BOREAL ENVIRONMENT RESEARCH 16: 451–472 © 2011
ISSN 1239-6095 (print) ISSN 1797-2469 (online) Helsinki 30 December 2011

Wave hindcast statistics in the seasonally ice-covered Baltic Sea

Laura Tuomi, Kimmo K. Kahma and Heidi Pettersson

Marine Research, Finnish Meteorological Institute, P.O. Box 503, FI-00101 Helsinki, Finland

Received 13 May 2010, accepted 8 Mar. 2011 (Editor in charge of this article: Kai Myrberg)

Tuomi, L., Kahma, K. K. & Pettersson, H. 2011: Wave hindcast statistics in the seasonally ice-covered Baltic Sea. *Boreal Env. Res.* 16: 451–472.

We used six years of wave hindcasts, calculated by the wave model WAM, to compile wave statistics for the Baltic Sea. The wave model was implemented taking into account the special features of the Baltic Sea: irregular coastline, archipelago and ice. To our knowledge, there is no single way to present annual statistics in seasonally ice-covered seas. We discuss five different possibilities to calculate the statistics, and the differences between them. According to verification against wave buoy and satellite altimeter measurements, the quality of the hindcast significant wave height is sufficient for presenting reliable wave statistics. The mean values of the significant wave height are smaller than 1.5 m. According to the mean values and exceedance probabilities, the severest wave climate is in the Baltic Proper. The wave climate in the other basins is considerably less severe. The maximum hindcast significant wave height is over 9 m, whereas the measured maximum is 8.2 m.

Introduction

Before 1970, only visual wave observations were available from the Baltic Sea. (The regions of the Baltic Sea are presented in Fig. 1.) The first instrumental wave measurements were made by Wahl (1973a, 1973b, 1973c), who used the measurements to calibrate the visual observations made from lightships along the Swedish coast. The first systematic wave measurement campaign in the open sea areas was made in the early 1970s by the Helsinki University of Technology and the Finnish Institute of Marine Research (FIMR). From 1972, measurements were made periodically in the Bothnian Sea (Kahma 1976, Kahma *et al*. 1983, Pettersson 1994). In 1977–1978, measurements were performed in the Bothnian Bay. In 1982, wave measurements were extended to the middle parts of the Gulf of Finland (Kahma and Pettersson 1993, Pettersson 2001).

The Swedish Meteorological and Hydrological Institute (SMHI) begun coastal wave measurements in Almagrundet and Ölands södra grund in 1979 (Broman *et al*. 2006). FIMR and SMHI carried out a joint measurement campaign near Bogskär in 1982–1985. This was the first time when near real-time wave information was available from the middle of the northern Baltic Proper via the receiving station at Svenska Björn.

The open sea wave measurements transmitted in real time were continued by FIMR in the northern Baltic Proper in 1996. In 2000, the wave measurements were restarted also in the Gulf of Finland, off Helsinki. Periodic measurement campaigns in different parts of the northern

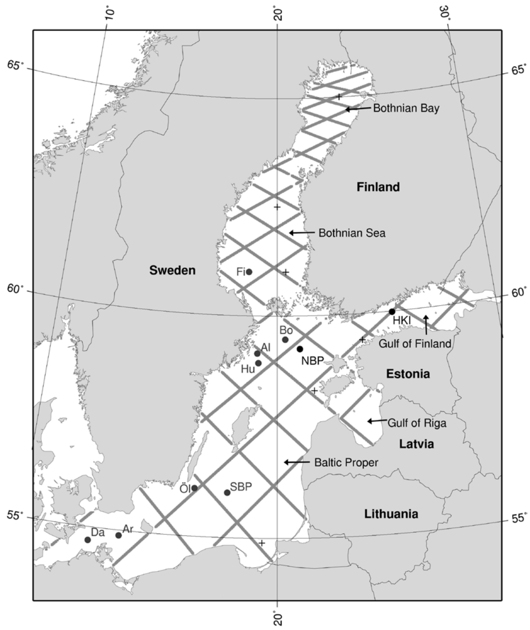

Fig. 1. Location of FMI's Directional Waveriders in the northern Baltic Proper (NBP) and off Helsinki (HKI). Location of SMHI's current wave measurement sites at Finngrundet (Fi), Huvudskär (Hu) and southern Baltic Proper (SBP), and SMHI's past wave measurement sites at Almagrundet (Al), Bogskär (Bo), and Ölands södra grund (Öl). Location of BSH's wave measurement site at Arkona (Ar), and GKSS's wave measurement site at Darss Sill (Da). Locations of Jason-1 altimeter tracks are shown with grey lines. Names of the countries whose coastal areas are discussed in this paper (e.g. visual wave observations). Locations of selected wave model points presented in Table 1 are shown with plus signs.

Baltic Sea were also carried out. The measurements are continued now by the Finnish Meteorological Institute (FMI) with which a part of FIMR was merged at the end of 2008.

