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Seasonal and Long-term Variations of Wave Conditions in the Northern Baltic Sea

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ABSTRACT

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Although the Baltic Sea is a relatively small water body, it may host significant wave heights up to 9–10 m. Several authors claim that the rough seas have already caused extensive erosion of depositional coasts of this body of water. We make an attempt to merge historical visual observations and numerical hindcasts to reveal the basic features of the wave properties. Wave conditions, their seasonal cycle, and inter-annual and long-term variations in the northern part of the Baltic Sea are studied based on (i) visual observations along its eastern coast at Vilsandi (1954–2005) and at Pakri (1954–1985), (ii) instrumentally measured wave properties at Almagrundet (1978–2003) on the western coast, (iii) directional wave statistics from the northern Baltic Proper (1996–2002), and (iv) wave hindcast near Saaremaa using a point model. The typical wave periods are 4–6 s and in coastal areas 2–4 s. The monthly mean wave height follows the seasonal variation in wind speed with a maximum in October–January. The observed annual mean wave height reveals nearly synchronous, substantial decadal-scale variations in the entire region, and a rapid increase (1–2% annually) until the mid-1990s. The increasing trend was replaced by a decrease of the mean wave height since 1997, although the mean wind speed continues to increase over the area. The model qualitatively represents the long-term variations of the wave intensity.

ADDITIONAL INDEX WORDS: *Wave climate, wave modeling, trends, climate change, Baltic Sea.*

INTRODUCTION

Studies concerning properties of complex wave fields in different sea areas and research towards the understanding of both the status and changes of the wave climate undoubtedly form one of the key elements of contemporary physical oceanography and coastal science. This is not only because surface waves are a major driver of processes in the surface layer, nearshore, and coastal area, but also because the wave climate is one of the most sensitive indicators of the changes in wind regime and local climate in semi-enclosed sea areas.

The complexity of physics and dynamics of the Baltic Sea extend far beyond the typical features of many other water bodies of comparable size (WULFF *et al.*, 2001; BACC, 2008). This water body is characterized by extremely complex geometry, highly varying wind fields, extremely rough wave conditions at times, extensive archipelago areas with specific wave propagation properties, and ice cover during a large part of each year. The combination of a relatively small size and vulnerability of its ecosystem makes this region particularly susceptible to climate changes and shifts.

Numerous changes of the forcing conditions and of the reaction of the water masses of the Baltic Sea have been reported during the latter decades (BACC, 2008). There is evidence that the increasing storminess in this region starting in the 1970s has already caused extensive erosion of the depositional coasts (ORVIKU *et al.*, 2003). This trend, however, has been severely questioned by many authors. The changes in the wave climate of some parts of the region have been found to be marginal, at least, until the mid-1990s (WASA GROUP, 1995; MIETUS and VON STORCH, 1997). The intensity and duration of severe wavestorms in the southern North Sea have decreased since about 1990–1995 (WEISSE and GÜNTHER, 2007). This decrease is consistent with the updated trends of storminess (ALEXANDERSSON *et al.*, 2000).

Very rough seas measured twice in December 1999 (KAHMA *et al.*, 2003) reinforced the discussion as to whether the wave conditions in the Baltic Sea have become rougher compared with the situation from a few decades ago. One exceptional storm, Gudrun (January 2005), highlighted inadequate awareness of extreme wave properties (SOOMERE *et al.*, 2008) and of the height and spatial extent of extreme water levels (SUURSAAR *et al.*, 2006).

Recognition of the wave climate changes, and, in particular, changes of extremes, presumes a thorough knowledge of the typical and extreme wave conditions. The global wave data set KNMI/ERA-40 Wave Atlas (1957–2002, STERL and CAIRES, 2005) allows the production of reliable wave climatology for open ocean conditions based on 6-hourly means of wave properties over an average of 1.5°×1.5° areas. This resolution is too coarse for the Baltic Sea conditions.

