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Variations in extreme wave heights and wave directions in the north-eastern Baltic Sea

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Abstract. Visual wave observations from the north-eastern coast of the Baltic Proper and from the southern coast of the Gulf of Finland and numerically hindcast wave properties for the entire Baltic Sea were used for the identification of combinations of wave heights and periods in extreme storms and long-term changes in extreme wave heights and wave propagation directions. The extreme wave heights and periods are about 7 m and 10–12 s in the northern Baltic Proper, about 6 m and 8–11 s at the entrance to the Gulf of Finland, and about 4 m and 6–8 s in the eastern part of this gulf. Wave hindcasts show no statistically significant trends in the 95%-iles and 99%-iles of the wave heights. Significant observed changes in the directional distribution of waves at Narva-Jõesuu from the 1980s are not represented in hindcasts.

Key words: wave modelling, wind waves, Baltic Sea, climate change, visual wave observations.

1. INTRODUCTION

Studies of properties of complex wave fields in different sea areas and research towards understanding both the status of and changes in the wave climate form one of the key elements of 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 robust indicators of changes in the wind regime in semi-enclosed sea areas. The potential for the increase in wave heights, for example, in the North Sea (18%) is substantially greater than that of the wind speed (7% for the 99%-iles; Grabemann and Weisse, 2008). An accurate picture of typical and extreme wave properties and their potential changes is, thus, of great value for a wide variety of research topics and engineering applications.

Research into long-term changes in wind properties over the Baltic Sea has highlighted greatly variable patterns of changes (Jaagus et al., 2008). The average wind speed has been increasing over most of this basin (Pryor and Barthelmie, 2003) while a decrease has been observed in a part of the West Estonian Archipelago and on the southern coast of the Gulf of Finland (Keevallik and Soomere, 2004; Kull, 2005). Storminess in the entire region gradually decreased over the first half of the 20th century and rapidly increased in the 1980s–1990s (Alexandersson et al., 1998), raising concerns about destructions to sedimentary coasts (Orviku et al., 2003). On the other hand, both the overall storminess and the number of storm days in the Finnish marine areas decreased since the mid-1990s (Alexandersson et al., 2000; Helminen, 2006).

Long-term changes in wave properties in water bodies adjacent to the Baltic Sea also reveal controversial patterns. Early reviews found an increase in the mean wave height over the whole of the North Atlantic and North Sea, possibly since 1950, of about 2%/year (Bacon and Carter, 1991, 1993). A statistical hindcast over the period of 1962–1986 revealed an increase in the significant wave height at several locations since about 1960 (Kushnir et al., 1997). Subsequent estimates concluded that the North Atlantic wave climate has under-

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gone significant decadal variations but revealed no clear trends (WASA Group, 1998) although there was an apparent artificial worsening of the storm climate in data-sparse areas (Günther et al., 1998). Wang and Swail (2002) argued that the north-east Atlantic has roughened in winters of the last four decades. Numerical reanalysis revealed that the number of rough wave conditions increased only in the 1960s–1970s, but both the intensity and duration of severe storms decreased in the 1990s (Weisse and Günther, 2007). A similar reduction was characteristic of the UK North Sea coast since the 1970s.

The existing long-term wave measurements, observations, and simulations from the Baltic Sea contribute to this pool of controversial patterns. Instrumental data from Almagrundet and visual data from Vilsandi suggest that during the 1980s there was a rapid increase in the annual mean wave activity in the northern Baltic Proper (nBP) (Broman et al., 2006; Soomere and Zaitseva, 2007), followed by a drastic decrease since 1997, and quite low average wave activity since about 2005 (Zaitseva-Pärnaste et al., 2009). At the same time in December 1999 extremely rough seas occurred in the Baltic Sea (Kahma et al., 2003), and windstorm Gudrun in January 2005 apparently caused the all-time highest significant wave height $H_S \approx 9.5$ m (Soomere et al., 2008). This raised the question as to whether the trends for average and extreme wave heights are different in the Baltic Sea basin (Soomere and Healy, 2008).

No such variation was found along the Lithuanian coast (Kelpšaite et al., 2008) and in the Gulf of Finland (GoF). Instead, a stable situation in wave heights was established for certain parts of this gulf (Kelpšaite et al., 2009). Numerical simulations failed to represent the above variations in the nBP (Räämet et al., 2009; Suursaar and Kullas, 2009; Zaitseva-Pärnaste et al., 2009) although they replicated a large part of the interannual variability of the wave fields. The discrepancies between the observed and modelled data apparently stem from the quality of model wind forcing that nowadays is generally adequate for the open ocean conditions (Winterfeldt and Weisse, 2009) but may severely underestimate wind speeds in semi-enclosed basins (e.g., Signell et al., 2005).

The shortages in forcing data and the scarcity of long-term instrumentally measured wave time series from the nBP make the available visually observed wave data sets an important source for the wave research in the Baltic Sea. The pattern of dominant winds (Soomere and Keevallik, 2001), the geometry of the Baltic Sea, and the existing wave climate hindcasts (Räämet and Soomere, 2010) suggest that the highest and longest waves usually occur either at the entrance of the GoF, at the eastern coast of the Baltic Proper (BP), along the Polish coasts, and in the Arkona basin. Historical visual wave data from the north-eastern (downwind) parts of the BP thus form an extremely valuable data set for identification of changes in the local wave climate.

