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Estimates of wave climate in the northern Baltic Proper derived from visual wave observations at Vilsandi

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Abstract. Wave conditions, their seasonal cycle and long-term variations in the northern part of the Baltic Sea Proper are studied, based on visual wave observations at the Vilsandi Island near the coast of Saaremaa in 1954–2005. Typical wave periods are from 2 to 4 s. The monthly mean wave height follows the seasonal variation in wind speed and varies from about 0.4 m in April–July to almost 0.8 m in January. The annual mean wave height shows a quasiperiodic behaviour. The wave activity varied insignificantly in the 1960s and 1970s, considerably increased in the 1980s, was the highest just before the turn of the century and is decreasing starting from about 1998.

Key words: wind waves, Baltic Sea, wave climate, visual wave data.

1. INTRODUCTION

Several cases of extremely rough wave conditions at the turn of the millennium [1] and two ferocious winter storms in 2004/2005 [2,3] have reinforced the discussion about whether the wave conditions in the Baltic Sea have become more rough compared to the situation a few decades ago. On the one hand, it is argued in [4] that the apparently increasing storminess in the Baltic Sea has already caused extensive erosion of depositional coasts. On the other hand, possible changes in the wave climate [5,6] have been found marginal, at least until the mid-1990s.

These discussions presume a thorough knowledge of the typical wave conditions. The information about the wave climate of the Baltic Sea, however, is relatively fragmentary. This feature can be partially explained by the fact that both numerical and experimental studies of wave conditions in the Baltic Sea area are very complex tasks. This water body is characterized by a relatively small size, extremely complex geometry, highly varying wind field, extremely rough wave conditions at times, extensive archipelago areas with specific wave propagation properties, and the ice cover during a large part of the year. The global wave data set KNMI/ERA-40 Wave Atlas [7] (based on an atmospheric reanalysis data set covering the period from September 1957 to August 2002 by the European Centre for Medium Range Weather Forecasts) reveals a reliable wave climatology for open ocean conditions. However, the basic wave parameters (such as the 6-hourly significant wave height, the mean zero-upcrossing wave period and the mean wave direction) are presented as an average of a $1.5 \times 1.5°$ area. This resolution is too sparse for the Baltic Sea conditions.

Contemporary wave recorders have been used in the northern Baltic Sea during a few decades [1,8]. High-quality wave data sets exist for the sea areas around Finland since the 1970s [1,8–13]. The wave climate of these areas is fairly well investigated. Regular wave measurements in the central area of the northern Baltic Proper (Fig. 1) were launched in September 1996 [1]. These data are particularly important for understanding the Baltic Sea wave climate; however, this time series is much shorter than 30 years, the interval recommended by the World Meteorological Organization for determining the climatological values of the environmental data [14].

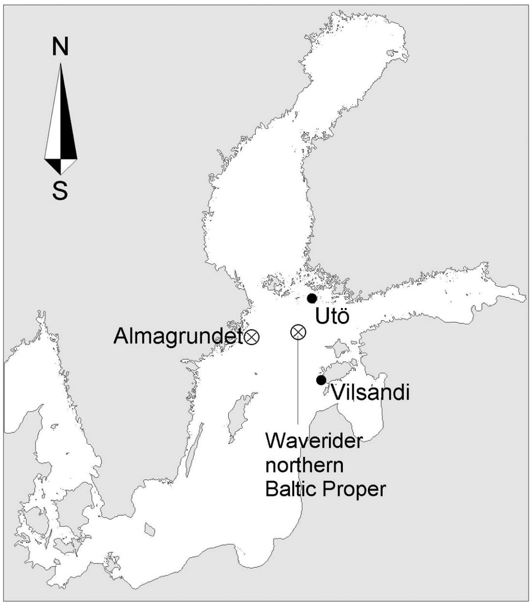

Fig. 1. Location of the observation site at Vilsandi and the wave measurement sites (marked by ⊗), data from which is analysed in [1,16].

Several semi-autonomous wave measurement devices were deployed in the shallow areas of the northern Baltic Sea about three decades ago [15]. A data set, recorded in 1978–2003 near the lighthouse of Almagrundet (the western sector of the northern Baltic Proper, 59°09′ N, 19°08′ E, Fig. 1) has been recently analysed in [16]. The data from the years 1978–1993 were found most reliable. Later recordings at the turn of the century showed quite an irregular behaviour of wave properties and were only partially analysed. This time period is also too short for the reliable description of the local wave climate. Also, the observation site is sheltered from a part of dominating winds. Hardly any instrumentally measured wave data is available from the coastal areas of Estonia, Latvia and Lithuania, except for sporadic measurements made with pressure-based sensors [17,18]. As a result, older sources such as [19,20] are at times still in use in estimates of wave conditions in the eastern part of the Baltic Sea.