In the south-western Baltic Sea, continuous real-time wave measurements have been made by GKSS Research Centre in Darss Sill since 1991, and by Bundesamt für Seeschifffahrt und Hydrographie (BSH) in Arkona since 2002 (e.g. Pettersson *et al*. 2007). In 2006, SMHI started real-time measurements in the southern Baltic Proper, in the western part of the Bothnian Sea (Finngrundet), and in the north-western part of the Baltic Proper (Huvudskär). Since 2005, yearly HELCOM indicator fact sheets of the Baltic Sea wave climate have been prepared in cooperation by the Baltic Sea countries (www.helcom.fi/BSAP_assessment/ifs/en_GB/cover/).

Even though the Baltic Sea is limited in size, according to these measurements both the mean significant wave height (defined as $H_s = H_{m0} = 4\sqrt{m_0}$, where m_0 is the 0th moment of the wave spectrum) and the exceedance levels are about half of those measured in the North Atlantic, and about the same level as in many of the oceans with less severe wave climates than the North Atlantic. The highest measured significant wave height in the Baltic Sea was 8.2 m, measured on 22 December 2004 by the wave buoy in the northern Baltic Proper. This value is from a recent analysis of the data logger time series during the storm, and exceeds the operationally reported value of 7.7 m. This latter value was transmitted by the Argos satellites, which have short gaps when the satellites are not in the visibility area of the buoy: the significant wave height 8.2 m was recorded by the data logger during one of these gaps. Significant wave height of over 7 m has been measured at this site four times since the measurements started in 1996. In January 1984 at the coastal site Almagrundet a significant wave height of 7.3 m was measured (Broman *et al*. 2006) and in October 2009 SMHI measured a significant wave height of 7.4 m in the southern Baltic Sea (www.smhi.se, Pettersson *et al*. 2010b). Even higher values of significant wave height have been predicted in the Baltic Proper by the operational wave models (Soomere *et al*. 2008).

Continuous wave measurements in the open sea areas are logistically a demanding task, and the time series are seldom continuous. In the northern parts of the Baltic Sea, the sea is covered by ice every winter, and the wave buoys have to be recovered well before the area freezes over. Since the measurements are local, the statistics based on wave measurements give an accurate description of the wave climate at the deployment site only. For these reasons, methods have been developed to extend the temporal and spatial representativeness of the measurements, e.g. by estimating the missing values from seasonal distributions or by more advanced methods (Pettersson 1992). As a result, by combining measurements and wave growth physics, it has been possible to generate adequate estimates of the Baltic Sea wave climate (Kahma *et al*. 2003).

The existing measurements are the basis of the information we have on the wave climate in the Baltic Sea. In the past 15 years, the performance of wave and atmospheric models in basins of the size of the Baltic Sea improved significantly. Wave modelling is an efficient tool for obtaining statistics that cover the entire Baltic Sea. Up-to-date wave model statistics have been published for the southern Baltic Sea by Gayer *et al*. (1995) and Blomgren *et al*. (2001) and for Estonian coastal areas by Soomere (2005). Jönsson *et al*. (2003) published hindcast wave statistics for the Baltic Sea covering a period of one year. Räämet *et al*. (2010), and Räämet and Soomere (2010) presented hindcast wave statistics for the Baltic Sea based on geostrophic winds.

In a relatively small Baltic Sea, the local geographic features have to be accurately included in the model. The archipelago and the irregular shoreline in the northern Baltic Sea affect the wave growth and propagation by sheltering or changing the fetch over which the waves grow. Another feature that affects the wave growth and the statistics is the ice cover in winter. The yearly ice cover in the northern Baltic Sea also raises the question of what is the proper way to calculate statistics in areas that are partially covered by ice for a part of the year. Handling the issue of the ice-covered season is not trivial, and the appropriate method depends on the purpose the statistics are intended for.

We show how the features that affect the wave climate in a sea area like the Baltic Sea are taken into account in the wave model implementation and the calculation of wave statistics. Another important issue is the quality of the forcing wind fields used in the calculations. The wave hindcasts are verified against wave buoy and satellite altimeter data. Different possibilities to calculate wave statistics in seasonally ice-covered sea areas are discussed, and hindcast wave statistics based on a 6-year period are presented.

Modelling

We calculated wave hindcasts for the Baltic Sea using the third generation spectral wave model WAM cycle 4 (WAMDI 1988, Komen *et al*. 1994). The starting date for the hindcast was chosen to be the beginning of November 2001 for two reasons. Firstly, the operational wave forecasting model was changed to WAM at FIMR in November 2001, and since that time we have the forcing wind fields available with sufficient horizontal resolution. Secondly, in November 2001 high waves were measured in the Gulf of Finland (Pettersson and Jönsson 2005). The wave buoy off Helsinki measured a record value of 5.2 m of significant wave height. Such high waves are rare in the central Gulf of Finland, and we wanted to include this event in the statistics. We extended the hindcast period to the end of October 2007 in order to have six full years.

