Spatial patterns of the wave climate in the Baltic Proper and the Gulf of Finland*

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Abstract

We make an attempt to consolidate results from a number of recent studies into spatial patterns of temporal variations in Baltic Sea wave properties. The analysis is based on historically measured and visually observed wave data, which are compared with the results of numerical hindcasts using both simple fetch-based one-point models and contemporary spectral wave models forced with different wind data sets. The focus is on the eastern regions of the Baltic Sea and the Gulf of Finland for which long-term wave data sets are available. We demonstrate that a large part of the mismatches between long-term changes to wave properties at selected sites can be explained by the rich spatial patterns in changes to the Baltic Sea wave fields that are not resolved by the existing wave observation network. The

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spatial scales of such patterns in the open sea vary from > 500 km for short-term interannual variations down to about 100 km for long-term changes.

1. Introduction

The Baltic Sea is a challenging area for regional marine science (Leppäranta & Myrberg 2009) and especially for wave scientists in terms of both wind wave modelling and measurements. Numerically reconstructed global wave data sets such as the KNMI/ERA-40 Wave Atlas (Sterl & Caires 2005) allow a quantification of the wave climate and its changes in the open ocean, but their spatial resolution ($1.5° \times 1.5°$) is insufficient for Baltic Sea conditions. Numerical simulations of the Baltic Sea wave climate require a high spatial resolution because of the extremely complex geometry and high variability of wind fields in this basin. The presence of sea ice often complicates both visual observations and instrumental measurements. As floating devices are normally removed well before the ice season (Kahma et al. 2003), the measured wave statistics has extensive gaps for the windiest period that frequently occurs just before the ice cover forms. Relatively shallow areas, widely spread in this basin, may host unexpectedly high waves, formed in the process of wave refraction and optional wave energy concentration in some areas (Soomere 2003, 2005, Soomere et al. 2008a).

Systematic studies into the properties of waves in the Baltic Sea go back more than a half-century (see Soomere 2008 and the references therein) and have resulted in several generations of wave atlases for this region. Several attempts to reconstruct the wave climate based on measured or visually observed data and/or numerical hindcasts have been undertaken for many areas of the Baltic Sea (e.g. Mietus & von Storch 1997, Paplińska 1999, 2001, Blomgren et al. 2001, Cieślikiewicz & Herman 2002, Soomere 2005, 2008, Broman et al. 2006, Soomere & Zaitseva 2007). Many of these studies cover either relatively short periods (a few years) or concentrate on specific areas of the Baltic Sea. This is not unexpected because long-term reconstructions of the Baltic Sea wave fields are still an extremely complicated task and usually contain extensive uncertainties (Cieślikiewicz & Paplińska-Swerpel 2008, Kriezi & Broman 2008). An overview of the relevant literature until 2007 and a description of the basic features of the wave climate (empirical distribution functions of the basic sea state properties such as wave heights and periods as well as a description of wave extremes and decadal changes to wave conditions) are presented in Soomere (2008).

As wave height is often proportional to wind speed squared, wave fields can be used as a sensitive indicator of changes in wind properties (Weisse & von Storch 2010). Storminess in the Baltic Sea region was relatively high at the beginning of the 20th century, decreased in the middle of that century and returned to the original level in the 1980s–1990s (Alexandersson et al. 2000). Consequently, one could expect that extensive changes in the reaction of the water masses have occurred along the coasts of the Baltic Sea. A number of relevant observations of changes to coastal processes that can be related to alterations in wave conditions have been reported during the last decade. These changes may have already caused extensive erosion of several depositional coasts (Orviku et al. 2003, Ryabchuk et al. 2009, 2011) and/or have even overridden the thresholds of wave loads for certain coastal sections.

In the international literature there is, however, highly controversial evidence about the reaction of the Baltic Sea wave fields to changes in the forcing conditions and to some extent also about the reaction of sedimentary coasts. The changes in the Baltic Sea wave climate were apparently marginal from the late 1950s until the late 1980s (Broman et al. 2006, Soomere & Zaitseva 2007). The situation evidently changed in the 1990s, however, when a drastic increase in wave heights was reported off both the eastern and western coasts of the northern Baltic Proper (at Vilsandi according to visual observations, Soomere & Zaitseva 2007, and at Almagrundet, where wave properties were measured with the use of an upward-directed echo sounder, Broman et al. 2006). A rapid decrease in annual mean wave heights has occurred in this area since the mid-1990s (Broman et al. 2006, Soomere & Zaitseva 2007). On the other hand, wave heights along the Lithuanian coast have shown no substantial changes, either during the 1990s or since then (Kelpšaitė et al. 2008).

Such spatially highly variable evidence suggests that wave properties in different regions of the Baltic Sea may reveal different patterns of temporal changes. It is well known that different sub-basins of this water body may host substantially different features of the wave climate. The anisotropic nature of the Baltic Sea wind and wave fields (Jönsson et al. 2002, 2005, Soomere 2003) suggests that considerable differences between typical and extreme wave properties may also exist in the vicinity of different coasts of the Baltic Proper and the Gulf of Finland. Therefore, certain spatial structures of the wave climate may exist in separate sub-basins. A systematic turn in the wind direction (Kull 2005) may obviously lead to opposite trends in wave heights and periods on upwind and downwind coasts. It has been, however, a common implicit belief in existing studies of potential changes in the Baltic Sea wave climate that, apart from the listed variations, major changes to the wave climate have mostly the same pattern in different sea areas.

In this paper, we make an attempt to consolidate the results from a number of recent studies of temporal variations and spatial patterns in

Baltic Sea wave properties. The analysis is based on historical wave data and the results of numerical hindcasts. As most of the available long-term wave data stem from the eastern and north-eastern Baltic Sea and the Gulf of Finland, the focus is on the eastern regions of the Baltic Sea.

We start with a short description of the long-term historical data and the modelling systems used for long-term wave hindcasts. A discussion of visually observed wave properties at selected points along the eastern coast of the Baltic Sea highlights several variations in wave heights, periods and propagation directions at scales from weekly to decadal. Spatial patterns of the long-term average wave heights and periods and extreme wave heights are discussed next. Finally, we provide evidence about differences in the patterns of changes in average and extreme wave heights and demonstrate why many such changes have gone unnoticed in the existing wave measurement network.

2. Long-term wave measurements and observations

There are only a few observation and measurement sites on the eastern coast of the Baltic Sea and in the Baltic Proper covering longer time intervals. In the discussion below, we use the data from Almagrundet, Nida, Palanga, Klaipėda, Vilsandi, Pakri and Narva-Jõesuu (Figure 1). Although the most reliable information about wave properties in the northern Baltic Proper stems from directional wave measurements at Bogskär in 1982–1986, in the northern Baltic Proper since 1996 (Kahma et al. 2003) and in the Gulf of Finland in 1990–1991 and 1994 (Kahma & Pettersson 1993, Pettersson 2001) and since 2001, the measurement period of this data (available only for 1996–2002, Kahma et al. 2003) is not long enough to determine the long-term changes in wave properties in terms of climatological information (WMO 2001). Wave statistics and scatter diagrams for the short-term instrumental measurement sites have been extensively used in comparisons of modelled and measured wave properties.

The data from Almagrundet, a shoal about 20 km south-east of Sandhamn (59°09′N, 19°08′E) on the offshore side of the Stockholm archipelago, form the longest instrumentally measured wave data set in this region (1978–2003, Broman et al. 2006). Although the site is somewhat sheltered from part of the prevailing winds (in particular, the fetch length for winds from the south-west, west and north-west is quite limited at this site), it is located far enough from the coast to capture to some extent the properties of waves created by winds blowing offshore from the mainland. Single waves were identified from the time series of the position of the water surface (sampled over 640 s each hour by upward-looking echo-sounders) using the zero-downcrossing method. Wave components with periods of less

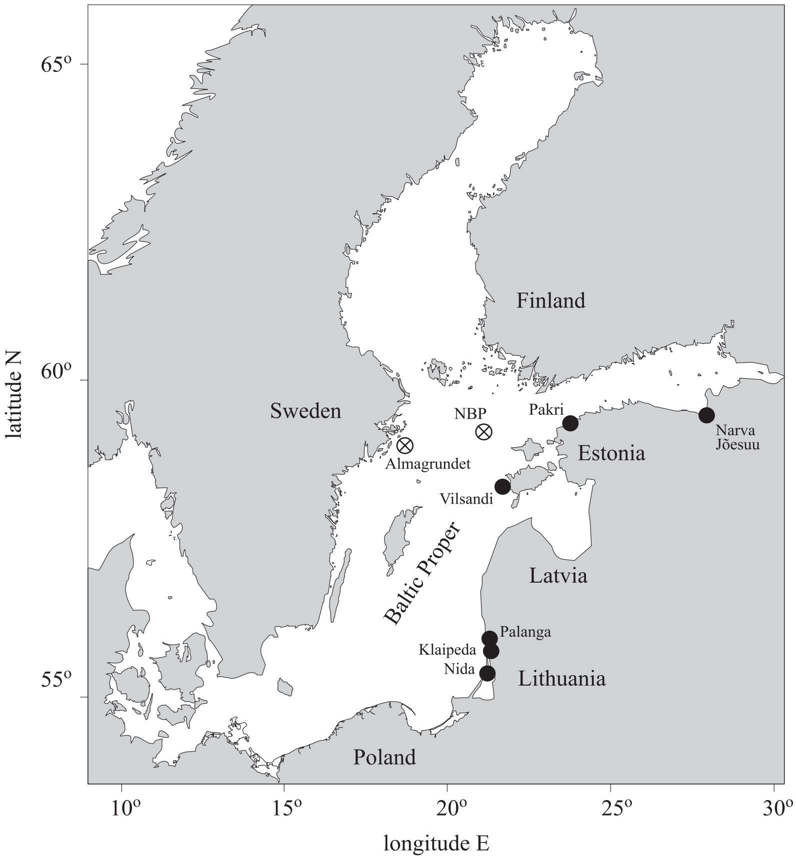

Figure 1. Locations of the long-term coastal observation sites (filled circles) and instrumental measurement sites (crossed circles) providing the data used in this study

than 1.5 s as well as the data probably reflecting wave interference, breaking waves and possibly very steep waves were discarded (Mårtensson & Bergdahl 1987). An estimate of the significant wave height H_S was found from the 10th highest wave in a record on the assumption that wave heights are Rayleigh distributed. Although the minimum water depth at Almagrundet is about 15 m, the water at the measurement site was deep enough (about 30 m) for most of the wave fields to follow the Rayleigh distribution of wave heights. The data from 1978–1995 reliably describes the wave properties in this region, while in the data gathered using another device in 1993–2003 the overall behaviour of the wave height is more or less adequate but the periods are not usable (Broman et al. 2006). In general, the data constitute one of the most valuable data sets for the Baltic Sea because of the long temporal coverage and good resolution (1 h when available).