Since the waves from the rest of the World Ocean practically do not affect the Baltic Sea waves, the wave properties here can be described with the use of local models. The existing numerical wave studies in the Baltic Sea basin have been recently discussed in [16,17]. The central conclusion is that the spatial distribution of the wave activity reflects the anisotropy of the wind regime in the Baltic Proper [21,22]. Statistically, the regions of the largest wave activity are found along the eastern coasts of the Baltic Proper [23,24]. A number of studies has been performed for limited areas of the Baltic Sea [25–27]. Yet an adequate long-term simulation of the Baltic Sea wave fields is still missing. For that reason, historical sources of wave information are highly valuable for this area.

A reasonable source of the open sea wave information form visual observations from the ships [28]. Such data have been used for description of wave fields also in the Baltic Sea [20]. Even the wave climate changes, estimated from the data observed from merchant ships, are consistent with those obtained from the instrumental records [29,30]. Only wave periods were somewhat underestimated by the observers.

Visual observations from the coast have been frequently interpreted as representing only wave properties in the immediate vicinity of the observation point. For example, visual data from Tallinn Harbour were found to represent wave properties only in the near-coastal regions and inadequate for describing open-sea wave fields [31]. Such data always contain an element of subjectivity, are not necessarily homogeneous in time, usually have a poor spatial and temporal resolution, inadequately reflect waves for several wind directions, reflect waves only during a short observation interval a few times a day, may give a distorted impression of extreme wave conditions because of wave breaking and reflection in shallow water, have many gaps caused either by inappropriate weather conditions or by the presence of ice, etc.

Yet the visual wave data are one of the few sources for detecting the wave climate and its long-term changes. Their basic advantage is the large temporal coverage. For example, records of hydrometeorological parameters at Tallinn Harbour started in 1805 and optionally contained visually estimated wave parameters (R. Vahter, personal communication 2003). In the second half of the 20th century, visual wave observations with the use of a unified procedure (partially with the help of some technical means) were performed in many locations of the eastern coast of the Baltic Sea.

In this paper, an attempt is made to estimate certain basic features of the wave climate and their long-term changes in the eastern sector of the northern Baltic Proper, based on visual wave observations from the coast. The data from the Vilsandi Island, located at the western periphery of the West-Estonian Archipelago are used in the analysis. The data are interpreted as regular samples of wave conditions that apparently reflect the basic properties of the wave climate. We start from the description of the measurement site and the procedure of quantifying the sea state. The quality of the data, the average wave properties at the site, the appearance of the distribution of wave heights and the joint distribution of wave heights and periods are discussed next. Finally we analyse the seasonal and long-term variation of wave heights, based on daily mean wave conditions. The results largely represent type A statistics in terms of the classification of [1]. Except for using all available observations at each day for the estimate of the daily mean wave height, no corrections have been made to compensate for missing values, for the uneven distribution of data, or for ice cover.

2. OBSERVATION SITE, PROCEDURE AND DATA

Regular visual wave observations have been performed at several coastal sites of Estonia during the second half of the 20th century (see www.emhi.ee). The majority of the sites are located either at the coasts of semi-enclosed basins of the Baltic Sea or are open to a few directions. An observation site, apparently well reflecting the open sea wave conditions, is located westwards from Saaremaa at the western coast of the Vilsandi Island (58°22′59″ N, 21°48′55″ E, Fig. 1). This island is also named Felsland on older maps after a limestone cliff along its western coast. Meteorological observations have a long tradition on this island. The first data exist from September 1865 but apparently observations have been performed also earlier.

The meteorological data from this site well reflect the open-sea wind properties [32]. They are frequently used in simulations of waves, water level, or circulation patterns [3,22]. This feature suggests that the observed wave properties also more or less adequately reflect the offshore sea state for most of the wind directions. The wave conditions at this site do not represent offshore wave fields for easterly winds; however, the frequency and strength of such winds is relatively low in this area [32].

Systematic wave observations at Vilsandi have been performed starting from 1954 [33]. The properties of waves, approaching from the western and partially from the northern directions (SW–NNE), are observed from a coastal site located about 1.5 m above the mean water level. For waves approaching from more southern directions, another observation point, located at a light pier, was used. Although waves, observable from the pier, are more affected by the coastline, small islands and shallow areas nearby, this site is more representative for waves, approaching from south and southeast. The seabed in the vicinity of both sites is gently sloping. The 4 m isobath is located at about 200 m from the coast-line [[33,34]]. Therefore the sea area, in which the waves were observed, apparently had a maximum depth of 3–4 m. Wave observations were only performed in daylight. The initial observation times (7:00, 13:00 and 19:00 Moscow time, or GMT +3 hours [[35]]) were later shifted to 6:00, 12:00 and 18:00 GMT according to the WMO guidelines [[14]]. This shift obviously has no large influence on the estimates of the wave climate.