We make an attempt to merge historical visual observations and numerical hindcasts to reveal the seasonal, annual, and decadal changes in the basic wave properties in the northern part of the Baltic Sea. As contemporary wave measurements are relatively scarce and short here, the reliable estimates of the wave climate

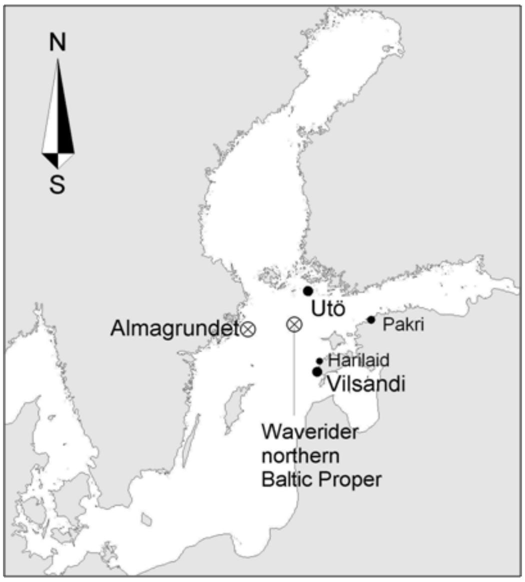

Figure 1. Location scheme of the long-term wave measurement and observation points, and points used for comparisons of modeled and measured data in the Baltic Sea.

require a combination of different data sources with extensive modeling resources. The analysis below is based on (i) visual observations at Vilsandi in 1954–2005 (Soomere and Zaitseva, 2007) and at Pakri in 1954–1985, (ii) instrumental measurements at Almagrundet (1978–2003) on the western coast of the Baltic Proper (Broman *et al.*, 2006), (iii) directional wave statistics from the northern Baltic Proper in 1996–2002 (Kahma *et al.*, 2003), and (iv) wave hindcast for the Vilsandi observation point using a point model forced by high-quality marine winds (Figure 1).

METHODS AND DATA

The data from Almagrundet (1978–2003, 59°09' N, 19°08' E, Figure 1, Broman *et al.*, 2006) form the longest and one of the most valuable instrumentally measured wave data sets in this region. The measurement site is at a 14 m deep shoaling area about 10 nautical miles south-east of Sandhamn in the Stockholm archipelago. The fetch for winds from the SW, W, and NW is quite limited at this site. The measurements were performed with the use of upward-looking echo-sounders placed at a depth of about 30 m. The position of the water surface was sampled over 640 seconds each hour. Single waves were identified based on the zero-downcrossing method. An estimate of the significant wave height H_S was found from the 10th highest wave in a record under the assumption that wave heights are Rayleigh distributed. The set of 95,458 measurements from 1978–1995 reliably describes the wave properties. Later, 46,671 recordings taken from 1993–2003 have certain quality problems: the overall behavior of the wave height follows the sea state, but the periods are not usable (Broman *et al.*, 2006), and they are not employed below.

A directional waverider has been operated by the Finnish Institute of Marine Research in the northern Baltic Proper at a depth of about 100 m (buoy 1 in Figure 1, 59°15´N, 21°00´E) since September 1996 during the ice-free seasons (Kahma *et al.*, 2003). This device, as well as contemporary spectral wave models, estimate the significant wave height as the four-fold zero-order moment of the wave spectrum (the total variance of the water surface displacement, e.g. Komen *et al.*, 1994). These data are the most representative of the open Baltic Sea wave fields. However, to date, this time series is not long enough for determining the climatological values of wave properties.

A coastal site reasonably reflecting the open sea wave conditions for the dominant wind directions in the northern Baltic Proper is located at the Island of Vilsandi (58°22´59´´N, 21°48´55´´E, Figure 1) and is operated by the Estonian Meteorological and Hydrological Institute. This site gives inadequate data only for easterly winds which are relatively weak and infrequent in this area. Wave observations were made starting from 1954 up to three times a day, there. The observer noted the five highest waves during a 5-minute time interval and recorded the highest single wave and the mean height of these waves at Vilsandi. Given the typical wave periods in the coastal zone 3–4 s (Broman *et al.*, 2006), the observed highest single wave height is approximately equal to the average height of 2.5–3 % of the highest waves. As the observers' estimates represent the significant wave height well (Gulev and Hasse, 1999), the visually observed data are interpreted as estimates of the significant wave height. The data represents the general features of the Baltic Sea wave fields well: relatively low overall wave activity, short wave periods, and substantial seasonal variation of wave conditions (Soomere and Zaitseva, 2007; Soomere, 2008).