To ensure good quality of the wave hindcasts, we took into account in the wave model implementation special features of the Baltic Sea, such as its small size, narrow gulfs, archipelago, irregular coastline and ice during winter. We used a regular grid with a resolution of 0.1° latitude × 0.2° longitude (ca. 11 km for both). The small size of the Baltic Sea and the narrow gulfs require a high resolution grid to predict the significant wave height (Tuomi 2008) and the directional properties of the wave field (Pettersson *et al*. 2010a) with sufficient accuracy. Furthermore, we generated the wave model grid using a technique in which the irregularities of the northern Baltic Sea shoreline are approximated by calculating an average shoreline (Kahma 1981). In addition to this, archipelagos that are impassable to waves at a given resolution, such as the area between the Åland main island and the mainland of Finland, are coded as land in the model grid. The model spectra comprise 24 directions and 35 frequency bands (0.042–1.073 Hz).

The northern parts of the Baltic Sea freeze over annually and, therefore, the ice conditions have to be taken into account to obtain good quality wave hindcasts. The ice season starts in October or November; the Bothnian Bay is the first part of the sea area to have ice cover. The ice season typically lasts until May or early June (Seinä and Peltola 1991). During an average winter, the ice cover extends over almost a half of the Baltic Sea: the Bothnian Bay, the Bothnian Sea, the Gulf of Finland, and the Gulf of Riga and the northernmost part of the Baltic Proper. During the severest winters practically the entire Baltic is covered by ice, and even in mild winters there is ice in the Bothnian Bay and the Gulf of Finland. During the period discussed in this paper, the ice season in the winter 2001/2002 was mild, followed by four average ice seasons in the winters 2002/2003, 2003/2004, 2004/2005 and 2005/2006 (Seinä *et al.* 2006, Seinä 2007). The last ice season of the period, 2006/2007, was again mild (Seinä 2008). For the hindcast the ice concentration for each grid cell was calculated from the ice data supplied by the Ice Service of FIMR (at present FMI). Ice conditions were updated daily, except in the beginning of the ice season when the update was done twice a week due to limited ice cover. The grid cells in which the ice concentration exceeded 30% were coded as land points for the hindcast. Grid cells having lower ice concentration were treated as open water. This method ensures that the wave model uses fetch starting from the average ice edge. Moreover, waves are not predicted in areas that have an ice cover.

Wind forcing for the hindcast was constructed from wind fields supplied by FMI's weather forecasting model HIRLAM (High Resolution Limited Area Model, Unden *et al.* 2002) hereafter FMI-HIRLAM, used in operational wave forecasts in 2001–2007. There have been several updates and improvements in the physics, parameterisations, and resolution of FMI-HIRLAM during the six years in question. Resolution of the wind fields has a major effect on the accuracy of wave prediction in small basins (Ponce de León and Guedes Soares 2008, Tuomi and Sarkanen 2008). Therefore, the wind fields with the highest possible resolution were extracted from the available operational versions of FMI-HIRLAM. From November 2001 until the end of 2002, the wind fields at the lowest model level (ca. 32 m) from the coupled atmosphere–wave model (Järvenoja and Tuomi 2002) with ca. 22 km resolution were used. WAM calculates the momentum flux at sea surface from the wind speed at a given height using neutral stratification. When wind fields at the 32-m height were used, we changed the level of input wind to 32 m instead of the standard 10 m. Since the beginning of 2003 FMI has run the HIRLAM model without coupling to the wave model. For the years 2003 and 2004, wind fields were extracted with 22 km resolution. The wind fields were from the lowest model level (ca. 32 m) until August 2003, after which surface wind fields at the 10 m height were available. In 2005, FMI started running a HIRLAM version with ca. 9 km resolution (e.g. Kangas and Sokka 2005). Wind fields from this HIRLAM version were used from the beginning of 2005 until October 2007.

We used the first six hours from each HIRLAM forecast, run four times a day, to build a continuous wind field dataset. There were 51 missing forecasts (of the total 8764), and these were replaced in the dataset from longer forecast lengths, most of them (34) with 6–12 hour forecast lengths. The longest forecast length used to fill in the gaps was 24 hours. There is no significant reduction in the quality of the forecast surface wind field or wave field up to 18 hours forecast length [*see* for instance Järvenoja (2005) and Tuomi (2008)]. Therefore, filling few gaps with data from longer forecast length in the dataset has no appreciable effect on the quality of the wave hindcasts. The wind field time-step was 3 hours for the years 2001–2002, and 1 hour for 2003–2007. As the resolution and the orientation of the wave model grid are different from those used in FMI-HIRLAM, we transformed the wind fields to the wave model grid by selecting the nearest point. Compared with the interpolation of the wind field (which is a commonly used method to convert wind fields from a coarser grid to a finer grid), the selection of the nearest points somewhat reduces the merging of the wind vectors over land and sea areas near the shoreline.