The interval between subsequent observations at Vilsandi is often (in particular, in autumn and winter, when only one observation per day is available) much longer than the typical saturation time of rough seas (about 8 hours [[36]]) in the northern Baltic Proper. The duration of a wave storm seldom exceeds 10 hours (see also [[16]]). Therefore even the strongest storms, if they were not long enough, or occurred during a night, or were accompanied by low visibility, are not necessarily represented in the data set. Consequently, the observations cannot be used for a reconstruction of the time series of the sea state. Instead, they are interpreted as a set of regular samples reflecting the sea state. Since the number of observations is quite large, the data apparently reflect the basic features of the wave climate at the site.

The number of observed parameters varied greatly in different years. In the first years of observations 1) the type of the sea state, 2) the general appearance of the wave field, 3) the wave direction, 4) the intensity of waves, 5) the maximum and 6) mean wave height, 7) wave steepness, 8) length and 9) period were recorded [[35]]. The type of the sea state is reflected in terms of 9 categories whether windseas or swell, or their combination dominates. The general appearance of the wave field was described in a scale of 10 qualitative units ranging from calm seas to extremely rough wave conditions. The wave direction was defined (with a resolution of 45°) as the direction from which the waves approached. For a combination of windseas and swell, or for cross seas, the wave parameters were given for the dominating component. If several wave systems had a comparable intensity, the preference was given to waves, propagation direction of which matched the local wind direction. The intensity of waves was characterized in 9 qualitative units ranging from calm seas to exceptionally rough seas. Not all the parameters are independent, and in the course of time the number of recorded properties was reduced. For example, the wave steepness was only observed during a short time and was occasionally replaced by observations of the appearance of the wave field, and the type of sea state has been recorded until 30 July 1961. The basic measurable parameters such as the wave height, direction, period and length have the largest temporal coverage. Although the qualitative characteristics of the sea state apparently cannot be linked with contemporary wave data, they were at times helpful in estimates of the data consistency.

The analysis below is mostly performed for wave heights and to a certain extent for wave periods. The observational procedure resembles the classical zero-crossing method [37]. The observer noted the five highest waves during a 5-minute time interval with an accuracy of 0.25 m for wave heights less than 1.5 m, 0.5 m for wave heights from 1.5 to 4 m, and 1 m for even higher waves. The highest single wave $H_{\max}$ and the mean height H of these 5 waves were filed.

The most widely used measure of wave heights today, the significant wave height H_s, has been originally defined as the average height $H_{1/3}$ of the 1/3 of the highest waves during a certain time interval. In contemporary wave measurement devices and in numerical wave models it is estimated as $H_s = 4\sqrt{m_0}$, where m_0 is the zero-order moment of the spectrum, or, equivalently, the total variance of the water surface displacement [38]. Typical periods of wind waves in the northern Baltic Proper are from 3 to 4 s [16]. Consequently, the mean wave height observed at Vilsandi is formally equivalent to the average height $H_{2.5\%} - H_{3\%}$ of 2.5–3% of the highest waves during the observation interval. Since the number of observed waves was quite small, the mean height usually insignificantly differed from the maximum wave height. The average ratio of $H/H_{\max}$ at Vilsandi is 0.94, thus the two measures are fairly close to each other. The experience with the visual observations, however, proves that the observer's estimate of the wave height represents rather well the significant wave height [29,30]. For that reason we shall interpret the mean wave height, observed at Vilsandi, as an estimate of the significant wave height.

The wave period (or length) was determined as an arithmetic mean from three consecutive observations of passing time (total length) of 10 waves each time. These waves were not necessarily the highest ones. The result could be formally interpreted as an estimate of the mean wave period. The experience with visual observations, however, suggests that the visually observed wave period is only a few tenths of seconds shorter than the peak period [30]. For that reason, we shall interpret the visually observed wave period as an estimate of the peak period.

The properties of waves in the observation area are affected by a number of shallow-water effects such as shoaling, refraction, the wave energy loss due to bottom friction and partial breaking, and partial reflection of wave energy from the underwater slope, among others. Since the water depth at the location, where the wave properties were determined, was less than 4 m, waves higher than 4 m evidently were in the breaking stage. Since the fraction of 4 m and higher waves is less than 0.4% in this area [16], errors in their observation insignificantly affect the overall wave statistics. Although the joint influence of the listed effects may considerably change the heights of the observed waves, in most cases it does not change the dominating wave period. Also, their joint effect apparently does not substantially affect the magnitude of the relative variations of the seasonal and long-term wave properties.

3. DATA PREPROCESSING

The data was recently digitized from the original observation diaries for the years 1954–2005 [33]. All obviously erroneous, ambiguously written or inconsistent entries (for example, the maximum wave height 5 m and the mean wave height 0.5 m, the sea state nearly calm) were omitted. There are many records of the wave height less than 0.25 m in older diaries. They have been digitized as 0.25 m, because completely calm seas are infrequent in this area [16].