Historically, the majority of wave information was obtained by means of visual observations. Ship-based observations of open sea wave properties are consistent with those shown by the instrumental records and have been extensively used for estimates of wave climate changes in the open ocean (Gulev & Hasse 1998, 1999, Gulev et al. 2003). Visual wave observations from coastal sites have been less frequently used for wave climate studies. Such data pose intrinsic quality and interpretation problems (Soomere & Zaitseva 2007, Zaitseva-Pärnaste et al. 2009): they contain a large fraction of subjectivity, properly represent only wave properties in the immediate nearshore and for a limited range of directions, and frequently miss long-wave systems (Orlenko et al. (eds.) 1984). They have a poor temporal resolution, often contain extensive gaps caused by inappropriate weather or ice conditions and fail to adequately represent extreme wave conditions. Their basic advantage is the large temporal coverage: regular observations started in the mid-1950s at many locations on the eastern coast of the Baltic Sea and have been carried out using a unified procedure until today (Soomere & Zaitseva 2007). Thus, historical visual wave data from the eastern and north-eastern (downwind) parts of the Baltic Proper and the Gulf of Finland do indeed form an extremely valuable data set for the identification of changes in the local wave climate.

Wave observations at three Lithuanian coastal sites started more than half a century ago but only a small fraction of the diaries for 1992–2008 have been analysed in the international literature (Kelpšaitė et al. 2008, 2011). The Palanga (55°55′N, 21°03′E) and Klaipėda (55°42′N, 21°07′E) observation sites are open to predominant wind directions from south-west to N-NW. At both sites, the water depth in the observation area (about 400–500 m from the coast) was 6–7 m and the observer was standing about 3 m above sea level. The observation site at Nida (55°18′N, 21°00′E) was fully open to waves approaching only from west to N-NW. The observer stood on a turret located 7 m above sea level and observed waves about 700 m from the coastline where the water depth was 6–7 m.

Visual observation sites on the coast of Estonia are located on the island of Vilsandi, on the Pakri Peninsula and at Narva-Jõesuu. Data from Vilsandi (58°22′59″N, 21°48′55″E) reasonably reflect the nearshore sea wave conditions for the predominant wind directions (south-west and N-NW) in the northern Baltic Proper and are available for 1954–2008 (Soomere & Zaitseva 2007, Soomere et al. 2011). This site provides inadequate data for easterly winds. Waves were observed from the coast or a small pier at a distance of 200–300 m from the coast in an area, which was about 3–5 m deep.

Pakri in the western part of the Gulf of Finland (59°23′37″N, 24°02′40″E) is the only wave observation site that is largely open to waves generated in the northern Baltic Proper (Zaitseva-Pärnaste et al. 2009). The observation conditions were particularly good: the observer was located on the top of a 20 m high cliff and the water depth of the area over which the waves were observed was 8–11 m. Data from the Narva-Jõesuu meteorological station in Narva Bay (59°28′06″N, 28°02′42″E) characterize wave properties in the eastern part of the Gulf of Finland (Räämet & Soomere 2010a, Räämet et al. 2010, Soomere et al. 2011). The site is open to waves approaching from west to north. Waves are observed from a 12.8 m high platform in an area 3–4 m deep and located about 200–250 m from the coast.

All the listed coastal sites only conditionally represent open sea conditions. The sheltering effect of the shoreline and the relatively small water depth may at times significantly alter the local wave properties compared to those in the open sea due to the shoaling, breaking and refraction of the waves. The potential distortions obviously affect the results of single observations (for example, they generally lead to a certain underestimation of wave heights) but apparently do not significantly alter the qualitative features of the overall wave statistics and evidently do not impact on the nature of long-term variations and trends in wave properties.

The routine and technology for the observations were identical at all visual observation sites. They are presented in several of the above-cited sources and we just describe the key features of the routine here. The entire procedure relies on the classical zero-crossing method. The observer noted the five highest waves during a 5-min time interval. Both the mean height H of these five waves and the highest single wave $H_{\max}$ were filed until about 1990. The mean wave height is normally used in the analysis; when it was missing, it was substituted by the maximum wave height. As the latter was, on average, only 6% higher than the mean wave height at Vilsandi (Soomere & Zaitseva 2007), the potential difference is much smaller than the accuracy of the determination of the wave height. The wave period was determined as a mean period of 30 waves from three consecutive observations of sections of 10 waves (not necessarily the highest ones). The visually observed wave height is usually a good representation of the significant wave height, whereas the estimated wave period is a few tenths of a second shorter than the peak period (Gulev & Hasse, 1998, 1999). The wave direction was determined in the 8-rhumb system (directional resolution 45°) as the approach direction of the largest wave components. In order to remove the bias caused by a systematically larger number of observations per day during relatively calm spring and summer seasons on the Estonian coasts, the analysis in the cited sources is based on the set of daily mean wave heights.

3. Wave climate modelling

Spatial patterns of wave properties and their changes in the course of time have been extensively studied during recent years based on numerical simulations and realistic wind patterns for the entire Baltic Sea (Cieślikiewicz & Paplińska-Swerpel 2008, Kriezi & Broman 2008, Räämet et al. 2009, 2010, Räämet & Soomere 2010a,b, Soomere et al. 2011). This research has been complemented by studies of local wave properties and their temporal changes using simplified one-point wave models and locally measured winds (Suursaar & Kullas 2009a,b, Zaitseva-Pärnaste et al. 2009). A combination of these approaches (a rapid method of calculation of the wave climate in small areas using high-resolution spectral wave models covering the entire Baltic Sea and one-point high-quality marine winds) has been developed in Soomere (2005) and Laanearu et al. (2007).

Relatively simple models (in particular, the so-called SMB model, also called the significant wave method, based on the fetch-limited equations of Sverdrup, Munk and Bretschneider (Seymour 1977) and forced by one-point wind data) have been applied in a number of recent studies. Such models calculate the basic wave properties under the assumption that the wind properties are constant over the entire fetch area. As strong winds are frequently highly homogeneous in the Baltic Proper and both the reaction and memory time of a large part of the wave fields in this basin are relatively short (Soomere 2005), such simple models are valuable tools for rapid estimates of the wave statistics and for deriving first approximations of the wave time series in this water body. The models usually need a certain tuning in order to compensate for the difference between the measured wind speeds from those on the open sea (Suursaar & Kullas 2009a,b, Suursaar 2010). They usually reproduce not only the basic wave statistics but also the time series of the wave properties at the calibration site (Zaitseva-Pärnaste et al. 2009). Such models only fail to reproduce remote swell and extreme wave conditions (which are rare in the Baltic Sea, Soomere 2008, Räämet et al. 2010) and some refraction-caused effects.

The identification of spatial patterns in variations of wave properties generally requires the use of contemporary spectral wave models that are able to adequately follow the wave patterns over the entire sea. In general, the WAM model gives good results in the Baltic Sea if the model resolution is appropriate and the wind information is correct (Tuomi et al. 1999). Long-term time series of wave properties for 1970–2007 for the entire

Baltic Sea were computed by Räämet & Soomere (2010a) with the third-generation spectral wave model WAM (Komen et al. 1994) with a resolution of about 3×3 nautical miles. The presence of ice was ignored. The regular rectangular grid (11 545 sea points) extends from 09°36′ to 30°18′E and from 53°57′ to 65°51′N. The wave energy spectrum at each sea point was represented by 24 equally spaced directions and 42 frequencies with an increment of 1.1. Differently from the standard configuration of the WAM model for open ocean conditions, an extended frequency range up to about 2 Hz (wave periods down to 0.5 s) was used to ensure realistic wave growth rates in low wind conditions after calm situations (Soomere 2005). The results were analysed from different viewpoints and compared with observed and measured data in Räämet et al. (2010) and Soomere et al. (2011).

The spatial resolution of the wave model in Räämet & Soomere (2010a) was 3 miles, which is generally thought to be acceptable in the Baltic Proper. This resolution, however, is not sufficient for smaller sub-basins such as the Gulf of Riga or the Gulf of Finland (Soomere et al. 2008b) and apparently also for the Bothnian Bay. The basic qualitative properties of wave fields and their spatio-temporal patterns, at least for the Gulf of Finland, still adequately match the observed ones (Soomere et al. 2010).