Constant development in weather forecasting models, in their physics, parameterisations and the vertical and horizontal resolution, will have an effect on the accuracy of the forecast. This may lead to using a wind forcing dataset in which the quality is not constant in time (Caires *et al.* 2004b), and this may have a considerable effect on the statistics, especially if trends in the hindcast wave parameters are studied. On the other hand, to have homogeneity in the quality of the wind fields would have required a re-analysis using a limited area atmospheric model for the Baltic Sea. Wind forcing for the wave statistics is typically taken from re-analyses of e.g. ERA-40 by the European Centre for Medium range Weather Forecasting (ECMWF) (e.g. Uppala *et al.* 2005) or NCEP/NCAR by the

National Centers for Environmental Prediction (NCEP) and National Center for Atmospheric Research (NCAR) (e.g. Kistler *et al*. 2001). The horizontal resolution of these global reanalyses is over 100 km. Even though these reanalyses have been used to produce wave statistics with sufficient quality for e.g. the North Atlantic (e.g. Swail and Cox 2000, Caires *et al*. 2004a), their resolutions are too coarse for the Baltic Sea.

The re-analyses in European coastal areas improved when the HIPOCAS project produced wind fields for Europe with 50 km resolution (e.g. Soares 2008). Although the usability of these wind fields in constructing the Baltic Sea wave climate was studied, for instance by Cieślikiewicz and Paplińska-Swerpel (2008), the resolution is still too coarse to properly solve the wind field characteristics in narrow bays such as the Gulf of Finland. In the coastal areas of the Baltic Sea, the accuracy of the wave predictions using over 50 km resolution wind forcing has been found poor (Kahma *et al*. 1997). In the Gulf of Finland, a comparison between wave forecasts forced with ECMWF wind fields (with ca. 25 km resolution) and FMI-HIRLAM wind fields (with less than 10 km resolution), showed that especially the high values of significant wave height were more accurately predicted when high-resolution wind fields were used (Tuomi and Sarkanen 2008). For these reasons, we chose to use the FMI-HIRLAM wind fields as forcing data for the wave hindcast, even though their quality slightly varies with time. Later we will discuss the effect of the inhomogeneities in the quality of the wind fields on the wave statistics.

Verification of the wave hindcasts

The accuracy of the wave hindcasts was evaluated by comparing the hindcast values of significant wave height with measured data in the northern Baltic Proper (NBP, 59°15´N, 21°00´E, depth 100 m) and off Helsinki (HKI, 59°57´54´´N, 25°14´06´´E, depth 62 m) (*see* Fig. 1). The measurements in the northern Baltic Proper transmitted via satellites have been carried out since September 1996 excluding the ice seasons. The measurements off Helsinki transmitted via a HF link have been carried out in 1990–1991, in 1994, and from the autumn 2000 excluding the ice seasons. The location of the wave measurement site has been the same during all these periods. In the northern Baltic Proper the measurement period varies from year to year. In 2004 and 2007, the wave buoy was in the NBP location for the whole winter. In 2002–2003 and 2005–2006, measurements are lacking from a few months, typically from February until the beginning of May. Off Helsinki, the typical measurement period is from May to December. Measurements in both locations are made every 30 minutes, the interval being sometimes longer for the NBP buoy due to the uneven coverage of the satellites. The significant wave height, H_s (defined as $H_s = H_{m0} = 4\sqrt{m_0}$) is calculated from the spectrum calculated on board the buoy from a time series of 1600 s following Longuet-Higgins *et al*. (1963). The only exception is the spectra from the northern Baltic Proper during the storm in 2004, which was obtained from the data logger calculated with the same method from a time series of 1320 s. A description of the measurement procedure can be found in Pettersson (2001) or Pettersson *et al*. (2003).

The hindcast significant wave height, H_s, at 1-h intervals, is compared against measurements from the NBP and HKI sites (Fig. 2). The highest measured significant wave height, 5.2 m, at HKI is missing from Fig. 2. This is because only the measurement values coinciding with the hourly hindcast values are taken into account here, and the maximum value at HKI was measured at 10:30 UTC on 15 Nov. 2001. The bias is slightly negative at both locations, meaning that the model tends to underestimate the significant wave height. The accuracy of the model hindcasts is good at both locations up to values of 4 m. H_s values of over 4 m have a significantly larger scatter than the lower values. This can be seen especially at the NBP site, where the values of significant wave height are higher than at the HKI site. The comparison against buoy data shows that the wave hindcasts have good quality and are suitable for producing representative statistics, provided that the slight underestimation in the hindcast significant wave height is taken into account. Comparison of the data for the whole 6-year period does not show the effect, discussed