Visual wave observations involve intrinsic quality and interpretation problems (Soomere and Zaitseva, 2007; Zaitseva-Pärnaste et al., 2009). They always contain an element of subjectivity, represent only wave properties in the nearshore and for a limited range of directions, usually have a poor spatial and temporal resolution and many gaps, may give a distorted impression of extreme wave conditions, etc. Their key advantage is the large temporal coverage. Regular visual observations started from the mid-1950s in many locations of the eastern coast of the Baltic Sea and have been carried out with the use of a unified procedure until today (Soomere and Zaitseva, 2007).

The basic features of wave fields and their long-term changes along the Estonian coasts such as the distributions of wave heights and periods and seasonal and interannual variations of the average wave properties have been analysed in detail in (Zaitseva-Pärnaste et al., 2009; Räämet and Soomere, 2010) based on comparisons of measured and observed data with the results of numerical hindcast.

In this study we mainly focus on the properties of the largest waves and their variations along the coasts of the north-eastern Baltic Sea. The analysis relies on comparison of joint two-dimensional (2D) distributions of visually observed and modelled wave properties (scatter diagrams) for historical wave data sets from the eastern part of the nBP (Vilsandi) and the GoF (Pakri, Narva-Jõesuu) and for results of modelling of wave properties over the last 38 years in this region. A relatively good match of these distributions allows for an adequate estimate of the combinations of wave heights and periods in the strongest storms over the entire time interval covered by the data. This match also suggests that numerically hindcast extreme wave conditions correspond well to the realistic roughest seas. Further on, we make an attempt to identify potential changes in the wave heights in strongest storms based on 99%-iles and 95%-iles of the modelled significant wave height for each calendar year. Finally, we take a short look at changes in the directional distributions of wave fields – a feature that may substantially affect the evolution of sedimentary coasts.

2. DATA AND THE MODEL

The analysis below is based on three visually observed wave data sets recorded at (i) the western coast of the island of Vilsandi (58°22′59″N, 21°48′55″E), (ii) Pakri in the western part of the GoF (59°23′37″N, 24°02′40″E), and (iii) Narva-Jõesuu in the eastern part of this gulf (59°28′06″N, 28°02′42″E) in Narva Bay (Fig. 1). Systematic wave observations at these sites started in 1954 and have been carried out until today (until 1985 at Pakri).

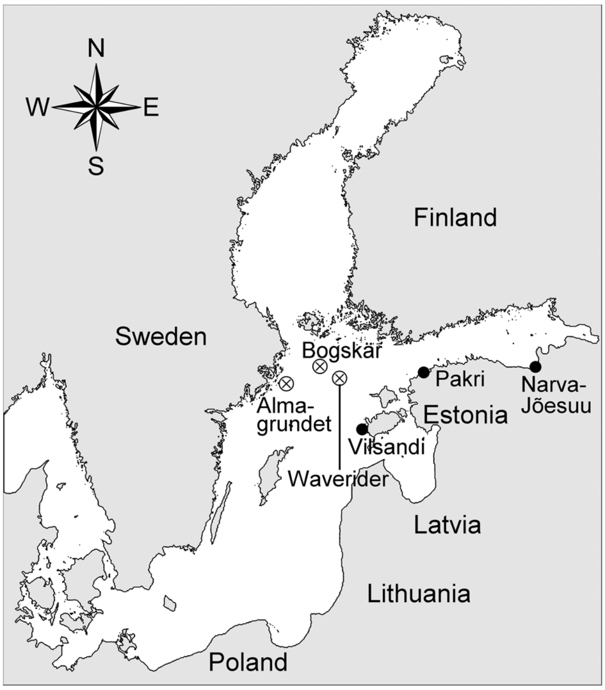

Fig. 1. Location scheme of the wave observation sites.

Data from Vilsandi reflect well waves coming from the westerly directions (Soomere and Zaitseva, 2007), but the largest waves may be distorted owing to a shallow water depth at the observation site. Pakri is the only deep-water wave observation site on the southern coast of the GoF that is largely open to waves generated in the nBP (Zaitseva-Pärnaste et al., 2009). Waves at Narva-Jõesuu are frequently locally generated and usually stem from the GoF. The site is fully open to waves approaching from the north-west and almost open to waves approaching from the south-west to the north. The height of the observation platform is 12.8 m above mean sea level. This allows even better wave observation conditions than at Vilsandi. The measurement routine was identical for all observation sites (Soomere and Zaitseva, 2007).

The properties of wave fields were hindcast with the use of the third generation spectral wave model WAM (Komen et al., 1994). The calculation was made for a regular rectangular grid (resolution about 3 × 3 nautical miles, 239 × 208 points, 11 545 sea points) based on the bathymetry prepared by Seifert et al. (2001) that extends over the ice-free sea from 09°36′E to 30°18′E and from 53°57′N to 65°51′N (Soomere, 2003). At each sea point, 1008 components of the 2D wave spectrum were calculated. The model uses 24 evenly spaced directions. Differently from the standard configuration of the WAM (which ignores waves with periods <2 s), an extended frequency range from 0.042 to about 2 Hz (wave periods 0.5–23.9 s, 42 frequencies with an increment of 1.1) was used to ensure realistic wave growth rates in low wind conditions after calm situations (Soomere, 2005).