As mentioned above, the number of observed wave parameters decreases in the course of time. Only the wave height has been observed during all the years. Both the maximum and mean wave heights are present in the diaries until 1993. Further on mostly only one measure is present although the two entries appear a few times afterwards until 23 April 1998. The wave period has been recorded until 30 April 1994 and the wave direction until 23 April 1998.

The total number of sensible observations, reflecting at least one parameter of the wave field, is 32 449 (Table 1). The majority of observations has been made at noon. Morning and evening observations are more fragmentary. They are absent during the late autumn and winter eventually because of the darkness. At least one sensible observation exists on 15 038 days, that is, on 79% from the total number (18 993) of days. The data coverage in different years and seasons varies greatly (Fig. 2). The gaps from January to March (Figs. 2, 3) apparently are connected with the presence of sea ice. The largest gaps during other seasons are in July–September 1991 (when the meteorological station was closed), and in August–November 1997 (Fig. 3). There are a few other shorter time intervals, which do not contain wave data. During the first years of measurements the data set contains a few unrealistically high waves. In many cases these entries correspond to very rough seas. The method used for correction of such entries is described below.

Table 1. Parameters of wave observations and properties at Vilsandi

	Total	Days covered	Morning	Noon	Evening
Sensible entries of wave data (maximum or mean) in the diaries in 1954–2005 (18 993 days)	32 449	15 038	10 893	14 484	7 072
Inconsistent data	707		206	351	150
Consistent maximum wave height entries	31 742	14 775	10 687	14 133	6 922
Consistent mean wave height entries	27 203	12 256	9 261	11 856	6 086
Sensible wave period entries in 1954–1994 (14 975 days)	28 016	12 553	9 495	12 266	6 255
Zero wave period	13 550		4 812	5 495	3 243
Records represented in Fig. 4	14 466	7 719	4 683	6 771	3 012
Corrected observations of $H_{max} > 4.5$ m	51		12	31	8
Corrected observations of $H > 4$ m	34		11	18	5
Average maximum wave height, m			0.56	0.65	0.48
Average mean wave height, m			0.49	0.57	0.42

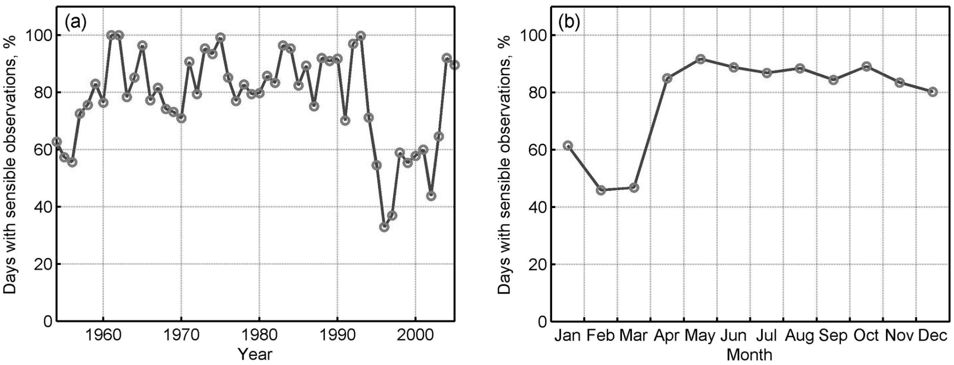

Fig. 2. Percentage of days with at least one sensible wave observation at Vilsandi: (a) in years 1954–2005, (b) in different months.

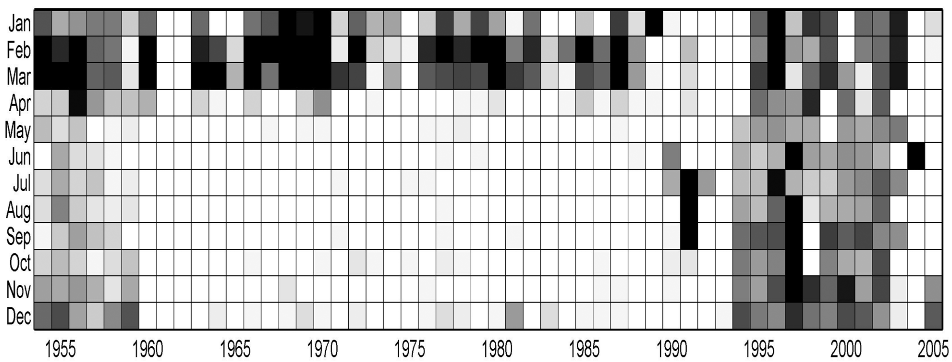

Fig. 3. Temporal distribution of days containing at least one sensible wave observation. The 100% coverage is indicated in white and low coverage corresponds to dark grey.