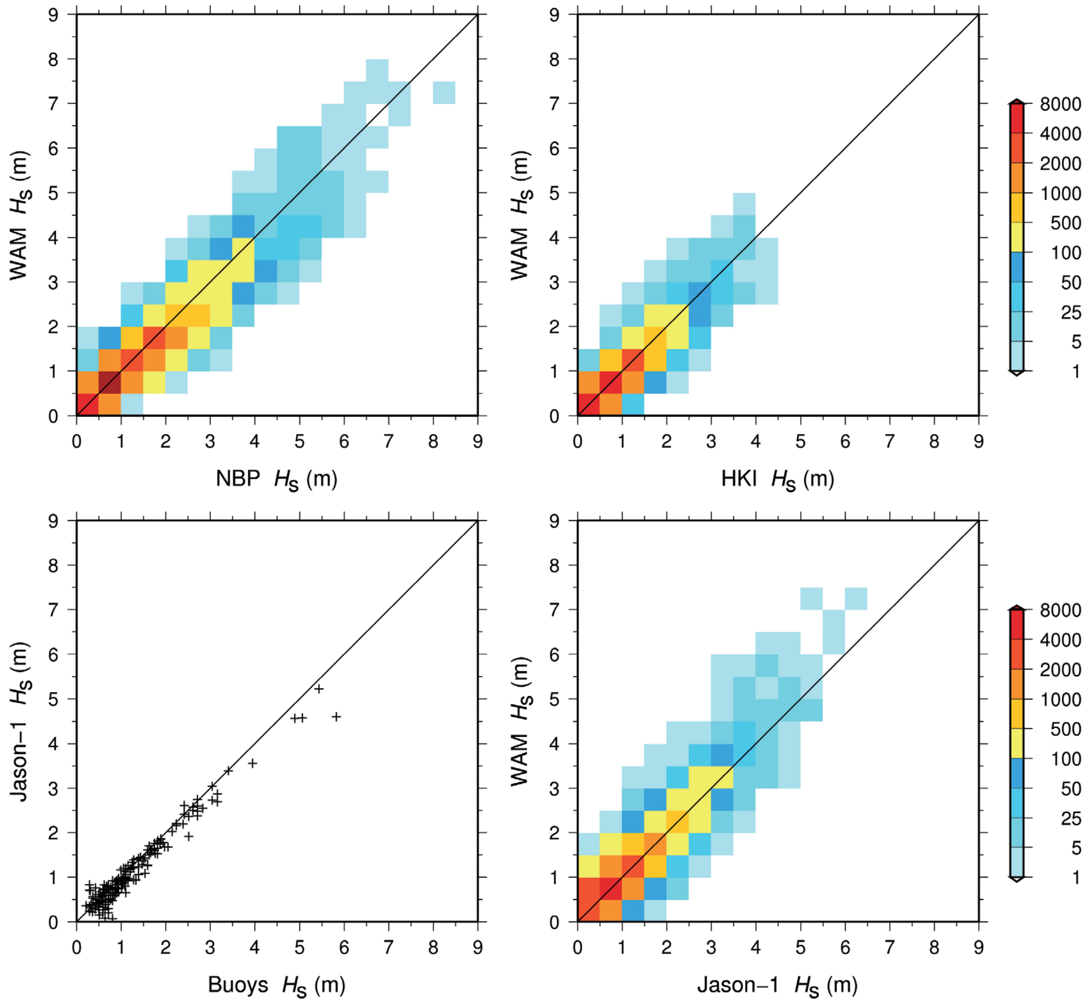

Fig. 2. Hindcast significant wave height (H_s) compared with measurements from the northern Baltic Proper wave buoy (NBP, on the upper left, bias = –0.07 m, rms = 0.29 m), and the Helsinki wave buoy (HKI, on the upper right, bias= –0.04 m, rms = 0.21 m). The significant wave height from the Jason-1 altimeter compared with buoy measurements from HKI and NBP (on the lower left, bias = –0.08 m, rms = 0.20 m). The Jason-1 H_s compared with hindcast significant wave height in the Baltic Sea (on the lower right, bias = 0.03 m, rms = 0.31 m). The colours present the number of entries within 0.5 m range.

above, of the heterogeneous quality of the wind forcing on the wave hindcasts. To be able to verify this, the comparisons have to be made separately for different years (Tuomi 2008); for example at the NBP site for the years 2003 and 2004 (Fig. 3). In 2004, significant wave heights of over 4.5 m are underestimated by the model, whereas in 2003 the higher values of significant wave height are more often overestimated than underestimated. During the period presented in this paper, the year 2003 is the only one with a positive bias (0.03 m) at the NBP site. All the other years have a negative bias (between –0.06 and –0.12 m). On the other hand, the scatter in the results is larger in 2003 than in any other year within the period in question. The heterogeneous quality of the wind forcing is not as clearly seen at the HKI site, since there most of the values of significant wave height are smaller than 4.5 m. The improvements of the atmospheric model HIRLAM after 2004 have lead to more accurate wind fields, and thus to more accurate wave hindcasts in the Baltic Sea area in the years 2005–2007 (e.g. Järvenoja 2005, Tuomi 2008).