The wind forcing at a 10 m level was derived from geostrophic winds as recommended by Bumke and Hasse (1989): the geostrophic wind speed was multiplied by 0.6 and the direction turned by 15° to the left. This approximation is used in many contemporary studies into the Baltic Sea dynamics (Myrberg et al., 2010). An analysis of the performance of the model is presented in (Räämet and Soomere, 2010). The results are called modelled or hindcast data below.

3. RESULTS

3.1. Wave properties in extreme storms

The combinations of wave heights and periods in the roughest storms can be best estimated from the empirical 2D distributions of the joint probability of the occurrence of wave conditions with different heights and periods (Fig. 2). Such distributions are sometimes also called scatter diagrams of wave heights and periods (Kahma et al., 2003). The most typical combinations of wave properties apparently correspond to the points that are located at the “crests” of this distribution, which is interpreted as a surface elevation map. An exact definition of these crests can be given in terms of differential geometry: the crests are the lines of the curvature corresponding to the minimum normal curvature of the surface and going through a maximum of the surface. In particular, the direction along a crest is normal to the direction of the steepest descent. If such lines can be constructed and extended towards extreme wave conditions, their location indicates the combinations of the expected properties of extreme wave storms.

For the Baltic Sea conditions such diagrams have a regular shape of an elongated hogback-like elevation that is slightly curved along the conditions corresponding to fully developed seas with the Pierson–Moskowitz (PM) spectrum (Fig. 2). Similar diagrams for the open sea conditions usually represent a superposition of two such elevations. One of them is equivalent to those in Fig. 2 and corresponds to windseas whereas the other represents swells with relatively large periods and moderate or low heights. The latter branch is almost degenerate in the Baltic Sea where it becomes evident as a pool of waves with periods of 8–12 s and heights below 0.5 m (Soomere, 2008: fig. 4). A specific feature of the Baltic Sea is that a large part of the wave conditions are represented by points lying considerably to the left of the curve reflecting the PM spectrum and corresponding to high and short, thus very steep waves. Such conditions are frequently connected with acute danger to ships (Toffoli et al., 2005).

The instrumental data from Almagrundet and Bogskär in the north-eastern part of the BP and from a directional