The key issue in surface wave hindcasts in basins such as the Baltic Sea with a very complex geometry and high coastal cliffs is the proper choice of wind information. Here, wind data even from sites that are known to predominantly represent the properties of open sea winds still reveal a major mismatch when compared to measured or visually observed wave data (Broman et al. 2006, Soomere 2008) or deviate from modelled wind data (Keevallik & Soomere 2010). This mismatch is also present in reproductions of wave fields using fetch-based wave models (Räämet et al. 2009).

The reliability of patterns and trends extracted from long-term simulations of the wave climate crucially depends on whether or not the wind data are homogeneous in time. In this aspect, the surface winds derived from geostrophic wind data are preferable. Hindcasts by local atmospheric models such as HIRLAM may better represent the wind details at a particular location but usually contain substantial inhomogeneities caused by continuous development of the modelling and data assimilation systems. It is also reasonable to assume that the basic changes to the near-surface wind regime should become evident in geostrophic winds.

The detailed reasoning for a particular choice of wind information for long-term simulations of the wave climate is presented in Räämet et al. (2009) and Räämet & Soomere (2010a). For long-term calculations, the near-surface wind at 10 m level was constructed from the Swedish Meteorological and Hydrological Institute (SMHI) geostrophic wind database with a spatial and temporal resolution of $1^\circ \times 1^\circ$ and 3 hours, respectively (6 hours before September 1977). The geostrophic wind speed was multiplied by 0.6 and the wind direction was turned counter-clockwise by 15°. Although this scheme ignores several details of the vertical structure of winds (Bumke & Hasse 1989), it has become increasingly popular in many contemporary studies of Baltic Sea dynamics (Laanemets et al. 2009, Myrberg et al. 2010). This forcing led to a good reproduction of the overall statistics of wave heights and periods, the seasonal course of waves and short-term (1–3 years) interannual variability in the wave heights (Räämet et al. 2010). The representation of the time series of wave properties was less satisfactory (Räämet et al. 2009) and quite large mismatches occurred in the course of measured and modelled annual mean wave heights (Soomere et al. 2011) as well as in long-term changes to the wave propagation direction (Räämet et al. 2010).

The quality of the WAM wave hindcast was checked against measured and observed wave statistics using three wind data sets (Räämet et al. 2009, Räämet & Soomere 2010a,b). MESAN wind (Häggmark et al. 2000) developed by the SMHI presents hourly gridded wind information with a spatial and temporal resolution of 22×22 km and 3 hours, respectively. It accounts to some extent for local wind variations in rough landscapes and coastal areas. Owing to the short temporal coverage (available since October 1996), this data was not suitable for climatological studies and was only used in model verification runs (Räämet et al. 2009, Räämet & Soomere 2010a). The wave properties were calculated over several windy weeks in 2001 and 2005 (Räämet & Soomere 2010b) using recently reanalysed wind fields developed by the European Centre for Medium-Range Weather Forecasts (ECMWF) and kindly provided by Dr. Luigi Cavaleri and Dr. Luciana Bertotti. The spatial and temporal resolution of this data was $0.25^\circ \times 0.25^\circ$

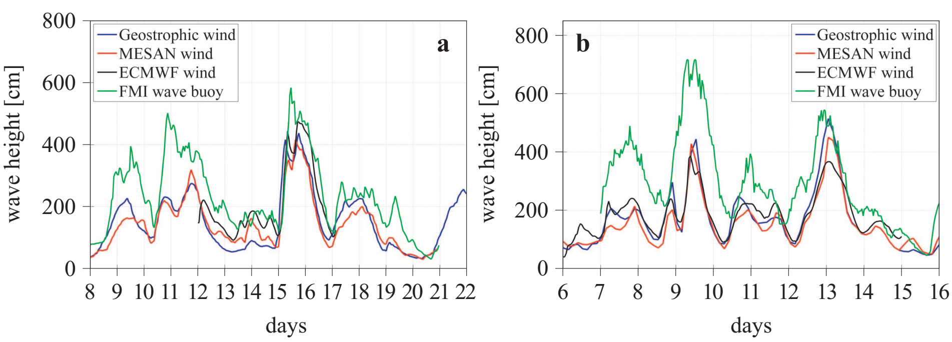

Figure 2. Measured and modelled wave heights in the northern Baltic Proper in November 2001 (left) and January 2005 (Räämet & Soomere 2010b)

and 1 hour, respectively. The overall courses of the significant wave heights simulated with the use of these winds match each other well, but none of the forcings led to a clearly better reproduction of measured wave heights (Figure 2). A typical feature of all model runs is that several storms are almost perfectly reproduced, whereas for others the model almost totally fails. The largest mismatch occurred during certain extreme wave events. For example, all the models underestimated the extreme wave events on 7–9.01.2005 by two to three metres.

The match between hindcasts using different wind sources and the measured data was found to be sensitive with respect to the particular location (Räämet et al. 2009). In the coastal areas of Sweden, simulations using MESAN winds led to a reasonable match of the modelled and measured wave properties, whereas the use of geostrophic winds caused wave heights to be underestimated by about 20%. On the other hand, in the central part of the northern Baltic Proper, the use of adjusted geostrophic winds usually gave much better results, whereas MESAN winds tended to substantially underestimate wave heights at this site. The mismatch between simulations using different wind data was especially large in offshore areas of Estonia, where the calibrated SMB model forced with local wind data measured at Vilsandi and the hindcast using geostrophic winds had almost no bias for coastal waters, whereas the MESAN winds substantially underestimated wave heights (Räämet et al. 2009).

The simulations with the wave model forced by adjusted geostrophic winds in most cases capture all important wave events and their duration (Räämet et al. 2010), although the maximum wave heights are somewhat underestimated during some storm events and for several wind conditions. Such mismatches in the time series of the measured and modelled wave properties are common in contemporary efforts to model wave conditions in the Baltic Sea (Tuomi et al. 1999, Jönsson et al. 2002, Lopatukhin et al. 2006a,b, Cieślikiewicz & Paplińska-Swerpel 2008, Soomere et al. 2008). As the maxima of many strong storms are correctly reproduced in terms of both timing and the maximum wave heights, no additional correction of the adjusted wind speeds was undertaken in the long-term simulations (Räämet & Soomere 2010a,b). Doing so apparently leads to reasonable estimates of the roughest wave situations but underestimates the average wave heights. Comparisons with available measured wave data showed that the hindcast using geostrophic winds (Räämet & Soomere 2010a,b) underestimated the wave heights by an average of about 10–20% all over the Baltic Sea (see below). This feature is consistent with the observations of many authors (e.g. Laanemets et al. 2009), who report that the above-described use of geostrophic winds tends to underestimate the actual wind impact on the sea surface.

The analysis below therefore involves wave heights specified in four different manners: visually observed wave heights, the significant wave height calculated using Rayleigh statistics at Almagrundet, the significant wave height estimated from the two-dimensional energy spectrum in the WAM model and, finally, the significant wave height found from semi-empirical fetch-based models. To a limited extent, the values of significant wave heights measured with the use of directional waveriders are also referred to. Therefore, it is not surprising that both the instantaneous values and the average characteristics found from different sources may differ to some extent. The reasons for such differences, however, can be assumed time-independent and thus always impacting on the results in the same manner. Consequently, it is reasonable to assume that the consistent (and homogeneous in the course of time) use of any particular method for obtaining an estimate for the wave height does not distort the basic features of temporal variations in the wave fields, such as their typical time scales and the direction and relative magnitudes of the trends.

Owing to the finite resolution of the wave model, there is always a certain difference between the location of an observation or measurement site and the nearest grid point for which the wave properties are calculated. This difference is an intrinsic source of deviations between modelled and measured/observed wave data. The match of the basic statistics of numerically simulated wave conditions with those observed at different sites is, however, quite good except for some coastal locations (Räämet et al. 2009, 2010, Zaitseva-Pärnaste et al. 2009, Räämet & Soomere 2010a).

4. Variations in wave properties at different scales

Weekly variations in observed wave heights. The observed data sets contain several gaps for different reasons (Soomere & Zaitseva 2007, Soomere et al. 2011). These gaps are distributed unevenly over the years. Therefore, their presence may affect the estimated course of seasonal and even interannual variations in the wave properties. In order to suppress their influence, Soomere et al. (2011) made an attempt to replace the missing observations by the relevant climatological mean values for wave heights for single calendar days[1]. These values, calculated for each calendar day over 55 years at Vilsandi and Narva-Jõesuu and over 31 years at Pakri, contain

[1]The use of monthly mean values for this purpose may introduce an additional bias because the wave activity may change considerably during transitional months such as March or September (Räämet & Soomere 2010a).