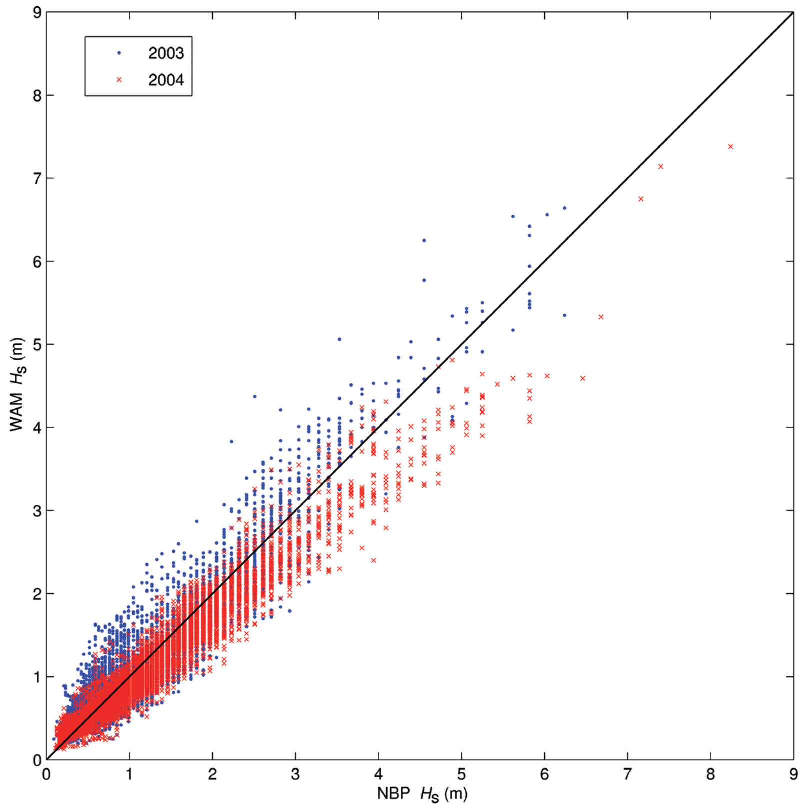

Fig. 3. Hindcast significant wave height compared with measured significant wave height at the NBP site for the years 2003 (blue), and 2004 (red). The quality of the wave hindcast is different between the years, especially in the high values of significant wave height, due to differences in the quality of the forcing wind fields.

The comparison of significant wave height in 2003 and 2004 showed that differences in the quality of the wind forcing have more effect on the higher values of significant wave height than the lower ones. According to the hindcasts, significant wave height of 4 m was exceeded during less than 1% of the time at the NBP location. This is close to the value presented by Kahma *et al*. (2003) for the northern Baltic Proper, according to which 4.5 m significant wave height was exceeded during less than 1% of the time. However, this statistic applies to a period different from the one considered in this paper. Nevertheless, most of the data are within the range where the effect of the inhomogeneities in forcing wind fields on the wave hindcasts is basically insignificant. Thus, the effect of inhomogeneities in the quality of the wind forcing will be discussed only when evaluating the highest values of significant wave height in the Baltic Sea.

To evaluate the accuracy of wave hindcast in other areas of the Baltic Sea, significant wave heights from Jason-1 altimeter's Ku-band for the years 2002–2007 were extracted from the Radar Altimeter Database System (RADS) hosted at the Delft University of Technology (Schrama *et al*. 2000). The extraction was made with RADS default corrections. To further improve the quality of the altimeter data in the Baltic Sea, an additional check on the values of significant wave height was made, especially near the shorelines, in the archipelago, and near the ice edge during the ice season. Values were excluded from the altimeter dataset if they did not fall within the natural spatial variation of the wave field.

The quality of the Jason-1 significant wave height is good in the oceans (for instance Queffelou 2004). In the Baltic Sea, the quality of Jason-1 significant wave height was analysed by Høyer and Nielsen (2006). The standard approach to comparing altimeter data with buoy measurements is the selection of the significant wave height from the altimeter data within 30 minutes of time of the buoy measurement and 50 km distance of the buoy location. This approach is not always applicable in the Baltic

Sea. For instance in the western Gulf of Finland, which is only about 50 km wide in the narrowest part (Fig. 1), this standard selection criterion would merge wave conditions over the entire Gulf in a south–north direction. For instance, in a case where high waves are propagating from the northern Baltic Proper to the Gulf of Finland the differences in the significant wave height between the central and coastal areas of the gulf can be of the order of meters. Also, in fetch-limited conditions the differences in the significant wave height within a 50 km area can be considerable. Since we wanted to have comparable results also close to the shorelines and the archipelago, we chose to compare the nearest altimeter track point within a 30-minute time-frame with the measurements. The same method was used when the co-located altimeter measurements were compared against hindcasts. In addition to the restricted selection criteria, every selected altimeter measurement was compared with the two nearest points in the altimeter track in both directions, filtering out large variations in space. The comparison of altimeter significant wave height with HKI and NBP buoy measurements shows that altimeter data in the Baltic Sea has good quality on average (Fig. 2). However, the scatter is quite high in significant wave height values of less than 1 m. Moreover, the altimeter underestimates the high values of significant wave height, which is typical for the Jason-1 and also for other altimeters (Queffelou 2004). The comparison of hindcast significant wave heights against all available altimeter data for the years 2002–2007 shows good agreement (Fig. 2). There is a large scatter in the low values of significant wave height and the highest values of significant wave height are overestimated by the model compared with the altimeter. Based on the comparison we made between buoy and altimeter data this behaviour is quite expected.