There are in total 10 838 (10 661) cases (33.4%) when the maximum (mean) wave height is zero. In 9399 cases they both are zero. The majority of such cases apparently correspond to calm seas. However, in some cases the diary reflects a zero wave height but its other entries suggest that the wave height was appreciable. The consistency of such records can be estimated until 30 June 1961 by a comparison with the record of the sea state and later on optionally with the use of another qualitative estimate of wave intensity. The sea state, corresponding to code 0, is perfectly calm and code 1 means very low waves. Code 2 corresponds to the start of breaking of relatively small waves. It is intuitively clear that the wave height under 0.25 m (which could have been filed as $H_{\max} = H = 0$ according to the resolution used) may only correspond to codes 0, 1 or 2. The same is true for the wave intensity that is recorded according to the 9-stage scale (see above). Therefore, in the cases when any qualitative measure of the sea state exceeds 2, the wave height cannot be zero. All such entries

(Table 1) have been omitted from further analysis. The resulting data set consists of 31 742 (27 203) measurements of the maximum (mean) wave height on 14 775 (12 256) days. In nearly all the remaining cases (27 188) the record of the mean wave height was accompanied by the record of the maximum wave height.

For observations where both the mean and maximum wave height were filed, the mean wave height is used below. Since the average ratio of these characteristics is about 0.94, the possible distortion of the wave properties, owing to the potential inhomogeneity of the time series, is fairly minor.

4. OCCURRENCE OF DIFFERENT SEA STATES

The joint distribution of the occurrence of wave heights and mean periods at Vilsandi (Fig. 4) represents all sensible wave observations with non-zero wave

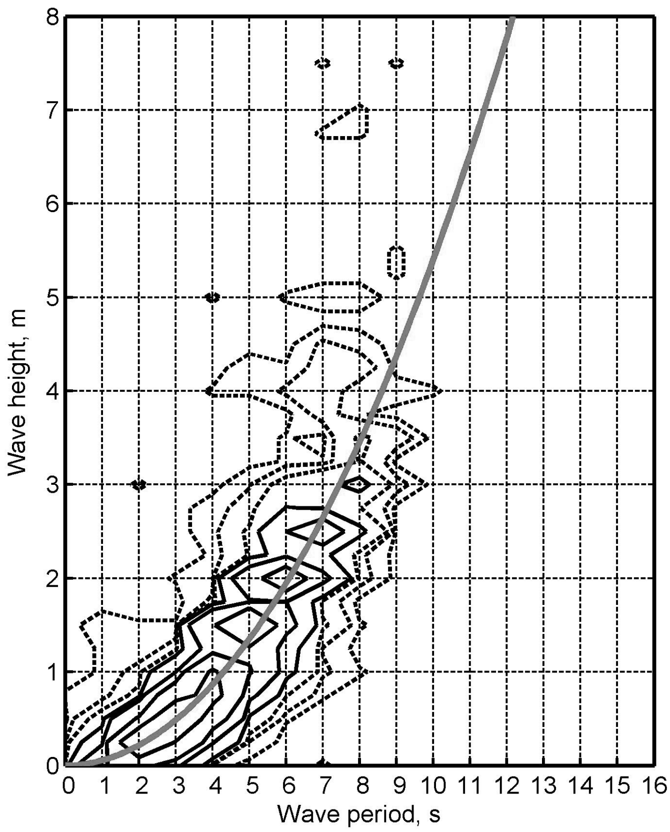

Fig. 4. Joint distribution of observed wave heights H and periods T at Vilsandi in 1954–1994. The wave height step is 0.25 m. The range of periods is shown on the horizontal axis, for example, 1 s means $0.5 \le T < 1.5$ s, 2 s means $1.5 \le T < 2.5$ s etc. Isolines for 1, 3, 10 (dashed lines), 33, 100, 330 and 1000 (solid lines) observed cases are plotted. The bold grey line shows the height of the saturated wave field with the Pierson–Moskowitz spectrum for the given peak period.

period. Since observations of the wave period were made in 1954–1994, the distribution does not reflect the wave properties during the last decade. The total number of records containing sensible wave period is 28 016 on 12 553 days from the total of 14 975 days in 1954–1994. The wave period was zero in 13 550 records. Figure 4 thus represents 14 466 observations on 7719 days. Since there are usually more observations on a day during the relatively calm spring and summer seasons than during the relatively windy autumn season (see below), this distribution may have a certain bias towards overestimation of the frequency of mild wave conditions. This bias, however, is very small in Fig. 4 that uses the logarithmically increasing values of the isolines.

This distribution has the shape, typical for the Baltic Sea wave fields [1,16]. The most frequent wave periods are 2–4 s (20–27% of the observations, Fig. 5a), with the largest number of waves with a period of 3 s. The periods from 2 to 3 s usually correspond to wave heights well below 1 m whereas waves with periods of 4 s have a typical height of about 1 m. Wave periods about 5 and 6 s also occur with an appreciable frequency (14 and 8%, respectively) and usually correspond to wave heights of about 1.5–2 m. Wave fields with periods about 7 s occur with a frequency of about 3%. The corresponding wave heights usually are close to 2.5 m. Wave periods over 8 s are seldom and occur with a probability of about 1%.