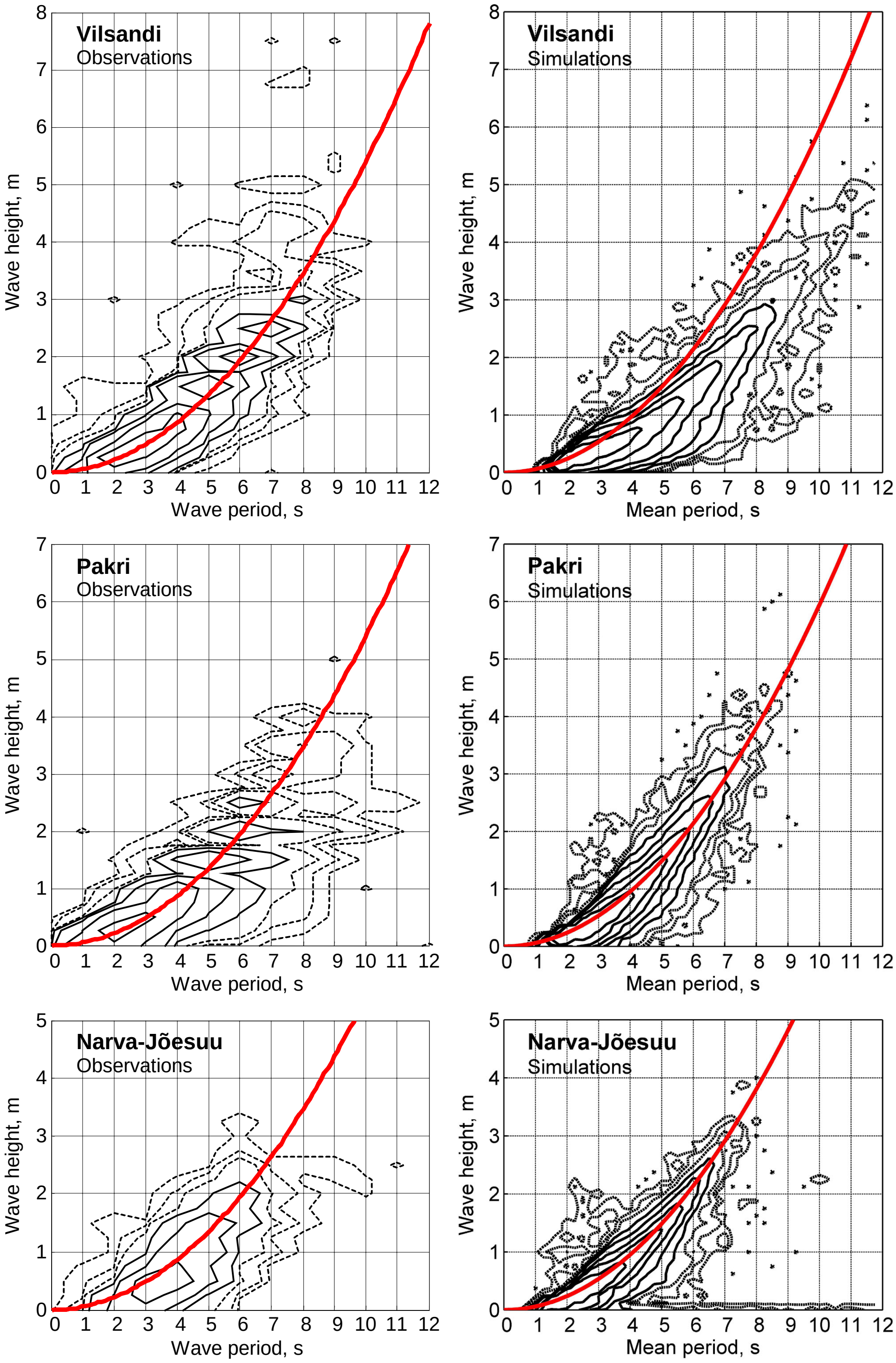

Fig. 2. Joint distribution of observed (all sensible wave observations with a non-zero wave period at Vilsandi (1954–1994), Pakri (1954–1985), and Narva-Jõesuu (1954–1974)) and modelled (1970–2007) wave heights and periods. The wave height step is 0.25 m for observed and 0.125 m for modelled data. Isolines for 1, 3, 10 (dashed lines), 33, 100, 330, 1000, and 3300 (solid lines) cases are plotted. The bold line shows the height of the fully developed waves with the PM spectrum for the given mean period.

waverider (Fig. 1) in the central part of the nBP (Kahma et al., 2003; Soomere, 2008) show that the roughest seas in the Baltic are generally steeper than the fully developed waves. The highest waves ($H_S \geq 7$ m) correspond to mean periods of 8–9 s at Almagrundet and to peak periods of 9–11 s at Bogskär and in the nBP (Soomere, 2008).

The scatter diagrams for observed and modelled waves are similar at all observation sites for low and moderate wave conditions up to wave heights of 3 m (Fig. 2). The properties of the most frequent low and moderate wave fields almost exactly match those of fully developed waves. While almost no swells have been recorded at Vilsandi, a larger proportion of relatively long waves for the given wave height is evident at Pakri and Narva-Jõesuu. This difference apparently reflects the more sheltered locations of these sites where swells may frequently dominate.

The distributions reflecting numerically simulated wave conditions are narrower. This feature probably reflects relatively large uncertainties in the visual detection of wave properties within a short time interval. Another source of differences is the finite resolution of the wave model: the observation site usually does not coincide with the nearest grid point for which the wave properties are calculated. The simulated distributions suggest that moderate and rough windseas are generally (i) clearly less steep than fully developed waves at Vilsandi, (ii) somewhat steeper at Pakri, and (iii) match the properties of wave fields with the PM spectrum at Narva-Jõesuu.

The largest difference in the shape of the distributions for observed and hindcast waves is found at Vilsandi. For example, the typical observed and modelled periods of 4 m high waves are about 8 and 10 s, respectively. A probable reason for this difference is the limited water depth (3–4 m) of the observation area at Vilsandi where waves higher than 3 m may already break and their heights may be easily overestimated. Thus, the hindcast distribution apparently provides a more adequate estimate for the wave properties in strong storms at Vilsandi.

The highest waves occurring once in about 40 years may reach 6.5 m in the deeper nearshore at Vilsandi and about 6 m at Pakri. Notice that observed wave heights of 7–8 m at Vilsandi are obviously overestimated because of quite a shallow depth at the observation area (Soomere and Zaitseva, 2007); yet wave heights >7 m have occurred about twice a decade in the northern Baltic Proper (Soomere, 2008). The corresponding mean wave periods were 11–12 s at Vilsandi, but much shorter, about 9–10 s, at Pakri. The difference in the periods apparently reflects the longer fetch for Vilsandi whereas the maximum wind speed in north-western storms (which create the largest waves at Pakri but have a shorter fetch) exceeds that for south-western storms (Soomere and Keevallik, 2001).

A similar difference in periods persists for somewhat smaller waves: about 5 m high waves have periods of about 11 s at Vilsandi but around 9 s at Pakri. The difference decreases for about 4 m high waves, which should have periods of 9–11 s and 7–9 s, respectively. At Narva-Jõesuu already 4 m high waves are extreme. Their period is expected to be about 7–8 s, that is, the same as at Pakri and by about 2 s shorter than at Vilsandi.

The 1D distributions of the frequency of occurrence of different wave heights and periods can be obtained from distributions in Fig. 2 by integration in the horizontal or in the vertical direction. They have been thoroughly discussed in earlier studies (Kahma et al., 2003; Broman et al., 2006; Soomere and Zaitseva, 2007; Soomere, 2008; Zaitseva-Pärnaste et al., 2009; Räämet and Soomere, 2010). The most frequent wave periods correspond to low waves of about 0.5 m and are 3–5 s in the open sea and 2–4 s in coastal areas. Larger waves have longer periods as indicated in Fig. 2. A somewhat unexpected feature is that the observed data set for Narva-Jõesuu contains a larger proportion of observed waves with periods 3–4 s compared to Pakri or Vilsandi. A probable reason for such a large content of longer waves is that frequent westerly winds may bring to Narva Bay appreciable quantities of remotely generated wave energy, optionally stemming already from the nBP.

The described overall match of the shape and basic properties of the analysed joint distributions of wave heights and periods suggests that the wave model in question properly reproduces the long-term statistics of wave fields in the north-eastern Baltic Sea. This conjecture motivates its use for the analysis of temporal variations of wave properties in severe storms.