Wave climate

Annual wave statistics in seasonally ice-covered seas

A common way to describe the wave climate is to present the mean and the maximum significant wave height and wave period, together with the annual exceedance probabilities (percentiles). In the Baltic Sea, the interpretation of wave statistics presented this way has some problems, which we will discuss here. To our knowledge, there is no single way to calculate annual wave statistics in a seasonally ice-covered sea. Several methods can be introduced, and they will give different results and therefore cannot be directly compared. As we show later by examples, no one of them can be said to be correct in the sense that they would give results (for example about the annual risk of wave-related damages, or wave-related fatigue of offshore structures during one year) that would be equivalent to the corresponding results in a sea that is ice-free throughout the year. Each one will have biases in one direction or the other, and the best choice depends on the application. Five different possibilities for presenting wave statistics from measurement and model data in seasonally ice-covered sea areas are presented. For measured data four of these types have already been presented in Kahma *et al.* (2003).

Type M: Measurement statistics. Only measured values are taken into account. No normalisations are made to compensate for the uneven distribution of missing values. This is a common way to calculate statistics from measurements (for example Kahma *et al.* 2003, Broman *et al.* 2006). It has the tendency to give values lower than type F and higher than type I.

Type I: Ice-time-included statistics. Wave height in the presence of ice equals zero. This together with type F is a common way to calculate statistics from model data, provided that ice conditions have been taken into account in the wave model run. This type gives a misleading impression of the wave climate of the ice-free time.

Type F: Ice-free time statistics. Only the part of the year when the sea is ice-free is taken into account when statistics are calculated. In case of measured data normalisations are made to compensate the bias introduced by the correlation of missing data and the seasonal variations. This type is close to measurement statistics (type M). This type of statistics has been presented from measured data in the Baltic Sea by Kahma *et al*. (2003).

Type ET: Exceedance time statistics. If either type I or type F statistics are presented in hours during a year instead of the percentage of hours per year, they are equal (except for the time when the wave height is zero). This is a very good way to avoid the bias in the annual statistics, if exceedance probabilities are not needed.

Type N: Hypothetical "no-ice" statistics. Statistics are calculated to represent the wave climate under the assumption that the sea remains ice-free throughout the year. In the Baltic Sea, this type of hindcast wave statistics were presented for example by Jönsson *et al*. (2003), Soomere (2005), Räämet and Soomere (2010). There is a special application when type N statistics can be recommended. This is the case when the application for which the statistics will be used, occurs only during the season when there is no ice anywhere in the Baltic Sea. During that time, annual statistics of type N are comparable with annual statistics from areas which are ice-free throughout the year.

In seasonally ice-covered seas annual wave statistics presented by statistics type I will give an impression of a less severe wave climate than there ever might be in the ice-free time. To illustrate the problem, let us consider a hypothetical example: a place in the High Arctic, where the sea is open only one month a year. At that location the 10% exceedance probability is exactly zero, even though the waves may well be quite high when the sea is open. The smaller exceedance probabilities, while not zero, will be much smaller than the corresponding exceedance probability during the time when there is no ice. For a location where the ice-covered period is shorter than in our hypothetical example, the bias will be less obvious, but it still exists. This is the case in the northern part of the Baltic Sea. For instance, the mean significant wave height in the Bothnian Bay in the summer is greater than the annual mean even though the waves are smaller in the summer than during any other ice-free time. (This will be shown later when we present the seasonal statistics.)

The difference between ice-time-included statistics and ice-free-time statistics is a good measure of the bias caused by ice. The exceedance values of significant wave height are greater in the northern part of the Baltic Sea for statistics of type F than for statistics of type I (Fig. 4). The differences are largest in the Bothnian Bay and the Gulf of Finland.

The importance of the ice conditions for the accuracy of wave hindcasts and thus for wave statistics is demonstrated by the difference between the ice-time-included statistics (I) and the hypothetical no-ice statistics (N). In the areas of the northern Baltic Sea that typically have ice cover, during that time of the year the statistics type N give greater mean values of significant wave height (Fig. 5). The largest differences are during February and March, when the ice extent typically has its maximum value. We would like to emphasize that the hypothetical no-ice statistics presented here are not suitable for estimating the future wave climate if a milder climate reduces the length of the ice season as well as the extent of the ice cover in the Baltic Sea (e.g. BACC 2008). The FMI-HIRLAM uses the ice information when calculating the surface fluxes. This means that over the ice-covered sea areas the wind speed has lower values than it would have if there were no ice. This is due to the greater surface roughness of ice compared with the sea surface roughness in HIRLAM.

When wave statistics are calculated from measured data, there will be one more source of bias: the gaps in the measurements. Wave buoys have to be recovered well before the freezing, because the buoy will be damaged if it is hit by drifting ice floes. The gaps will not be randomly distributed, and may bias the statistics. In the Baltic Sea these gaps partly coincide with the windiest time of the year.