The wave period was found as an arithmetic mean of three consecutive observations of the time for 10 waves to pass. Since the visually observed wave periods are only a few tenths of seconds shorter than the peak periods (Gulev and Hasse, 1999), the results are interpreted as estimates of the peak period. At least one sensible observation of the wave height has been made on 15,038 days (coverage 79 %). Most of the gaps occur from January to March apparently owing to the presence of sea ice.

Another observation site where observed wave properties reasonably represent the open sea conditions is at Pakri in the western part of the Gulf of Finland (59°23´37´´N, 24°02´40´´E, Figure 1). Pakri is the only wave observation site on the southern coast of this gulf that is largely open to waves generated in the Baltic Proper. The average depth of the area over which the waves were observed was 8–11 meters. The procedure of wave observations was identical to the one used at Vilsandi. Waves were observed from a steep, >20 m high cliff, 24 m from the mean sea level. Regular wave observations are available from 1954. The recently digitized data set is discussed here for the first time. Unfortunately, this data set covers only 32 years up to 1985. The total number of records is 13,916. At least one sensible observation exists on 9,170 days from a total of 11,657 days.

The calculation of wave parameters near the Harilaid Peninsula was based on the fetch-limited equations of Sverdrup, Munk, and Bretschneider (SMB-model, see e.g. Seymour, 1977; Huttula, 1994). Also called the significant wave method, the model is forced by wind speed data, effective fetch and water depth and it calculates the significant wave height, wave period and wavelength for the chosen location. The effective fetch is the distance over which the wind blows. It can be calculated from the wind direction as the headwind distance for the nearest shore point. In shallow, nearshore areas with complex shoreline geometry and bottom topography, long-term hindcast simulations with more up-to-date wave models may be time-consuming and complicated. In such conditions, fetch-limited point models may offer a simple alternative (Özger and Sen, 2007). Among other tasks, we were interested in wave forcing conditions near the geomorphically interesting accumulative Kelba Spit of the Harilaid Peninsula (Suursaar *et al.*, 2008).

The chosen location for hydrodynamic measurements and modeling was 1–1.5 km off the coast. For meteorological forcing of the SMB wave model, we used wind data from the Vilsandi meteorological station, which is the most open among the Estonian stations and located just 7 km south of the Harilaid (Figure 1). The data was available in digital form for the period 1966–2006. The wind has been measured with wind vanes from 1966–1976, with automatic anemorhumbometers from 1976 to 2003, and with MILOS-520 automatic weather complexes starting from September 2003. The older data in the database has been slightly corrected for homogeneity. The time interval was 3 hours from January 1966 to August 2003. MILOS provides hourly average wind speed and gust wind speed with the value step of 0.1 m/s, and hourly prevailing wind direction with a resolution of 1°.

For comparison and calibration of the SMB-model, an self-contained oceanographic measuring complex RDCP-600 (Aanderaa Data Instruments) was deployed to the seabed at the same location (58°28'N, 21°49'E) for which the wave calculations were made. The mooring depth was about 14 m. The upward looking instrument recorded from 20 December 2006 to 23 May 2007.

RESULTS

During the 5-month calibration period, the SMB model slightly underestimated the measured waves. In order to achieve the best fit of statistical parameters between the measured and modeled data sets, the model output was slightly corrected using a fourth-order polynomial, which produced both high correlation coefficient (0.880), low RMSE (0.233) and nearly equal RDCP average and maximum values (Figure 2). The same settings were further used in the 1966–2006 wave hindcast, presented in this study (Figure 3).

Although the Pakri observation site is sheltered from a part of the dominant SW winds, wave properties at this site mostly match the ones observed, measured or hindcast for the northern Baltic Proper. The distribution of the occurrence of wave height and mean periods at Pakri (Figure 4) reflects sensible wave observations with non-zero wave periods. This distribution has a shape typical for the Baltic Sea region (KAHMA *et al*., 2003). The most frequent wave periods are 2–3 s. The total mean wave height (calculated based on daily mean wave heights (SOOMERE and ZAITSEVA, 2007)) over all 32 years is 0.59 m. The average mean value of the recorded maximum wave heights is 0.61 m.