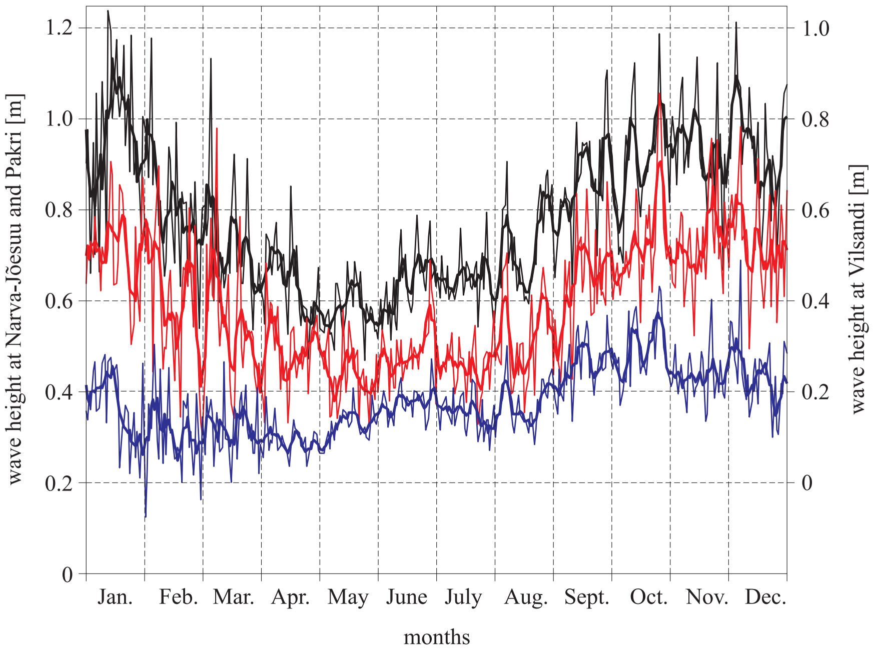

Figure 3. Climatological mean wave height at Vilsandi (black, scale at the right-hand side shifted by 0.2 m), Pakri (red) and Narva-Jõesuu (blue) over all available wave observations (thin line) and its 5-day running average (bold). Data from February 29 are merged with data from March 1

some noise, the level of which is the largest for the season with a relatively small number of measurements (Figure 3). The resulting values show several interesting variations in wave intensity in weekly scales, a part of which are synchronous at all three sites.

The most impressive short-time feature in the wave activity is the relatively calm period at the end of December and the beginning of January. It is well pronounced in the Vilsandi and Pakri data, and somewhat less evident at Narva-Jõesuu. Shorter time periods with noticeably larger wave intensity occur at all sites during the first week of August, in the middle of September, at the end of October and at the beginning of December. Their presence suggests that there might exist quite a strong intraseasonal variability in weather conditions in the north-eastern Baltic Sea region. The spatial extension of this variability is large enough to create a footprint in the wave intensity from the Baltic Proper to the south-eastern part of the Gulf of Finland. A minor feature, probably created by strong easterly winds specific to the Gulf of Finland (Soomere & Keevallik 2003), is the relatively large wave intensity at Pakri in some weeks of April/May and at the end of June.

Seasonal variations in observed, measured and simulated wave heights. The presence of a strong seasonal course in the wave heights in the entire Baltic Sea region is a well-known feature that stems from the similar course in the wind speed (Rzheplinski 1965, Rzheplinski & Brekhovskikh 1967, Kahma et al. 1983, Launiainen & Laurila 1984, Mårtenson & Bergdahl 1987, Kahma & Pettersson 1993, Pettersson 1994, 2001, Mietus (ed.) 1998, Jönsson et al. 2002, Kahma et al. 2003). The seasonal cycle basically follows the annual variation in the wind speed in the northern Baltic Proper (Mietus (ed.) 1998), which obviously mirrors the analogous cycle in cyclone generation over the North Atlantic. This variation is evident at all long-term observation and measurement sites (Broman et al. 2006, Soomere & Zaitseva 2007, Räämet & Soomere 2010a, Räämet et al. 2010) as well as in numerical simulations using different models (Suursaar & Kullas 2009b, Zaitseva-Pärnaste et al. 2009, among others). For the available data from contemporary wave measurement sites it is the strongest at Bogskär where, for example, the probability for significant wave height to exceed 1 m varies from about 90% in November to about 10% in May (Kahma et al. 2003). It is also quite strong at Almagrundet (Figure 4), where the mean wave heights in the roughest and in the calmest months differ 2.2–2.6 times (Broman et al. 2006).

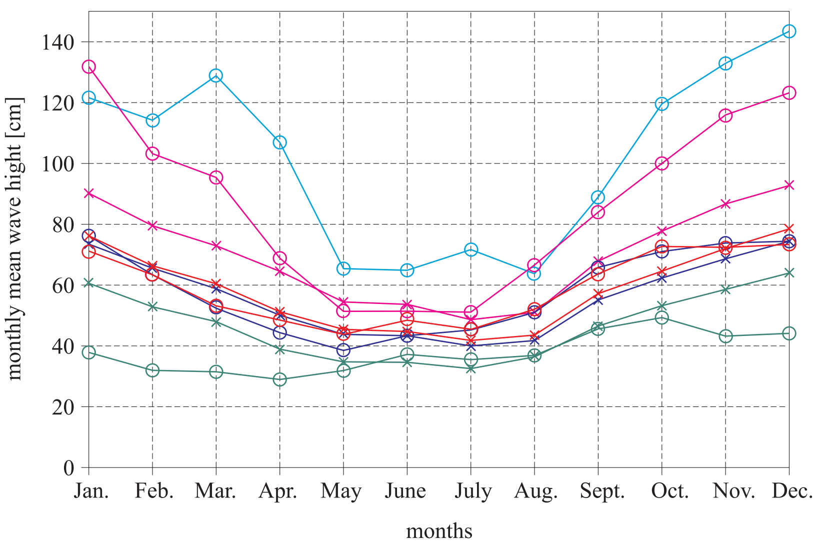

Figure 4. Seasonal variation in the monthly mean wave height at Vilsandi (blue), Pakri (red), Narva-Jõesuu (green) and Almagrundet (magenta 1978–1995, cyan 1993–2003). Circles – observations and measurements; crosses – WAM model

The seasonal course is somewhat less pronounced at coastal sites (Figure 4). The monthly mean wave height varies at Vilsandi from about 0.38 m during summer to about 0.75 m in winter. The highest wave activity occurs in January, and waves are almost as high from October to December. The calmest months are the spring and summer months from March to August, with a well-defined minimum in April or May. The seasonal variation at Pakri almost exactly coincides with that at Vilsandi. There is a less pronounced annual cycle in wave activity at Narva-Jõesuu (Figure 4), where the roughest months are September and October. Relatively low values of the monthly mean wave heights at this site in November–December may reflect the frequent presence of sea ice in the eastern Gulf of Finland in late autumn (Sooäär & Jaagus 2007). The large difference between the magnitudes of the seasonal cycle at Almagrundet and at the Estonian coastal sites most probably reflects the impact of the coast upon visually observed wave conditions (Soomere & Zaitseva 2007). Almagrundet is located far enough from the coast to capture to some extent the properties of waves created by winds blowing offshore from the mainland, while at the coastal sites the observer usually files calm seas under such conditions.

Time lag between windy and high-wave seasons. Long-term hindcasts using the adjusted geostrophic winds and the WAM model showed that during the first half of the calendar year the model overestimates, and in the second half underestimates, the monthly mean wave heights at several wave observation sites (Räämet & Soomere 2010a). This feature may stem from the time lag between the seasonal patterns of the geostrophic wind speed and observed wave heights. It becomes evident as quite a large time shift (up to 2.5 months) between the courses of observed and modelled wave heights in the coastal areas of Estonia. Interestingly, it also becomes evident for measured wind speeds and modelled wave heights.

Thus, the windiest season does not necessarily coincide with the season with the largest wave activity in this region. The time lag is estimated in Räämet & Soomere (2010a) in that the transitional period between the stormy (from October to February) and calm (from April to August) half-years is identified. The clearest separation of these half-years in terms of high-quality marine winds measured on the island of Utö in the north-eastern Baltic Proper occurs when September is allocated to the windy season and March to the calm season. These seasons revealed quite different increase rates in wind speed at Utö: while an increase of about 2% is found for March–November, a much faster increase, about 3.5% annually, has occurred in December–February. But a clear separation of rough and calm seasons in terms of the monthly mean modelled wave height takes place when September is attached to the calm half-year. More detailed estimates of the time lag between the overall patterns of seasonal variation of wind and wave conditions are found in Räämet & Soomere (2010a), who approximated the relevant variation with a sinusoidal function (cf. Launiainen & Laurila 1984). The time lag between the wind speed at Utö and the observed wave height at Vilsandi is about half a month. It is almost a month between the observed and modelled wave heights at Vilsandi and about two months between the observed and modelled wave heights at Pakri. Consistently with the relatively large increase in wind speed at Utö in December–February, a substantial increase in wave heights only occurs at Vilsandi in early winter, whereas during all other seasons there were almost no changes in the wave intensity.

Interannual variations in observed and measured wave heights. The Baltic Sea wave fields reveal a wide range of variations in different time scales. Interestingly, the appearance and spatial coherence of such variations has undergone major changes over the last 60 years. First of all, the years with relatively high or low wave activity compared to their adjacent years occurred simultaneously in the southern and northern sections of the eastern coast of the Baltic Proper for 1993–2005 (Kelpšaitė et al. 2008). For some years the high wave activity at Vilsandi is mirrored by relatively low wave heights at Almagrundet (Broman et al. 2006, Soomere & Zaitseva 2007, Soomere et al. 2011). This peculiarity is not surprising and is apparently caused by changes in the prevailing wind direction.

Variations in the annual mean wave height at Pakri are the most similar to those at Vilsandi (Zaitseva-Pärnaste et al. 2009) except for the first three years of visual observations (1954–1956). The wave heights may have been overestimated at Vilsandi during the very first years of observations (Soomere & Zaitseva 2007); however, there is some evidence that storminess was quite high in the Baltic Proper during these years (Bergström et al. 2001). The similar variations at Narva-Jõesuu completely follow those at Pakri for 1954–1985 (Soomere et al. 2011). In other words, the short-term (1–3) year interannual variability in the wave intensity seems to have the same pattern over a large region from the southern Baltic Proper up to the eastern part of the Gulf of Finland from the mid-1950s until the mid-1980s. Therefore, since the beginning of the visual wave observations, wave heights have behaved similarly at all Estonian coastal observation sites over about thirty years. This coherence and in-phase manner of interannual variations (which can be tracked down to the Lithuanian coast and up to the Swedish coast of the northern Baltic Proper) suggest that the interannual changes to wave fields were caused by certain large-scale phenomena embracing the entire Baltic Proper and the Gulf of Finland, that is, with a typical spatial scale > 500 km.