Wave data, recorded in the northern Baltic Proper [1], at Almagrundet [16] and in the Gulf of Finland [12], contain a certain amount of swell-dominated wave fields with (peak or mean) periods over 10 s. A wave period close to 10 s has been observed only once and larger periods never at Vilsandi. This feature eventually reflects specific features of visual observations. They tend to over-estimate the proportion of windseas [31] and systematically underestimate the peak periods by a few tenths of seconds [29,30]. The Almagrundet data indicate

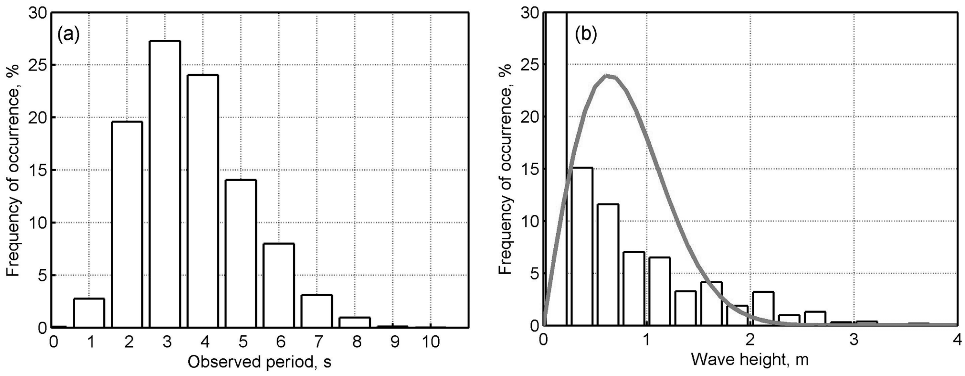

Fig. 5. Distribution of the occurrence of different wave periods (a) and daily mean wave heights (b) at Vilsandi. Notice that panel (a) reflects wave conditions only with non-zero periods, that is, the calm seas are excluded, whereas panel (b) reflects also observed calm conditions. The solid line in panel (b) reflects the corresponding Rayleigh distribution.

that long waves with periods over 10 s usually correspond to low swell conditions when the wave height is well below 1 m. Such waves are not easy to detect from the coast.

Figure 4 suggests that the wave heights in very rough seas (in particular, unrealistically high waves with the height over 4 m) are probably overestimated or reflect groups of large breaking waves. They may also represent a superposition of the incoming and reflected waves, or some specific cross-seas conditions. It is improbable that such combinations of wave heights and periods may occur at the open sea because typical periods in the wave conditions in question range from 5 to 9 s and mostly are from 6 to 8 s. They are much smaller than typical wave periods in extremely rough seas in the Baltic Proper [1,16].

The maximum (mean) wave height was reported to exceed 4.5 m (4 m) several times. There are 26, 9, 6 and 8 observations of wave heights over 4 m in 1954–1957, respectively. The diaries report 8 m high single waves in 5 observations on 17 and 28 September 1954 and on 15–16 October 1955. A wave height of 6.5 m is reported on 9 January 1954 and a 6 m high wave on 31 August 1956. Starting from 1958, the observed maximum (mean) wave height never exceeded 5 m (4 m). Five metres high single waves are once reported in 1997 and once in 2000. Since all the described observations were made in quite strong wind conditions and the maximum and mean wave heights were in a reasonable balance, they eventually correspond to a certain overestimation of wave parameters in relatively rough seas in the early years of the observations.

As a first approximation, the observations of over 4.5 m high single waves (51 observations) were corrected to physically reasonable 4.5 m, and observations of over 4 m high mean wave heights (34 observations) to 4 m. The difference of the mean and maximum wave heights was kept 0.5 m in such cases in order to match the average ratio of 0.94 of these measures. The listed values also roughly match the relevant wave periods in other cases of very rough seas (Fig. 4). The number of corrected entries is about 0.1% from the total number of sensible observations (Table 1). The potential errors of the average wave properties are small; for example, the overall average of maximum wave heights decreases less than 0.2% after the correction. Further analysis has been performed with the use of the corrected wave heights.

5. DISTRIBUTIONS OF WAVE HEIGHTS AND PERIODS

The average wave height at different observation times varies significantly (Table 1). This variation obviously has its origin in the seasonal course of the wave conditions. Statistically, rough seas occur more often in late autumn and winter when only the noon observation can be made in daylight. Therefore the straightforward use of the set of the observations would result in a certain bias of the mean wave properties. For that reason, further analysis relies on the daily average wave height, calculated as an arithmetic mean of sensible observations of each day.

The average wave height at Vilsandi, calculated from daily mean wave heights, is 0.575 m. This is clearly smaller than the mean significant wave height at Almagrundet (0.876 m in 1978–1995 and 1.04 m in 1993–2003 [16]). The wave height median is 0.3 m that is also much smaller than at Almagrundet.