All the observed and hindcast data sets reproduce the basic features of the northern Baltic Sea wave fields (SOOMERE, 2008) such as (i) the overall mild wave regime in the basin, with the overall mean wave height in the open sea approximately 1 m and in the coastal areas 50–60 cm, (ii) a large proportion of wave conditions with the significant wave heights around 0.5 m (Figure 3), and (iii) the most frequent peak periods 4–6 s in the open sea and 2–4 s in the nearshore regions (Figure 4). All the listed values are characteristic to relatively small or semi-sheltered basins and are several times smaller than the similar values for the open ocean.

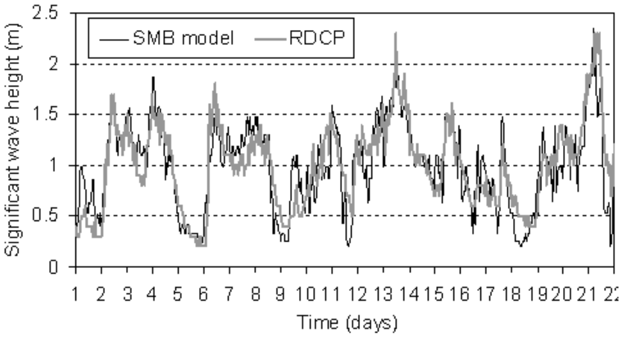

Figure 2. Measured (RDCP) and modeled significant wave height for the period of 21 December 2006 – 10 January 2007.

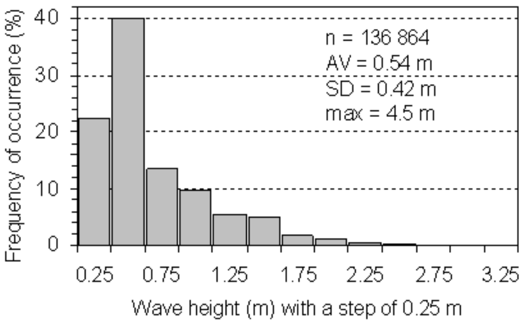

Figure 3. Frequency of occurrence of significant wave heights in hindcast data in 1966–2006.

A few (about 50 from total >32,000 recordings) recorded wave heights over 4 m were interpreted as erroneous at Vilsandi. The water depth in the observation area is about 4 m, but quite high single wave crests may at times occur owing to different shallow-water effects. Their properties may be filed by the observer because of the short observation period, but they do not adequately represent the open sea wave fields. Much higher waves, however, may occur at Pakri. The data set contains 6 cases when a maximum wave height of ≥5 m was recorded. These cases evidently correspond to realistic wave conditions in rough seas. The highest waves (6 m) were recorded in all available observations (twice each day) on 6–7 August 1967 when a strong NW storm excited extremely rough wave conditions and caused extensive damage to the forests. Waves with height of 5 m were recorded on 21 January 1964 and on 23 September 1969.

All data sets also reveal strong seasonal variability of the Baltic Sea wave fields (Figure 5). The amplitude of the seasonal cycle is quite large, for example, for the monthly mean wave heights it is up to ±40% from the annual mean value. The calmest months are April–June and the largest wave intensity can be found from October–January. The monthly mean wave height at Vilsandi varies from 0.4 m during summer to 0.8 m in winter. The seasonal cycle is also clearly visible in the most typical wave conditions, dominant wave periods, and higher percentiles of observed, measured, and hindcast wave heights. The seasonal cycle basically follows the annual variation of the wind speed in the northern Baltic Proper (MIETUS, 1998), which obviously mirrors the analogous cycle in cyclone generation over the North Atlantic.

Although Pakri is sheltered from some of the waves excited by the most frequent (SW) winds, the overall mean wave height at

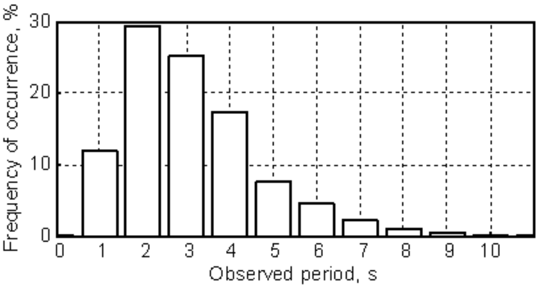

Figure 4. Frequency of occurrence of mean periods at Pakri.