Surprisingly, this coherence is completely lost in the mid-1980s (Soomere et al. 2011), but subsequently, both wave height trends and details of interannual variations in the wave intensity are different at Vilsandi and at Narva-Jõesuu (Figure 5). Moreover, in contrast to the period before the 1980s, years with relatively high wave intensity at Vilsandi correspond to relatively calm years in Narva Bay and vice versa. The similarity of short-term interannual variations, however, can still be tracked in the northern Baltic Proper until the end of the wave data series at Almagrundet (2003) and to a limited extent to the south-eastern sector of the Baltic Sea until 2008 (Kelpšaitė et al. 2011, Soomere et al. 2011).

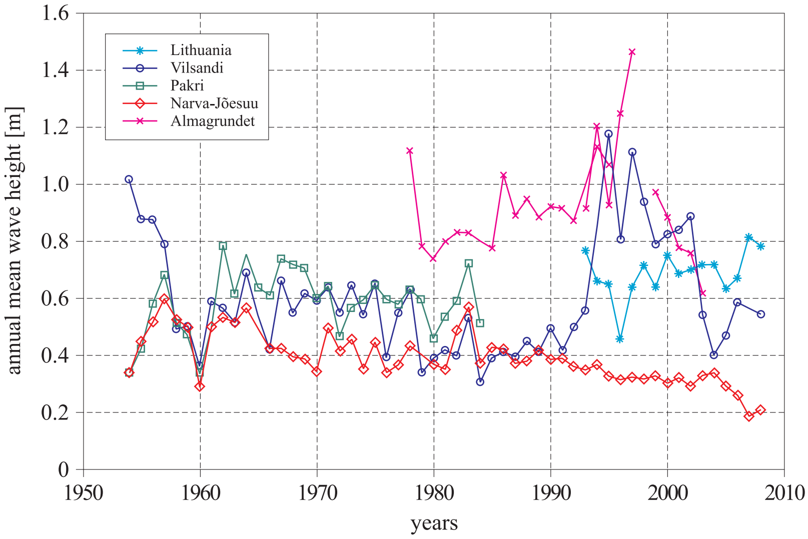

Figure 5. Long-term variations in wave heights at Vilsandi, Pakri, Narva-Jõesuu and Almagrundet and the average over Lithuanian sites (Kelpšaitė et al. 2008, Soomere et al. 2011)

The short-term interannual variations in the temporal course of the annual mean wave heights calculated from climatologically corrected data sets of visual observations are almost identical to those in Figure 5 (Soomere et al. 2011). The climatological correction of observed wave data leads to a substantial increase in the correlation between simulated and observed annual mean wave heights, in particular, for years of coherent observed and simulated interannual changes (Soomere et al. 2011). This feature is not unexpected, because introducing such a correction is equivalent to largely ignoring the ice cover.

Decadal and long-term variations. Both observed and measured wave data reveal substantial variations in the annual mean wave height in the northern Baltic Proper. There is an increase in the mean wave height at Vilsandi and for a few years at Pakri around the year 1960 and an overall slow decrease until the mid-1970s. The most significant feature in the long-term behaviour of the Baltic Sea wave fields is the rapid increase in the annual mean wave height in the northern Baltic Proper from the mid-1980s until 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% (Soomere & Zaitseva 2007)). This trend follows the analogous trends for the southern Baltic Sea and for the North Atlantic (Gulev & Hasse 1999, Weisse & Günther 2007). The increase only existed for about 15 years and was replaced by a drastic decrease after 1997.

Such extensive variations raised the question about the significance of different factors (such as instrument failure, observers' error or noise in the data, Broman et al. 2006, Soomere & Zaitseva 2007) affecting the observed and measured changes. The relevant data from Almagrundet was even assessed as doubtful by Broman et al. (2006) because the annual mean wind speed in the northern Baltic Proper continued to increase. As the recorded changes occurred simultaneously at Almagrundet and Vilsandi, and with a similar relative range on both the eastern and the western coasts of the sea, they appear to show large-scale decadal variations in wave properties, although the magnitude of the changes may be overestimated (see below). The decrease is mirrored by a certain decrease in the intensity and duration of severe wave heights in the North Sea since about 1990–1995 (Weisse & Günther 2007). As a result, the wave activity in 2004–2005 was equal to the global minimum that occurred at the beginning of the 1980s.

Similar variations were much weaker or almost missing in the semi-enclosed bays of the northern coast of Estonia and on the Lithuanian coast (Kelpšaitė et al. 2008, 2009) as well as in the eastern part of the Gulf of Finland (Soomere et al. 2011). Interestingly, the wave intensity clearly increases on the Lithuanian coasts in 2006–2008. This suggests that the decadal variations – unlike the interannual ones – are essentially uncorrelated in the southern and northern parts of the Baltic Proper.

Despite drastic decadal variations, the overall course in the wave activity in different parts of the Baltic Sea reveals no clear long-term trend (Soomere & Zaitseva 2007, Soomere 2008) except for Narva-Jõesuu, where wave intensity is gradually decreasing (Soomere et al. 2011). 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. Another period of very high wave activity occurred in the 1990s.

The use of climatologically corrected data sets does not change the overall pattern of decadal variations but considerably suppresses their magnitude (Soomere et al. 2011). The climatologically corrected annual mean wave heights differ by up to 30% from the relevant values based on the original data at Vilsandi in 1970–1990. The corrected values are larger for years with relatively low wave intensity and long ice cover (for example, in the 1970s). On the other hand, they are smaller by up to 20% in the 1990s and at the turn of the millennium. The best estimate for the wave intensity apparently lies between the two values. The large decadal variations in the 1980s and 1990s are still clearly evident. The two estimates for the annual mean wave heights differ much less for Pakri and Narva-Jõesuu (except for the few most recent years). The largest difference becomes evident for Narva-Jõesuu starting from 2005. Interestingly, the original and corrected values for Vilsandi almost exactly coincide for these years.

Interannual, decadal and long-term variations of modelled data for single sea points. The relatively small size of the Baltic Sea and especially its sub-basins, frequent large-scale homogeneity in the wind fields (Soomere 2001), and the short saturation time and memory of wave fields in changing wind conditions make it possible to use simplified wave hindcast schemes (Soomere 2005, Laanearu et al. 2007), high-quality wind data from a few points (Blomgren et al. 2001) and/or simple fetch-based wave models (Suursaar & Kullas 2009a,b, Suursaar 2010) to reproduce wave statistics with an acceptable accuracy. Early attempts to simulate the wave climate for the southern Baltic Sea (e.g. Blomgren et al. 2001) do not account for changes in the wind direction over large sea areas and thus tend to overestimate wave heights to some extent. For the same reason, fetch-based models usually need a certain calibration (Suursaar & Kullas 2009b, Suursaar 2010). The relevant results, although highly interesting for understanding long-term changes in the wave fields, are only adequate in the vicinity of the wind measurement site.

Interestingly, long-term simulations with the properly calibrated SMB model often nicely restore the time series of wave properties and reproduce several qualitative features of long-term changes to the wave fields but generally fail to capture the substantial variations in wave properties in the Baltic Proper discussed above (Räämet et al. 2009, Zaitseva-Pärnaste et al. 2009). For example, near the Harilaid Peninsula, located about 15 km from Vilsandi, the modelled long-term variations in average wave height showed quasi-periodic 30–40 year cycles with above-average values during a few years at the beginning of the 1980s and especially around 1990 and

1997, and lower values for 1975–1980 and 2000–2005 (Suursaar & Kullas 2009a,b). Consistently with the observed data, the wave intensity reveals no statistically significant trend (Figure 6). 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), whereas the threshold for the 1% highest waves a year (called extreme wave height below) showed a clear increase (Zaitseva-Pärnaste et al. 2009). There is almost no change in the annual standard deviation of the wave height over the simulation period. Not surprisingly, the variations in the modelled winter (December–March) wave heights were found to be in good correlation with the NAO index (Suursaar & Kullas 2009b).