3.2. Long-term variations of extreme wave heights

Recent analyses of visually observed data at three sites in question, instrumentally measured data at Almagrundet, and numerically simulated data revealed no clear trend in the annual mean wave heights (Soomere and Zaitseva, 2007; Räämet and Soomere, 2010). Instead, there is drastic interannual and decadal variability, with a typical time scale of 20–30 years, the increasing phase(s) of which have been at times interpreted as evidence of an increase in wave heights (Broman et al., 2006).

The above analysis suggests that visual observations provide no adequate data for estimates of long-term changes in extreme wave conditions. As the observed and simulated wave statistics match each other well, we discuss such variations based on the simulated values of the 99%-ile and 95%-ile of H_S for each calendar year.

The temporal course of both percentiles (Fig. 3) reveals quite large, mostly synchronous interannual and decadal variability in extreme wave conditions at all sites. There were relatively low extreme waves in 1976–

1980 and 1985–1988 whereas in 1989–1995 they were clearly higher. The correlation coefficients between the 95%-ile and the annual mean wave height are quite high, 0.9 at Vilsandi and Pakri and 0.84 at Narva-Jõesuu. The correlation of the 99%-ile with the 95%-ile varies from 0.76 to 0.79 and is somewhat smaller, about 0.7 with the annual mean wave height. The variations are also highly correlated at different sites: the relevant correlation coefficients are 0.75–0.88 for both percentiles.

A qualitative comparison of the discussed results for Vilsandi with similar data calculated with the use of a fetch-based model and one-point wind (Suursaar and Kullas, 2009; Zaitseva-Pärnaste et al., 2009) reveals that the short-term variability in the results of different models is qualitatively similar, but decadal variations are at times quite different and are almost not correlated for some decades. This feature apparently stems from the better ability of the WAM model and adjusted geostrophic wind fields to reproduce the extreme events.

The analysis in (Suursaar and Kullas, 2009; Zaitseva-Pärnaste et al., 2009) indicated a pronounced increase in the 99%-ile and a clear decrease in the mean wave height for the Vilsandi area over the recent past. Somewhat surprisingly, the modelled data show no statistically significant trend of any of the percentiles. There is, instead, a very small increase in the modelled values at Vilsandi (Fig. 3). A very slight increase is present in the 95%-ile and a similar slight decrease in the 99%-ile at Pakri and Narva-Jõesuu. Moreover, no statistically significant trend exists for any of the numerically simulated attributes of the wave fields under discussion.

3.3. Wave directions

The direction of visually observed wave propagation was interpreted as the direction from which the waves approach, similarly to the definition of the wind direction (Soomere and Zaitseva, 2007). The opposite interpretation in the WAM model is reversed below so that all the figures reflect the wave approach direction. The observations were recorded with the resolution of 45°. The ambiguity in the use of zero values at different sites and times (calm seas or waves propagating from the north) was resolved based on other measured parameters. A few doubtful cases are left out from the analysis. The main difference here compared with the analysis of the observed wave heights (Soomere and Zaitseva, 2007; Zaitseva-Pärnaste et al., 2009) is that all consistent observations of wave directions up to three times a day have been taken into account. A large number of wave conditions with zero wave heights and various wave directions from the eastern sector filed at Vilsandi apparently correspond to weak wave fields excited by winds blowing offshore from the measurement site. There are very few such cases at the other sites. The directional resolution of the WAM output in terms of the position of the spectral peak is 1° but the realistic resolution obviously cannot be considerably better than the directional resolution of the grid (15°), and the simulated wave propagation directions are divided into 32 sectors, each covering 11.25°.

The predominant wave directions match the directional structure of the prevailing winds and the geometry of the nearshore of the observation sites (Fig. 4). Vilsandi is fully open to winds and waves from the south-western, western, and north-western directions. The two-peak distribution of modelled waves follows the wind pattern in the nBP where strong winds blow from the south-west or north-west (Soomere and Keevallik, 2001). The observed distribution follows the same pattern but is to some extent smoothed due to the low directional resolution. Waves approach Pakri mostly from the west (although the site is also fully open to the north), and Narva-Jõesuu from the W–NW direction and again the modelled and observed directions generally match each other.

The simulated propagation distributions for all waves and for moderate and high waves $(H_S > 0.5\text{ m})$ almost coincide whereas the ones for the higher waves have slightly narrower and higher peaks. Thus, one of the most interesting properties of wind fields in the GoF (that the direction of the strongest winds does not match the direction of most frequent winds (Soomere and Keevallik, 2003)) is not represented in wave simulations.

The directional distributions of wave approach show a certain interannual and decadal variability for Vilsandi and Pakri but reveal no substantial long-term changes of the predominant direction. As expected from Fig. 4, this distribution has a specific two-peak structure at Vilsandi (Fig. 5) and one peak for an almost fixed direction at Pakri.

Substantial changes in the predominant wave direction have occurred in Narva Bay during the half-century of observations (Fig. 6). Waves mostly approached from the W–NW direction in the 1950s and until about 1965. The predominant approach direction moved almost to the north for the 1970s. Further on, it turned considerably, from the north-west to the south-west (for some years even almost to the south) over the 1980s. Then it switched between the W–SW and the south and has been mostly from the south within the latter decade. The most frequent observed propagation direction, therefore, has changed by more than 90° over the half-century of the observations. The second most frequent wave direction (S–SE) has turned in a similar manner but to a lesser extent. Interestingly, none of these changes are reflected in simulated wave propagation directions (Fig. 6).