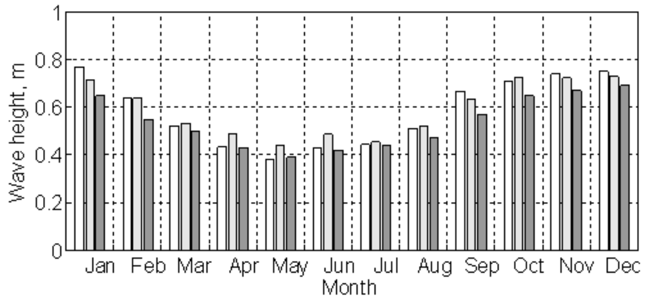

Figure 5. The monthly mean wave height at Vilsandi (white), at Pakri (light grey) and at Harilaid (dark grey).

Pakri and its seasonal variation almost exactly coincide with those at Vilsandi. This feature suggests that Pakri wave data also adequately represents the wave conditions in the open sea.

The overall course of wave activity (Figure 6) reveals no clear, long-term trend at Vilsandi and Pakri. Instead, a quasiperiodic variation can be identified for all the data sets. The interval between subsequent periods of high or low wave activity is about 25 years. The sea was comparatively calm at the end of the 1950s, became slightly rougher in 1965–1975, and then calmer again at the end of the 1970s. A rapid increase in the annual mean wave height occurred from the mid-1980s to the mid-1990s. The increase was well over 1% per annum depending on the particular choice of the time interval and the site (Almagrundet 1979–92: 1.3%; 1979–95: 1.8% (BROMAN *et al.*, 2006); Vilsandi 1979–95 as high as 2.8 % per annum (SOOMERE and ZAITSEVA, 2007)). This trend follows the analogous trends for the southern Baltic Sea and for the North Atlantic (GULEV and HASSE, 1999; WEISSE and GÜNTHER, 2007). The overall increase of wave heights is consistent with the increase of wind speed over the northern Baltic Sea (BROMAN *et al.*, 2006) that is frequently associated with the increasing storminess occurring in the 20th century over most of the North Atlantic and northern Europe (ALEXANDERSSON *et al.*, 2000).

This trend only existed for about 1.5 decades and was replaced by a drastic decrease in the mean wave height since 1997. The relevant data from Almagrundet was even estimated as doubtful by BROMAN *et al.* (2006) because the annual mean wind speed in the northern Baltic Proper continued to increase, as suggested by data from the island of Utö (Figure 1). The match of the long-term variation of wave properties at Almagrundet and Vilsandi suggests that both data sets adequately reflect the changing wave situation.

Variations of the annual mean wave height at Pakri are the most similar to those at Vilsandi (Figure 6). The largest difference is in the data from first three years of visual observations (1954–1956) during which apparently wave properties have been overestimated at Vilsandi (SOOMERE and ZAITSEVA, 2007). There is an increase in the mean wave height at Vilsandi and for a few years at Pakri and Harilaid around the year 1960, and an overall slow decrease until the the mid-1970s. The almost perfect match of short-term variability (1–3 years) of the annual mean wave heights and a high correlation coefficient (0.58) between these values in 1957–1985 at Vilsandi and Pakri once more confirms that the visual wave observations reproduce the basic properties of wave fields and their changes. Although the Pakri data exist only until 1985, still the above discussion suggests that the drastic variations of wave properties at Vilsandi reflect real changes in wave fields in the Baltic Proper even if they are not reproduced by models.

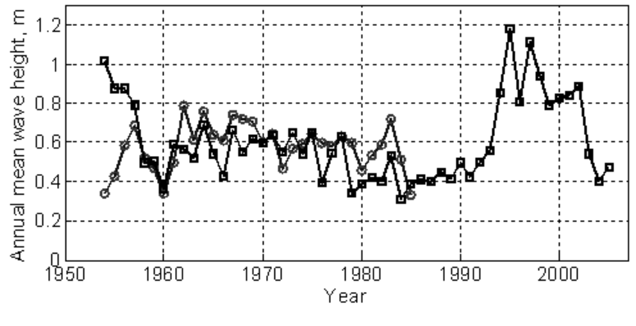

Figure 6. The annual mean wave height at Vilsandi (squares) and Pakri (circles, 1954–1985).

Near the Harilaid Peninsula, the results on long-term variations of averages (Figure 7) showed quasi-periodic 30–40 year cycles with above-average values roughly from 1980–1995, and lower values from 1970–1980 and up until 1995. 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).

