Figure 8a). Based on these two regressions, a reconstruction of wave conditions was performed (Figure 8b, c). We stress here: though statistically significant, the regressions were not particularly high ($r = 0.61 \ldots 0.72$), and the outcome is strongly dependent on the quality of the NAO reconstructions. Both series display some 23–35 year quasi-periodic cycles. The winter subset showed an overall positive (but statistically insignificant) trend (Figure 8c) over the period from 1825 to 2006, while the whole annual data showed a very small and statistically insignificant decreasing trend (Figure 8b).

While the NAO-based reconstruction of past (1825–2006) wave climates should be treated with the utmost caution, for the last 40–50 years, decadal tendencies in wave heights quite similar to ours have been reported from some other locations in the Baltic and Northern Seas (WASA Group 1998, Vikebø et al. 2003, Weisse & Günther 2007). Although the wave conditions in fetch-limited areas are supposed to be highly site-dependent, some recent changes in regional wind climate and cyclone trajectories (Siegismund & Schrum 2006, Yan et al. 2006) may have had a similar effect on wave conditions in different, though not necessarily adjacent marine areas. The main factor seems to be the similar exposure of a location to a certain direction, the importance of which in wind distribution is changing. High wave events increased during 1958–92 (thereafter levelling off or decreasing) in the SE section of the North Sea along the windward coasts of Germany, the Netherlands and Denmark (Weisse & Günther 2007) under conditions of increased westerlies and cyclonic activity (Bauer 2001, Siegismund & Schrum 2006). At the same time, the frequency, duration, and intensity of extreme events have decreased along the leeward coast of the British Isles (Weisse & Günther 2007). Similarly, Broman et al. (2006) have reported increases for 1979–95 and decreases in more recent years in the northern Baltic Proper. The results of visual (coastal) observations of waves at the Vilsandi station (Soomere & Zaitseva 2007), based on relatively coarse and uncertain data, show higher wave heights in the 1990s and a decrease in the 2000s, but they are hardly comparable to our data for the 1960s–1980s. Finally, wave conditions are usually strongly site-dependent, especially in fetch-limited nearshore areas; therefore, our results are probably not directly applicable to the open Baltic Sea wave climate.

## 4. Conclusions

It is shown that a simple fetch-limited significant wave model is capable of reproducing a reasonably good hindcast for a specific shallow nearshore location. Also, possible restrictions of the model and problems due to simplifications are pointed out.

During the calibration period near Saaremaa Island from 20 December 2006 to 23 May 2007, the significant wave height measured by the RDCP reached 3.2 m (maximum height 4.6 m) and the correlation coefficient between the modelled and measured data was 0.88. Although the results of the hindcast study are site-dependent and do not necessarily reflect variations in the open Baltic, the robustness and convenience of the method offers some new insight into the wave climate of the northern Baltic Proper.

The mean wave heights and wave periods show quasiperiodic cycles with the last high stage in 1980–95 and a slightly decreasing overall trend

−0.001 m per year in 1966–2006. At the same time, the December to March subset of mean wave heights shows an increasing trend of 0.0017 m per year. On the basis of annual series of 90 and 99 percentiles, as well as annual maxima, the trend is increasing. Thus, the trends in the average properties of wave fields and in extreme wave conditions are different. The second most interesting outcome of the study is that the trends of wave properties are different in different months. The tendencies in wave heights and variability seem to correspond to the long-term tendencies in mean and extreme wind speeds at the Vilsandi meteorological station. The time series of waves are strongly correlated with wind speed, the W–E wind component, and the NAO index.

For the period and location under investigation, the roughest wave storms were associated with prominent W-storms on 2 November 1969 and 9 January 2005, whereas a few other extreme wind events (e.g. in 1967, 1999, 2001) did not produce equally prominent waves owing to the fetch-limited properties of the model.

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