The nature of the described changes obviously needs further research, which is out of the scope of this paper. The observed data on wave propagation do not reflect all wave conditions at Vilsandi where for certain years only wave height was recorded (Soomere and Zaitseva, 2007). At Narva and Pakri, wave direction is recorded more regularly (Fig. 7), but still the amount of sensible wave direction recordings is smaller than the number of recorded wave heights. Consequently, the reliability of the analysis of the number of wave conditions (that have been divided between different directions) is much lower than that for wave heights.

Another phenomenon potentially affecting the results in question is that the observer may tend to overestimate the role of relatively short waves whereas a long low swell frequently remains undetected as documented for the Tallinn Bay conditions (Orlenko et al., 1984). As the proportion of long waves is quite large at Narva, this feature of visual observations may lead to a certain overestimation of the frequency of locally generated wave fields.

There are still several arguments suggesting that the turn in question reflects certain changing features of the local wave fields. The change in the coverage of observations in the annual scale, albeit clearly visible from Fig. 7, concerns only the lengthening of the typical observation season by 1–2 months. As in these months only one observation per day was possible in daylight, the changing amount of observations evidently cannot affect so strongly the predominant wave direction. The turn in question evolves gradually over many years and evidently is not related to potential inhomogeneities stemming, for example, from the change of observers. It is highly unlikely that changes in the local wave generation conditions (for example, the diurnal breeze cycle) have led to the described phenomenon.

4. DISCUSSION AND CONCLUSIONS

Comparison of modelled and observed wave statistics confirms that the model satisfactorily represents the basic statistics of the north-eastern Baltic Sea wave fields and is an appropriate tool for studies of the combinations of wave heights and periods in strong storms and of long-term changes in properties of rough seas. The overwhelming domination of windseas suggests that the impact of remote swells is negligible.

Both visual wave observations and simulations with the WAM model and properly adjusted geostrophic winds suggest that there has been no clear trend in severe wave heights (in terms of simulated 95%-ile and 99%-ile) in the north-eastern Baltic Proper and in the western part of the GoF. Although this conclusion does not entirely match the results of several earlier studies, it reflects the limits of the reproduction of the Baltic Sea wave climate with the use of the geostrophic winds. These winds are generally believed to mirror the basic changes in the wind fields in the open ocean but may fail to do so in semi-enclosed basins surrounded by substantial topographic features. Therefore, it is not entirely surprising that the performed simulations failed to reproduce some wave properties in the Baltic Sea basin and that simulations based on more elaborated wind data are necessary to replicate certain aspects of wave climate in this water body.

The north-eastern coasts of the Baltic Proper develop under the impact of high waves that come alternatively from the south-west and the N–NW. The duration of wave events generated by south-westerly winds is clearly longer, but the impact of waves approaching from the N–NW may be almost as strong because winds from this direction may be stronger.

A highly interesting feature, however, is the substantial turn of the predominant observed wave propagation direction in Narva Bay. Even though the visual observations may contain errors and are strongly observer-dependent, the systematic rotation by more than 90° over half a century can be interpreted as an evidence of certain changes in the wind fields over the GoF, possibly connected with the overall increase in the role of south-western winds over Estonia (Kull, 2005).

This turn, however, does not necessarily bring about drastic consequences for the evolution of the sedimentary coasts nearby. For example, the evolution of beaches in Narva Bay is governed by the predominant largest waves that continue to approach from the west to the north even when the formal frequency of wave conditions from these directions has somewhat decreased. The increase in the frequency of waves from southerly directions obviously will cause no large changes in the coastal processes in Narva Bay as these waves are small and short and never occur in high water level conditions.

Further understanding of the spatial extent of the described phenomenon and its magnitude in terms of changes to the energy flux are highly important because it is not excluded that such changes reflect not yet identified properties of wind and wave fields in the eastern part of the Gulf of Finland that may have consequences in the coastal development in affected areas.

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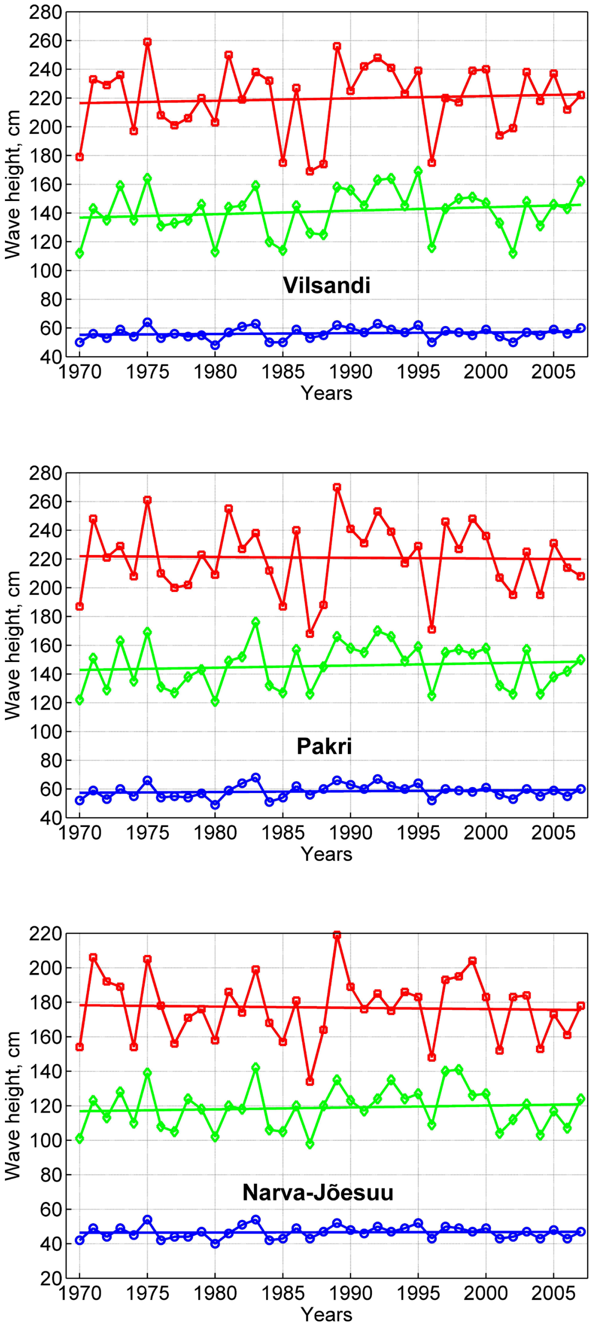