According to this data set, the highest wave storm (HS about 4.5 m) probably occurred on 2 November 1969, when wind with sustained speed of 24 m/s, blew from the direction of 290º (W–NW). The second highest event occurred on 9 January 2005 during the hurricane Gudrun (significant wave height 4.2 m, wind speed 23 m/s, 270º). However, due to malfunction of the equipment at Vilsandi station, the existing wind data (and therefore also wave hindcast) might be slightly underestimated. Probably the roughest wave conditions ever estimated for the Baltic Sea were associated with windstorm Gudrun in January 2005. Significant wave height, in this instance, probably reached 9.5 m and the peak wave period exceeded 12 s 10–30 km off the coast of NW Saaremaa (Soomere et al., 2008).

DISCUSSION

In the case of Harilaid data, the correlation coefficients between wave and wind statistics were rather high (0.86, both in average wind speed and westerly wind component) and the trends in wave

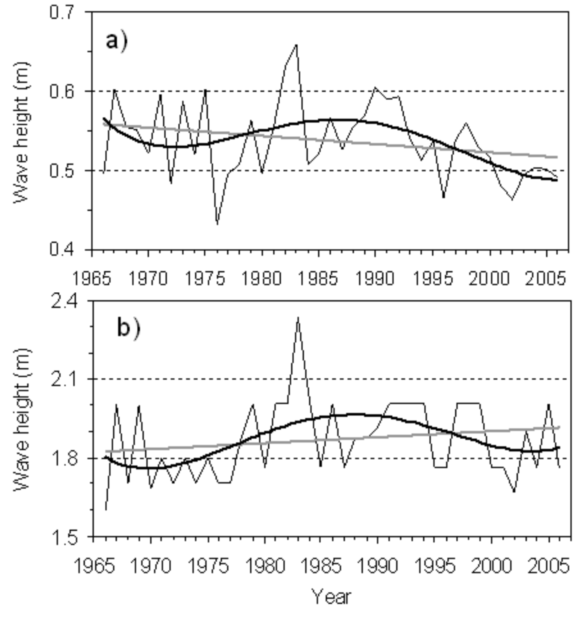

Figure 7. The annual average of significant wave height (a) and its annual 99% value (b) near Harilaid in 1966–2006.

parameters were quite similar to those in wind statistics. This is quite natural, as the SMB wave model is directly forced by the corresponding wind data. Still, the connection is not always straightforward due to the fetch-limited study area. For example, there were a number of strong windstorms in the record, which, due to unfavorable direction, did not yield equally prominent wave storms. Such storm events occurred, for example, on 12–13 March 1992, 27 February 1990, and 17 December 1999.

While the annual means of wave height at the two observation sites are highly correlated, the match between the modeled wave properties at Harilaid (Figure 7) and visually observed wave data at Vilsandi is far from perfect. Although a period of increase in modeled wave heights occurred in 1975–1993 with a subsequent decrease since 1998, the modeled data do show a large increase at the turn of millennium. This is not unexpected, because the model in use does not account for spatial variability of wind fields. Yet several aspects become evident from both data sets. The modeled data also do not reveal any distinct trend; instead, a quasi-periodic variation of the overall wave activity can be identified.

However, the series of 99% percentiles showed a clear increasing trend (Figure 7). This feature is particularly interesting, because it may be interpreted as evidence of an increase in the wave heights of extreme storms on the background of a decreasing trend of the overall wave activity (SOOMERE and HEALY, 2008).

CONCLUSIONS

The analyzed data sets represent the basic properties of the wave climate in the northern Baltic Sea. The typical wave periods are 4–6 s (2–4 s in coastal areas). The monthly mean wave height follows the seasonal variation in wind speed with a maximum in October–January and with the late spring and early summer months as the calmest. The annual mean wave height reveals nearly synchronous, substantial decadal-scale variations in the entire region, and a rapid increase of wave height (1–2% annually) until the mid-1990s. The increasing trend was replaced by a decrease in the mean wave height since 1997, although the mean wind speed continues to increase over the area. The models qualitatively represent these long-term variations. The presented features, in particular, the long-term changes, apparently are site-specific in the sense that they represent long-term changes in the storminess over the North Atlantic and related changes in the wind patterns over the Baltic Sea.

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