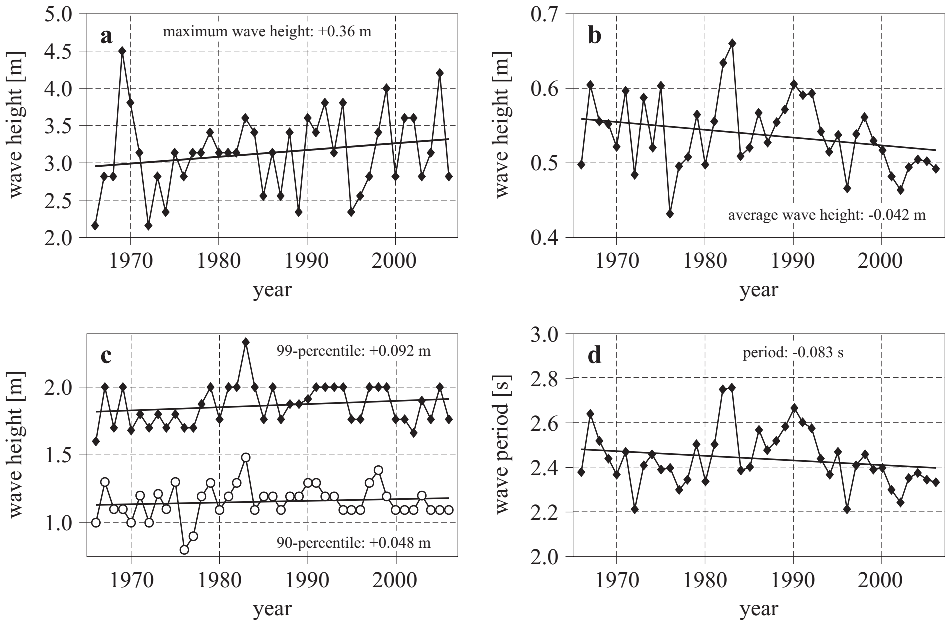

Figure 6. The modelled annual maximum (a) and average (b) wave height, thresholds for the largest 1% and 5% (called also 99-percentile and 95-percentiles, respectively (c), and wave period (d) at Vilsandi based on the SMB model and wind data from Vilsandi (adapted from Suursaar & Kullas 2009b). The average wave height increased by 0.16 cm year^{-1} until 1990 and has decreased by 0.57 cm year^{-1} since then (Räämet et al. 2009)

Simulations using the SMB model and wind data from Kunda for the Letipea area located about 80 km to the west of Narva-Jõesuu revealed, like the data from this site, a gradual decrease in the average and extreme wave heights for 1966–2006 (Suursaar 2010).

Seasonal variations in wave heights and the qualitative course of short-term interannual variations in the annual mean wave height are almost perfectly captured by the WAM model forced by adjusted geostrophic winds for both Estonian (Soomere et al. 2011) and Lithuanian (Kelpšaitė et al. 2011) coastal data. The match of observed and modelled data is equally good for wave heights calculated over 1-year sections containing the entire windy season (from July 1 to June 30 of the following year, Soomere et al. 2011).

In the light of the almost perfect reproduction of the seasonal and short-term interannual variation, it is highly surprising that the WAM model, too, almost entirely fails to reproduce the above-discussed decadal variations in wave properties along the eastern coast of the Baltic Sea (Räämet et al. 2010). A reasonable match only exists for Narva-Jõesuu until 2004 but is lost from 2005 (Soomere et al. 2011). Interestingly, climatological correction clearly increased the correlation between simulated and observed wave data until the mid-1980s. In contrast, the correlation between the simulated and observed annual mean wave heights is completely lost for the years 1988–2007.

Wave periods and approach directions. Large variations in the average wave periods (from about 2.3 s in the mid-1970s up to 2.65 s around 1990) with the same typical time scale of about 30 years were found in simulations with the SMB model (Suursaar & Kullas 2009b). Kelpšaitė et al. (2011) noted that the direction of high waves differs substantially from the most frequent wave approach direction at the Lithuanian observation sites. Further analysis revealed quite large interannual variations in the wave direction for 1993–2008. Only a weak prevalence of waves from the south-west and west was observed in 1993–1994. A wide directional distribution with a slight prevalence of waves from easterly directions occurred in 1996–1997 and around 2000. These distributions became much narrower from about 2002 onwards, and most waves have been arriving from the south-west since then. Although there have been single years with similar narrow distributions before, by the end of the 2000s, narrowness became the dominant feature at Palanga. As the data from this site are apparently the most representative of the Lithuanian coastline (Klimienė 1999, Kelpšaitė et al. 2008), this narrowness probably represents a certain rearrangement of the wind regime. The described changes may be responsible for decadal changes to the balance of accumulation and erosion of sections of the Lithuanian coast (Kelpšaitė et al. 2011).

The analysis in Kelpšaitė et al. (2011) highlighted the importance of the wave approach direction in the Baltic Sea basin and the potential for its change, and triggered subsequent studies into this property. The two-peak structure of the predominant observed wave directions (Räämet et al. 2010) matches the similar directional structure of the prevailing winds at Vilsandi (Soomere & Keevallik 2001) but is to some extent smoothed owing to the low directional resolution of the observations. Waves approach Pakri mostly from the west. The simulated propagation distributions for all waves and for moderate and high waves almost coincide. Thus, one of the most interesting properties of wind fields in the Gulf of Finland (that the direction of the strongest winds does not match the direction of the most frequent winds (Soomere & Keevallik 2003)) is not represented either in wave observations or in simulations. The directional distributions of the wave approach show a certain interannual and decadal variability for Vilsandi and Pakri but reveal no substantial long-term changes of the predominant direction.

A much clearer pattern of the changes in wave direction was found for Narva-Jõesuu during the half-century of observations (Räämet et al. 2010). Waves mostly approached from the west or north-west until about 1965 (Figure 7). The most frequent approach direction moved almost to the north

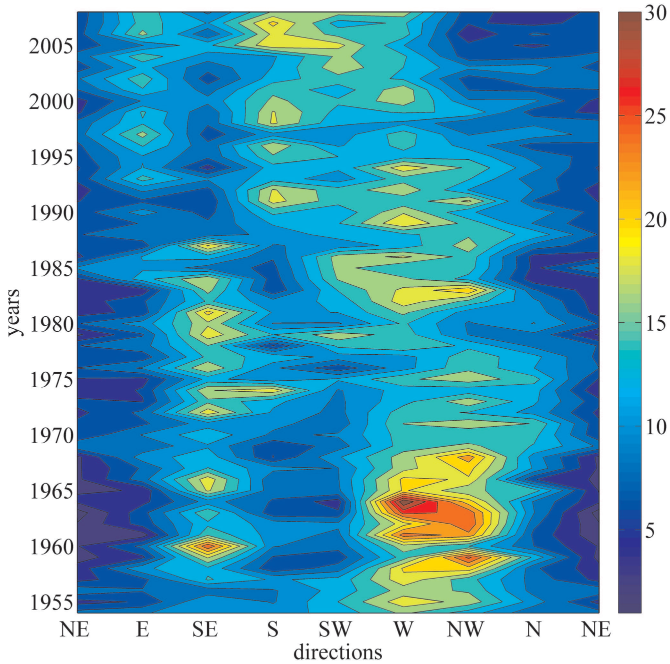

Figure 7. Observed directional distribution of the wave approach at Narva-Jõesuu for 1954–2008. The colour code shows the frequency of occurrence [%] of waves from a particular direction (Räämet et al. 2010, with permission from Estonian Academy Publishers)

in the 1970s. Later, it turned considerably, from the north-west to the south-west during the 1980s, and has been mostly from the south since about 2000. The most frequently observed propagation direction, therefore, has changed by more than 90°. The second most frequent wave direction (SE) has turned in a similar manner. Interestingly, none of these changes are reflected in the simulated wave propagation directions, which are concentrated around W-NW (Räämet et al. 2010).

Extreme waves from scatter diagrams. The combinations of wave properties in the roughest storms can be estimated from the empirical two-dimensional distributions of the joint probability of the occurrence of wave conditions with different heights and periods (called scatter diagrams in some sources, Kahma et al. 2003). The empirical distributions of the frequency of occurrence of different wave heights and periods can be obtained from scatter diagrams by integration in the relevant direction.

For the Baltic Sea conditions such diagrams for both observed and measured data are dominated by an elongated region corresponding to the most frequently occurring wave conditions. Its location largely matches the curve corresponding to fully developed seas (Soomere 2008). The instrumental data from Almagrundet and Bogskär and from a directional waverider in the northern Baltic Proper (Kahma et al. 2003, Soomere 2008) show that the roughest seas in the Baltic Sea 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 northern Baltic Proper (Soomere 2008).

The scatter diagrams for observed waves are very similar to those constructed using the WAM model at all observation sites for low and moderate wave conditions, up to wave heights of 3 m (Räämet et al. 2010). The distributions reflecting numerically simulated wave conditions are narrower, probably because of relatively large uncertainties in the visual observations. Based on the analysis of these distributions, it is estimated that the highest waves may, once in about 40 years, reach 6.5 m in the deeper nearshore at Vilsandi and about 6 m at Pakri (Räämet et al. 2010). The corresponding mean wave periods are 11–12 s at Vilsandi but much smaller, about 9–10 s, at Pakri. At Narva-Jõesuu 4 m high waves are already considered extreme: their period is expected to be about 7–8 s.

5. Spatial variability of the hindcast wave climate and its changes

Differences in temporal course along the eastern coast of the Baltic Sea from Lithuania to Narva. This analysis highlights the very different nature of long-term changes in the wave properties along the eastern coast of the Baltic Sea. No substantial changes have occurred to the overall wave intensity along the Lithuanian coast except for a certain increase in 2006–2008 (Kelpšaitė et al. 2011). On the other hand, substantial variations are reported for the entire northern Baltic Proper. Furthermore, hardly any changes to the average wave heights have occurred in Tallinn Bay (Kelpšaitė et al. 2009). A gradual, statistically significant decrease in both average and extreme wave heights apparently takes place on the southern coast of the Gulf of Finland in the eastern section of this water body (Suursaar 2010). Moreover, different signs for trends of average and extreme wave heights and large variations in average wave periods and predominant wave directions have been reported at selected locations (Suursaar & Kullas 2009a,b).

Another important feature of the wave conditions since the mid-1990s is the seeming increase in the number of extreme wave conditions against the background of the overall decrease in mean wave heights in the northern Baltic Sea (Soomere & Healy 2008). Extremely rough seas occurred in December 1999, and the legendary storm in January 2005 caused probably the all-time highest significant wave height $H_S \approx 9.5$ m (Soomere et al. 2008). These events have raised a number of questions: whether or not coastal processes in the Baltic Sea have become more intense compared to a few decades ago; whether the trends for average and extreme wave heights are different, etc. A recently completed hindcast of the entire Baltic Sea wave fields for 38 years (1970–2007) makes an attempt to shed light on the above questions (Räämet & Soomere 2010a,b) by means of a systematic analysis of the spatial patterns of modelled changes to the wave properties.