Fig. 3. The annual 99%-ile (red line) and 95%-ile (green line) values of wave heights and the annual mean wave height (blue line). The straight lines show the linear trends.

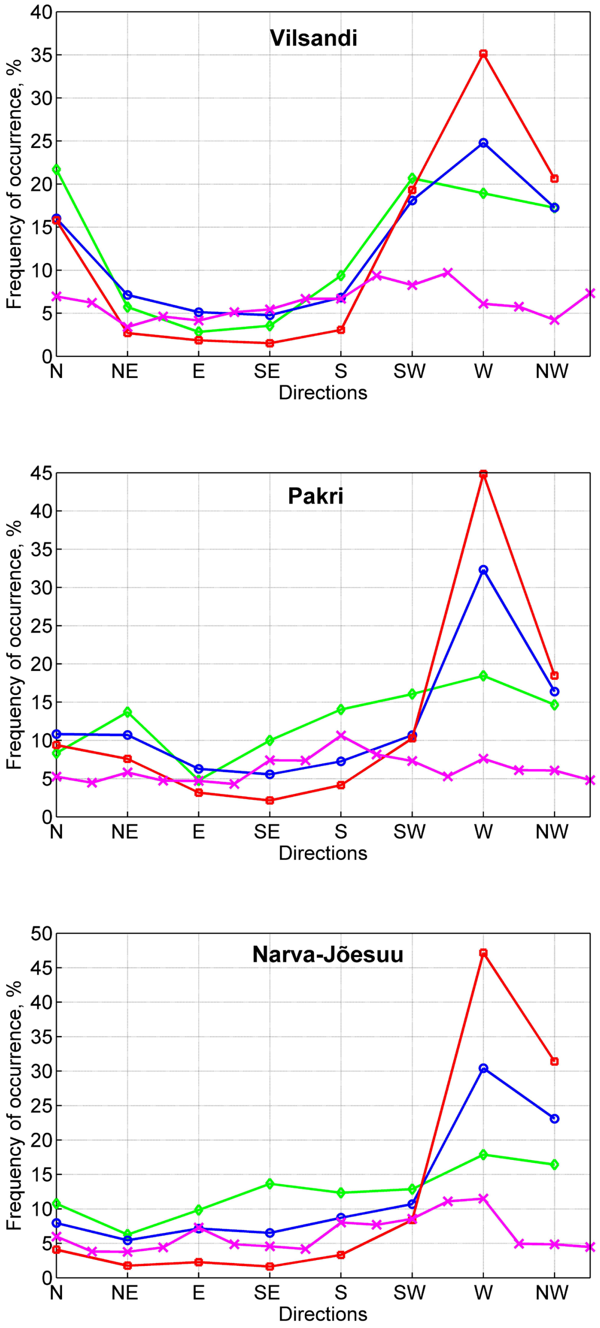

Fig. 4. Distribution of the wind directions (magenta; Kalbådagrund data are used for Narva-Jõesuu) and approach directions of observed (green, all sensible observations) and modelled waves (blue: all waves, red: waves >0.5 m).

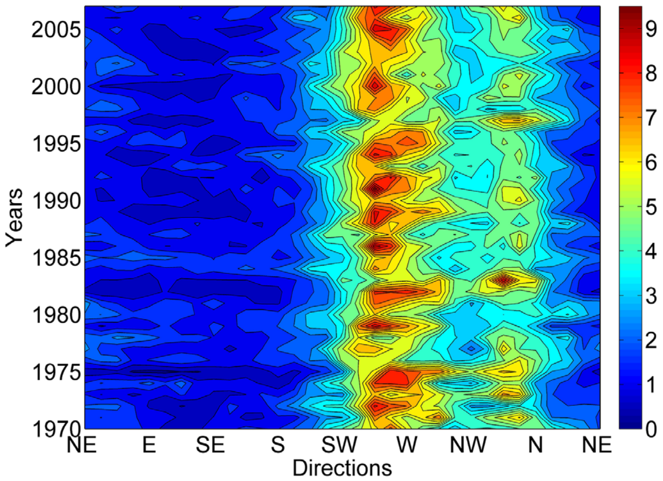

Fig. 5. Modelled directional distribution of wave approach for 1970–2007 at Vilsandi. Colour code shows the frequency of occurrence (%) of waves from a particular direction.