A large part of these differences is apparently caused by the specific location of the observation site. A very rough estimate of the open sea wave climate, based on the Vilsandi data, can be made using the wave statistics from the open part of the Baltic Proper. The fraction of calm situations (wave height less than 0.25 m) is about 5–7% in the northern Baltic Proper [1] but it is much higher in the Vilsandi data. The excess proportion of calm days evidently is largely due to the absence of observable waves in many cases of easterly winds. Removing a fraction of calm days from the Vilsandi data set is therefore roughly equivalent to ignoring such wind conditions. If the number of calm records is reduced to 6% from the total number of non-zero wave conditions, the average wave height at Vilsandi would be 0.74 m and the wave height median close to 0.5 m. These estimates match much better wave conditions at Almagrundet. Note that such an ignoring of a part of calm conditions (equivalently, waves created by easterly winds) insignificantly affects the distribution of relatively rough wave conditions, because easterly winds usually are weak in this area [32]. The relevant correction coefficient for the above estimates of the long-term properties of wave fields is about 1.28.

The probability distribution of the occurrence of different wave heights (Fig. 5b) resembles analogous distributions of wave heights in semi-sheltered bays of the Baltic Sea [17]. It is largely different from the analogous distribution at Almagrundet that resembles the Rayleigh distribution [16]. The probability of the occurrence of the wave height $H \geq 4$ m is about 0.2% that well matches the analogous probability for $H_{1/3} \geq 4$ m (about 0.42%) at Almagrundet in 1978–2003. Yet these estimates are not directly comparable, because a part of observations of over 4 m high waves from the first years of wave observations at Vilsandi may be overestimated and extremely rough wave conditions that occur during a short time in the Baltic Proper may be undersampled in the Vilsandi data.

6. SEASONAL VARIATIONS AND LONG-TERM TRENDS OF WAVE HEIGHTS

The observed wave conditions exhibit a strong seasonal variability at Vilsandi (Fig. 6a). The monthly mean wave height varies from about 0.4 m during the summer to about 0.8 m in the winter. The highest wave activity occurs in January but from October to December a comparable wave activity is observed. The calmest months are the spring and summer months from March to August, with a well-defined minimum in May. Such an annual variation mostly matches the annual variation of the wind speed in the northern Baltic Proper [21]. It also

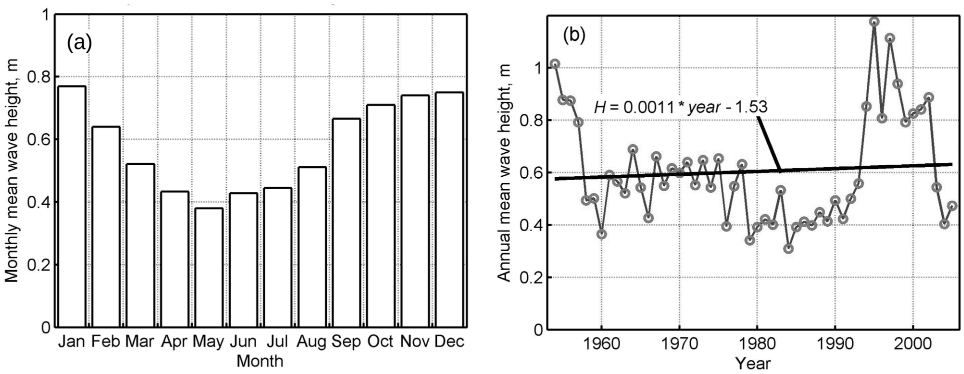

Fig. 6. (a) Seasonal variation of the monthly mean wave height at Vilsandi; (b) annual mean wave height at Vilsandi in 1954–2005.

resembles the similar cycle of water level at this site [39]. The two cycles are only shifted by 1–2 months with respect to each other. The seasonal variation of the wave height at Vilsandi is somewhat less pronounced than at Almagrundet, where the mean wave heights at the most rough and at the calmest months differ from 2.2 to 2.6 times [16]. This difference may reflect different measurement procedures but most probably it reflects the above-discussed absence of waves, excited by eastern winds at Vilsandi.

The total coverage of the measurements is 52 years. This time interval is long enough to extract long-term features of the changes in the overall wave activity. Figure 6b presents the annual mean wave height, calculated from the daily mean heights. The wave heights in the first four years of observations (1954–1957) may be overestimated, because most of the unrealistically high waves were observed during these years. However, the qualitative behaviour of the mean wave height in 1954–1957 apparently reflects a decrease of the wave activity during these years.

The most important conclusion from Fig. 6b is that no simple trend exists in the long-term variation of the annual mean wave height at Vilsandi. The formal trend is indistinct, about 0.1% per annum. The correlation coefficient between the linear trend and the mean wave height is fairly small ($R^2 \cong 0.0063$). Instead, a quasiperiodic variation of the overall wave activity can be distinguished. The interval between subsequent time periods of high or low wave activity is about 25 years. The wave heights are relatively large in 1965–1975 and at the end of the 1990s. The latter maximum is much more pronounced than the former one. The wave activity decreases fast starting from the end of the 1990s. The sea was comparatively calm in the end of the 1950s and in the middle of the 1980s.