Long-term average wave heights. The spatial pattern of hindcast long-term average wave heights in the Baltic Sea for 1970–2007 (Figure 8) is asymmetric with respect to the axis of the Bothnian Sea, the eastern part of which has higher waves (> 0.8 m on average) than its western area. Interestingly, the spatial pattern of the areas of large wave activity has several local maxima in the Baltic Proper. The largest average wave heights (> 0.9 m) occur south of Gotland and east of Öland. The average wave height reaches 1.01 m at one location of relatively shallow depth in the Arkona Basin. This maximum is not represented in some other wave hindcasts (M. Meier, personal communication) and may be caused by certain local effects; however, it may also stem from the overestimation of geostrophic wind speeds in this part of the basin because of the low spatial resolution of the relevant information (cf. Pryor & Barthelmie 2003).

The highest wave activity in the northern Baltic Proper occurs along the coasts of Estonia and Latvia. The wave heights are relatively low in the south-eastern part of the sea, although this area has a relatively long

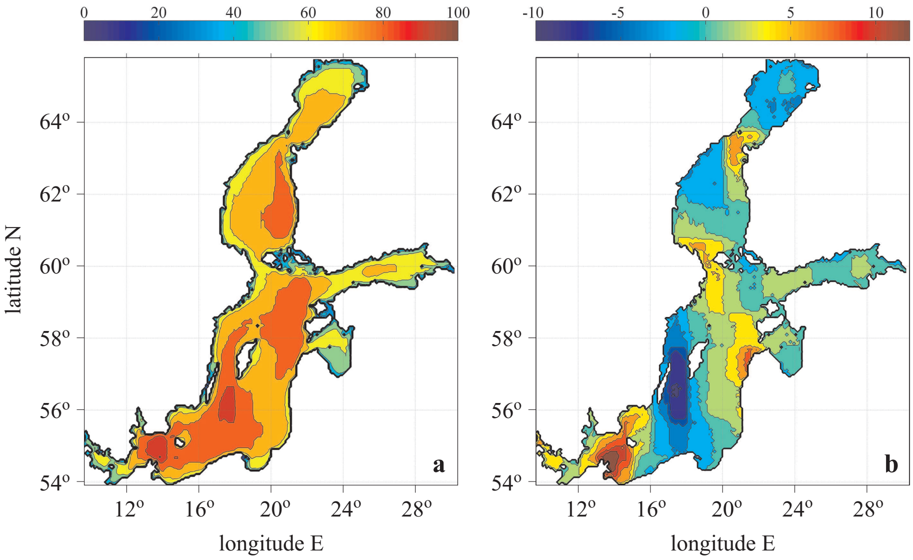

Figure 8. (left) Numerically simulated average significant wave height (colour bar, cm; isolines plotted after each 10 cm) in the Baltic Sea in 1970–2007 (Räämet & Soomere 2010a, with permission from Estonian Academy Publishers), (right) long-term changes in the significant wave height (cm, the interval between isolines 2 cm) for 1970–2007 (adapted from Soomere & Räämet 2011)

fetch. The average wave heights reach 0.7 m at the entrance to the Gulf of Finland and in its central part (Soomere et al. 2010). The Gulf of Riga is even calmer, with the average wave height slightly exceeding 0.6 m in the open sea (Räämet & Soomere 2010a).

The hindcast average wave heights underestimate the reliably measured ones by about 18% at Almagrundet (Räämet et al. 2009, Räämet & Soomere 2010a) and almost exactly coincide with the observed ones at Pakri and Vilsandi (Räämet & Soomere 2010a). This suggests that the model underestimates the average wave heights in the open Baltic Sea by about 15–20%. The modelled values for the Gulf of Finland, however, match well a similar estimate for the vicinity of Tallinn Bay (0.56 m) based on one-point forcing of the WAM model with high-quality marine wind data (Soomere 2005) and considerably (by 21%) exceed the observed wave heights at Narva-Jõesuu. This suggests that, despite the relatively low resolution of the wave calculations, the modelled results may be a good representation of the long-term wave properties in semi-enclosed sub-basins of the Baltic Sea.

Changes to average and extreme wave heights. The modelled trends in wave activity over the 38 years of simulations in the Baltic Sea have an even more complicated spatial pattern (Soomere & Räämet 2011). The largest changes have occurred in the southern Baltic Proper. The increase in wave heights in the Arkona basin is consistent with the reported gradual increase in the modelled wind speed over this sea area (Pryor & Barthelmie 2003, 2010). The decrease in wave intensity has been the greatest between Öland and Gotland, and to the south of these islands down to the Polish coast. A considerable increase in wave activity is indicated by the model from the coast of Latvia to the sea area between the Åland archipelago and Sweden. A large part of these changes represent statistically significant trends. The significance is the highest, about 99%, for the area to the south of Bornholm.

The spatial pattern of changes is largely uncorrelated with the areas of high and low wave intensity. The already large wave heights in the Arkona basin increase, while the wave activity in the neighbouring area of large waves decreases at almost the same rate (by about 15% in 40 years). The area of intense waves near Latvia shows an increase in wave heights, as does the area of overall moderate wave intensity near Åland.

A very similar pattern is found for extreme waves (the threshold for 1% highest waves, or equivalently, for the 99%-iles of significant wave height for each year, is calculated over the entire set of hourly hindcast wave heights for each year in Soomere & Räämet (2011)). The spatial pattern of changes to the extreme wave heights largely follows the one for the average wave heights. There are, however, areas in which the changes to the average and extreme wave heights are opposite, as hypothesized in Soomere & Healy (2008) based on data from Estonian coastal waters.

The case of the Gulf of Finland: no changes in averages, large variations in extremes. A particularly interesting pattern of changes to wave conditions, complementary to the changes to wave directions, is found for the Gulf of Finland (Soomere et al. 2010). The gulf is the second largest sub-basin of the Baltic Sea, extending from the Baltic Proper to the mouth of the River Neva (Figure 9). It is an example of an elongated water body (length about 400 km, width from 48 to 135 km) oriented obliquely with respect to predominant wind directions. The marine meteorological conditions of the Gulf of Finland are characterized by a remarkable wind anisotropy (Soomere & Keevallik 2003). State-of-the-art wave information for this area can be found in Lopatukhin et al. (2006a) and Soomere et al. (2008b). Both long-term average and maximum wave heights in the gulf are about half those in the Baltic Proper, whereas the wave periods in typical conditions are almost the same as in the Baltic Proper (Soomere et al. 2011). As the gulf is wide open to the Baltic Proper and the predominant strong winds are westerlies, in certain storms long and high

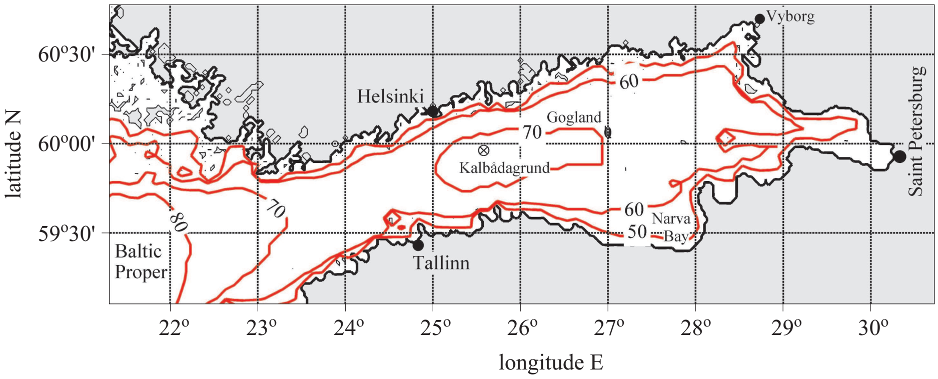

Figure 9. Spatial distribution of the long-term average of the modelled significant wave height [cm] in the Gulf of Finland (adapted from Soomere et al. 2010)

waves partially generated in the Baltic Proper may penetrate quite far into the Gulf of Finland (Soomere et al. 2008a). The average wave directions are often concentrated in narrow sectors along the gulf axis, although the wind directions are more evenly spread (Alenius et al. 1998, Pettersson 2004). This feature reflects the relative large proportion of so-called slanting fetch conditions (Pettersson et al. 2010), under which relatively long waves travelling along the axis of the gulf (that is, to the east) are frequently excited in this water body, even when the wind is blowing obliquely with respect to this axis, whereas shorter waves are aligned with the wind.

As the fetch length in most storms is relatively short in the Gulf of Finland, the changes in wind properties are rapidly reflected in the sea state. This feature allows the local wave climate to be estimated with the use of the one-point marine wind, which still adequately represents wave conditions in more than 99.5% of cases (Soomere 2005) and works well when the simplest one-point fetch-based models are used (Suursaar 2010).

The main properties of the wave climate in this water body extracted from visual wave observations at Pakri and Narva-Jõesuu (Zaitseva et al. 2009, Soomere et al. 2011) and from measurements near Letipea and the SMB model (Suursaar 2010) are discussed above. The long-term average significant wave height estimated using the WAM model (Soomere et al. 2010) is quite small, normally 0.6–0.65 m in the entire Gulf of Finland (Figure 9). The only exception is the entrance area to the gulf and in the central part of this basin, where the average wave height reaches about 0.7 m. The wave height occurring with a probability of 1% is about 2.5 m in the entire open part of the gulf, from the entrance to the Neva Bay.