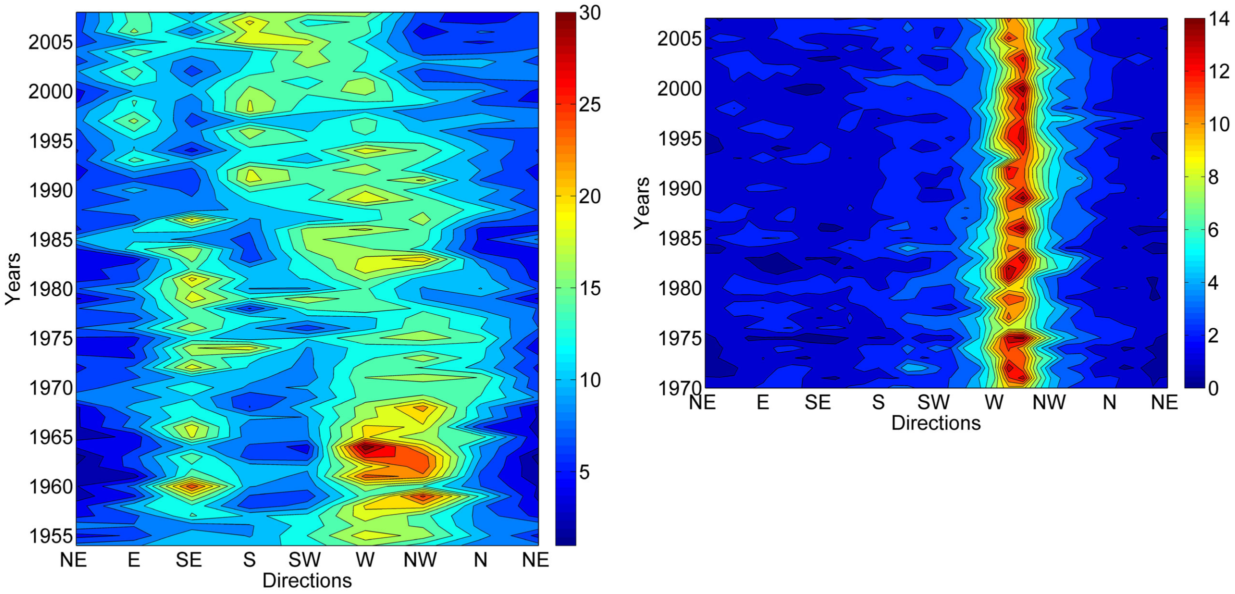

Fig. 6. Observed (left panel, 1954–2008) and modelled (right panel, 1970–2007) directional distribution of wave approach at Narva-Jõesuu. The colour code shows the frequency of occurrence (%) of waves from a particular direction.

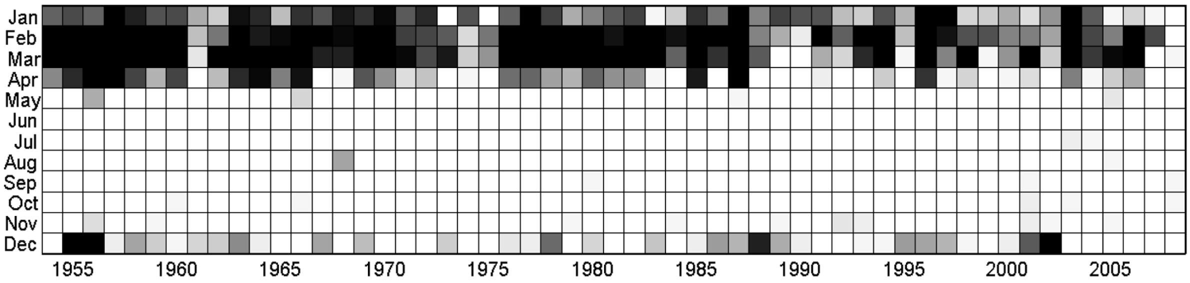

Fig. 7. The number of days with at least one sensible observation of wave directions at Narva-Jõesuu. White cells show 100% coverage, different shades of grey correspond to lower coverage with black indicating absence of observations for the relevant month.

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Ekstreemsete lainetuse tingimuste ja lainete levikusuuna muutustest Eesti rannavetes

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Vilsandil, Pakril ja Narva-Jõesuus tehtud lainevaatluste ning kogu Läänemere lainete numbrilise modelleerimise baasil on hinnatud lainete kõrguste ja perioodide kombinatsioone ekstreemsetes tormides Läänemere kirdeosas ning Soome lahe lõunarannikul, kõrgeimate lainete omaduste muutusi aastail 1970–2007 ja lainete levikusuundade nurkjaotuse muutusi aastail 1954–2009. Ekstreemsetes tormides vastavad ligikaudu 7-meetrisele lainekõrgusele Läänemere avaosas lainete perioodid 10–12 s, 6-meetrisele lainekõrgusele Soome lahe suudmes perioodid 8–11 s ja 4-meetrisele lainekõrgusele perioodid 6–8 s lahe idaosas. On demonstreeritud, et modelleeritud lainekõrguste 95% ja 99% protsentiilid püsisid vaadeldaval ajavahemikul stabiilsetena. On näidatud, et lainete valdav saabumise suund on Narva-Jõesuus alates 1980. aastast muutunud ligikaudu 90° võrra loodest edelasse. Need muutused ei kajastu modelleeritud lainetuse omadustes.