The Almagrundet data from the turn of the century were considered as doubtful in [16]. It was argued that the large variation of the wave heights in 1995–2003 did not match the analogous variation of the annual and monthly mean wind speed at Utö, although the wind data from this small island in the northern Baltic

Proper (Fig. 1) represents well the open-sea wind conditions [1,22]. Comparison of Fig. 6b with Fig. 8 of [16] shows that the Almagrundet data from 1995–2003 are in good agreement with the Vilsandi data. Consequently, both data sets probably reflect the changing wave situation in these years.

A fast increase in the annual mean wave height at Vilsandi occurred in 1979–1995. The increase rate is as high as 2.8% per annum, with a reasonably high correlation coefficient $R^2 = 0.44$. This trend follows the increase of the annual mean wave height at Almagrundet as well as analogous trends for the southern Baltic Sea, the North Sea and for the North Atlantic [30,40–42]. It also matches the general tendency of the wind speed to increase over the northern Baltic Sea [16]. Yet this trend existed only during 1.5–2 decades and has been replaced by a decrease of the overall wave activity at the end of the century.

7. CONCLUSIONS AND DISCUSSION

The data set of visual wave observations at Vilsandi cannot be used as an adequate approximation of the time series of the sea state because of their low temporal resolution. Yet the performed analysis suggests that the data represent well general features of the Baltic Sea wave fields, extracted from other data sets. They apparently reflect the basic properties of the wave climate in this area such as a relatively low overall wave activity, short wave periods, and a substantial seasonal variation of the wave conditions that mostly match an analogous variation of the monthly mean sea level.

The central and somewhat surprising outcome from the Vilsandi data is that no clear trend of increasing wave activity can be identified in the northern Baltic Proper. This conclusion is supported by the match of the long-term behaviour of the annual mean wave height at Almagrundet and at Vilsandi. The wave activity at both sites considerably increased in the 1980s, was the highest at the turn of the century and is quickly decreasing starting from about 1998 [16].

Both the temporal behaviour of the wave activity and the water level usually reflect certain features of the wind impact. Somewhat counter-intuitively, the long-term behaviour of the mean wave height does not match the behaviour of the annual amplitude of the monthly mean sea level at the Finnish coast. This amplitude drastically increased in the 1970s and 1980s, and decreased again at the end of the century. Also, the short-term water level variability had a local minimum in the 1960s, increased until the 1980s, and then decreased until the end of the century [43].

The average wave height not necessarily exactly follows the temporal behaviour of the mean wind speed. Yet it is intuitively clear that a larger wind speed generally causes a greater wave activity. This feature eventually causes the similarity of the seasonal cycles of the monthly mean wind speed and the wave height. The match of the temporal behaviour of the Utö wind data and the wave data from Almagrundet in 1979–1995 exists even in years, poorly covered by wave measurements. Quite surprisingly, the rapidly falling trend of the annual average wave height both at Almagrundet and at Vilsandi after 1998 does not match the relevant Utö wind data (see Figs. 8 and 9 in [16]).

The mismatch of the changes of the wind and wave properties in the northern Baltic Proper is a highly interesting feature and needs further investigation. It was hypothesized in [16] that secular changes in the dominating wind directions may affect the trends of Almagrundet wave heights. The qualitative match of the long-term variation of wave properties at the opposite coasts, however, suggests that this is unlikely. Consequently, changes of certain other properties of the wind fields such as the duration of winds from different directions or changes in wind patterns related to the shifts of the trajectories of cyclones [3,44] may play an important role in the forming of the long-term variations of the Baltic Sea wave fields.

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Läänemere põhjaosa lainekliima hinnang Vilsandil tehtud visuaalsete vaatluste alusel

Tarmo Soomere ja Inga Zaitseva

On analüüsitud Läänemere avaosa põhjapoolse sektori lainekliima põhilisi parameetreid ja lainekõrguse sesoonset ning pikaajalist muutlikkust Vilsandil aastail 1954–2005 visuaalselt hinnatud lainetuse omaduste alusel. Lainete tüüpilised perioodid on 2–4 s. Kuu keskmise lainekõrguse aastane varieerumine on analoogiline tuulekiiruse varieerumisega. Kuu keskmine lainekõrgus on väikseim, ligikaudu 0,4 m, aprillist juulini, kuid ulatub 0,8 meetrini jaanuaris. Aasta keskmine lainekõrgus muutus suhteliselt vähe 1960. ja 1970. aastatel, kuid suurenes oluliselt 1980. aastatel, saavutas viimase poole sajandi maksimumi 1990. aastate teisel poolel ja on kiiresti kahanenud alates 1998. aastast.