The seasonal variation in the wave activity is clearly evident in both observed and numerically simulated wave data on the south-eastern coast of the Gulf of Finland. The largest observed waves occur within a four-month period from October to January. The same is largely true for the modelled wave heights, which have a more clearly pronounced maximum in December–January. The seasonal courses of modelled waves and wind speeds match each other well, but the observed wave heights show more irregular behaviour, with a secondary maximum in June, and April being the calmest month. This secondary maximum does not appear for wave fields in the Baltic Proper. There is a secondary maximum in wave intensity in October (which is the overall maximum at Narva-Jõesuu). This feature is not evident in the Baltic Proper either (Räämet & Soomere 2010) and can thus be attributed to the wave climate of the southern Gulf of Finland. The wave model and forcing in use do not reproduce this maximum in the wave activity, which is apparently caused by ageostrophic wind properties. A potential reason is that at times the wind field in the Gulf of Finland contains quite strong easterly and westerly winds blowing along the axis of the gulf (Soomere & Keevallik 2003). This wind system is specific to the Gulf of Finland and does not become evident in other parts of the Baltic Sea; it is much weaker in the eastern part of the gulf.

In contrast to the wave directions, wave heights in the Gulf of Finland generally reveal much smaller interannual and decadal variations than those in the Baltic Proper (Kelpšaitė et al. 2009, Soomere et al. 2011). In particular, numerical simulations using one-point wind data suggest that the changes to wave conditions in Tallinn Bay area have been much smaller than those reported for the Baltic Proper (Kelpšaitė et al. 2009). This is not unexpected because the fetch length is relatively short here and the resulting changes to the wave height, especially in the relatively sheltered southern part, should follow the changes in the wind speed, which have been negligible since 1980 (Soomere et al. 2010).

The above-discussed changes in storminess in northern Europe do not necessarily become evident in the interior of the Gulf of Finland, where the ageostrophic component of the surface level wind is at times substantial (cf. Keevallik & Soomere 2010). Also, the directional structure of the winds in the Gulf of Finland differs considerably from that in the Baltic Proper (Soomere & Keevallik 2003). In contrast to the gradual increase in the mean wind speed over most of the Baltic Proper (Pryor & Barthelmie 2003, Broman et al. 2006), there is a very slow decrease (about 0.01 m s^{-1} $year^{-1}$) in the annual mean wind speed at Kalbådagrund (Soomere et al. 2010). Therefore, drastic long-term variations in the wave properties are unlikely in this gulf.

The numerical simulations indicate very minor changes in the annual mean wave height in the entire gulf, including its entrance area (Soomere

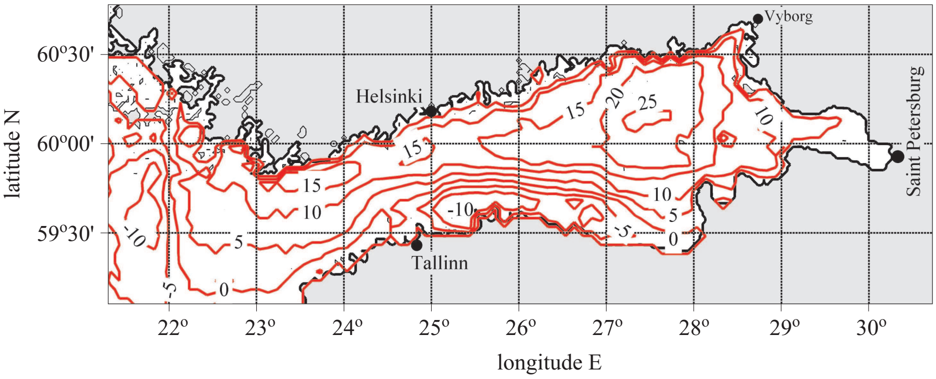

Figure 10. Spatial distribution of the long-term changes [cm] to the threshold for waves occurring with a probability of 1% in the Gulf of Finland (adapted from Soomere et al. 2010)

et al. 2010). Suursaar & Kullas (2009b) noted a decreasing trend in 99%-iles near the north Estonian coast and a weak, opposite, gradually increasing trend in the average wave height. Simulations using the WAM model show that, unlike the average wave height, maximum wave heights have exhibited a clear pattern of changes since the 1970s (Figure 10). There has been a substantial decrease (by about 10%) in the threshold in question near the southern coast of the gulf (especially in the narrowest central part of the gulf). This is accompanied by an almost equal increase to the north of the axis of the gulf and especially in the widest sea area. The changes reach about 0.40 m, that is, up to 20% of this wave height threshold over the 38 simulated years. Therefore, although the average wave heights have remained basically the same, the wave heights in very strong storms show a clear decreasing trend near the southern coast. This feature is apparently related to the major changes in the wind direction over the Estonian mainland: the frequency of south-westerly winds has increased considerably over the last 40 years (Kull 2005).

6. Discussion and conclusions

A key message from these results is that the extension of spatial patterns of wave climate changes is substantially different for phenomena at different scales. While interannual variations in wave heights are correlated well over distances > 500 km during about a half-century, the decadal variations embrace much smaller areas and are of a different nature at distances exceeding 200–300 km. The spatial pattern of changes to the average and extreme wave heights signifies that open sea areas as small as about 100×200 km may host changes of a completely different nature. This feature calls for a much more detailed analysis of the patterns of climatological changes in the Baltic Sea than is usually thought to be sufficient for open sea areas (BACC 2008). Such small scales of long-term variations in wave properties may considerably change our understanding about the past, present and future of wave-driven coastal processes and the relevant spatial resolution of wind and wave information necessary for their adequate modelling.

An amazing design feature of the existing wave observation and measurement network in the Baltic Sea is that virtually all the information comes from areas where average and extreme wave heights have hardly changed. Although the relevant spatial distribution of changes is currently based exclusively on numerical hindcast, a number of matches of the simulation results and observed and measured data at selected locations suggests that the major features of the spatial patterns discussed reflect real changes to the sea state statistics.

These numerical simulations have also resolved several questions about large mismatches between observed, measured and modelled data for selected locations. An important message is that the trends for average and extreme wave heights do not necessarily coincide for large sea areas. In this respect the most impressive are the relevant patterns in the Gulf of Finland (Soomere et al. 2010). Average wave heights have not changed significantly in the gulf since the 1970s, whereas extreme wave heights have increased considerably in the northern and north-eastern sections of the gulf. A very simple but also very probable reason for the changes is the increase in south-westerly winds over the last 40 years at the expense of some other wind directions. The southern part of the gulf has thus become more sheltered and the northern part more open to wave activity. This increase, combined with the potential change to the wave approach direction more to the west and south-west (Räämet et al. 2010), may lead to a major increase in the wave loads in the north-eastern part of the gulf, especially in the vicinity of Neva Bay, where substantial coastal erosion events have been recently reported (Ryabchuk et al. 2011).

Another lesson is that the features of long-term changes to the wave properties in the sub-basins of the Baltic Sea may be quite different from those in the Baltic Proper. Moreover, the nature of the changes may be similar for some periods but then change abruptly to another regime within a few years. This sort of regime change (cf. Keevallik & Soomere 2008) is of ultimate interest in climate studies. This analysis suggests that they can be extracted from historical wave data. This is stressed by the comparison of long-term changes to the wave properties. While in the 1960s and up to the 1980s the overall wave activity in the gulf and in the open Baltic Sea had a similar interannual variation, the further course of changes in the Gulf of Finland is very much different (Räämet et al. 2010).

The reason for the changes described may be connected with the gradual changes to the directional structure of predominant winds in the areas adjacent to the Gulf of Finland: namely, during the last 40 years, there has been a significant increase in the frequency of south-westerly winds and a decrease in southerly and easterly winds all over Estonia (Kull 2005, Jaagus 2009). Such a change may be responsible for a large part of the increase in the maximum wave heights in the downwind part of the Gulf of Finland, as it leads to a systematic increase in the fetch length typical of the northern part of the basin.

The material presented also highlights a number of questions. A problem that calls for further research is the mismatch between the course of decadal variability in wave heights and the gradual increase in wind speed over the northern Baltic Proper. While the wave activity reveals rapid decadal-scale variations, the annual mean wind speed at the island of Utö shows a gradual increase over this time (Broman et al. 2006). Progress in the understanding of the reasons behind this mismatch may essentially contribute to our ability to reconstruct the wind properties and other meteorological parameters in the open sea. The reason behind the reported changes to the wave periods and directions as well their potential consequences in terms of coastal and offshore engineering and coastal zone management need to be clarified. Also, it is not fully clear why there is effectively no correlation between the interannual variability in the wave intensity and the ice conditions on the Estonian coast (Soomere et al. 2011).

It is well known that wind fields reconstructed from atmospheric models frequently underestimate open sea wind speeds. It is therefore not unexpected that runs based on high-quality ECMWF wind fields result in a certain underestimation of the wave properties. It is, however, remarkable that the highly sophisticated ECMWF model consistently leads to results that differ only insignificantly from those obtained with the use of the simplest adjustment of the geostrophic wind. Therefore, although the geostrophic wind suffers from shortcomings for semi-enclosed sea areas, its use for long-term wave hindcast properties seems to be a very reasonable, if not the best, way to account for realistic wind fields in the Baltic Sea today. There are, of course, clear limitations to its use. For example, one can trust general statistics and selected trends but generally not hindcast time series or instantaneous values. Therefore, an alternative source of wind information is necessary in order to reproduce the temporal course of wave fields in particular storms. A first-order solution would be, for example, the use of altimeter data and, if possible, scatterometer data.

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