The problems discussed above can be minimised when wave statistics are seasonally or monthly stratified. The disadvantage with seasonal and monthly statistics is that they are voluminous: Monthly statistics with ten percentage classes means an atlas of 120 individual maps. Making conclusions about the wave climate for a particular application from such an atlas will itself be a small project. Even more important is that most applications based on wave statistics

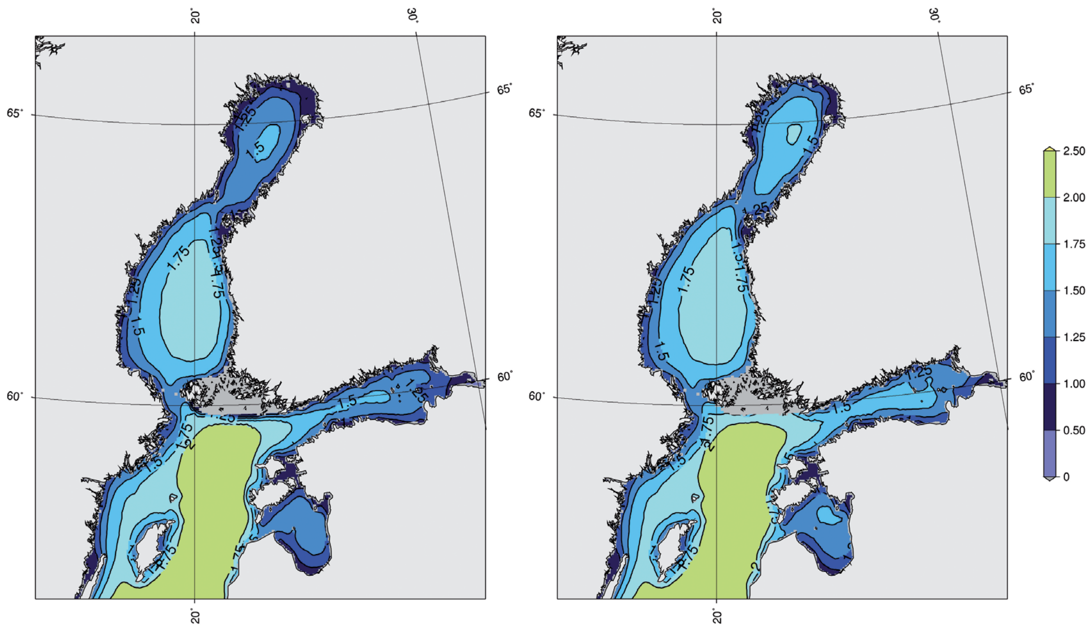

Fig. 4. Significant wave height exceeded 10% of the time in the northern Baltic Sea by the ice-time-included statistics (type I, on the left) and by ice-free-time statistics (type F, on the right). Contour lines are given at 0.25 m intervals for H_s values between 1–2 m and at 0.5 m intervals for H_s values below 1 m and over 2 m.

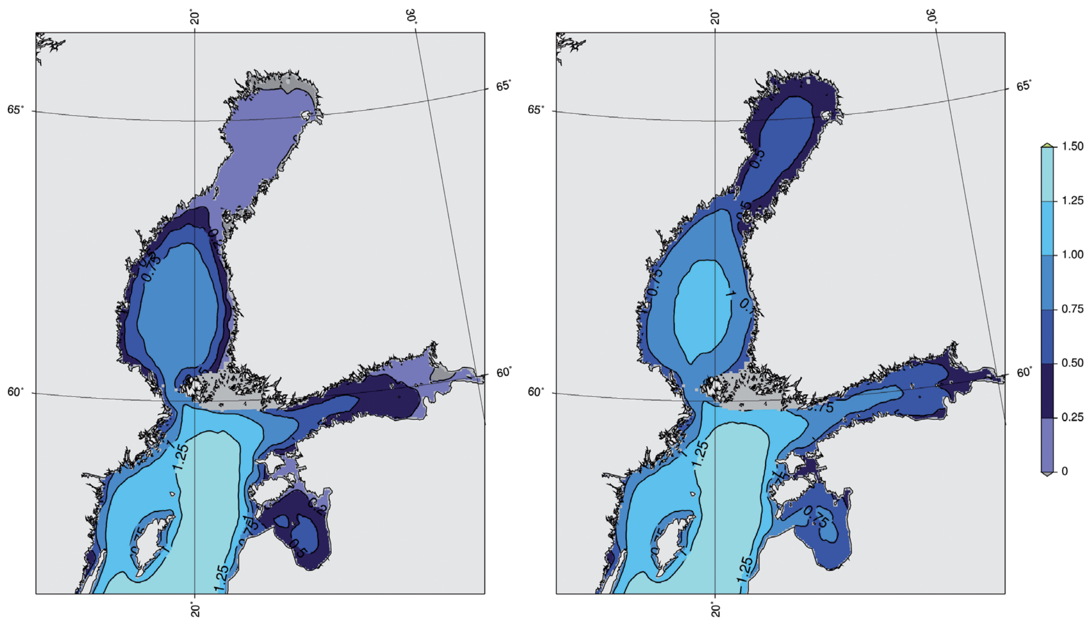

Fig. 5. Hindcast mean significant wave height in the northern Baltic Sea in February by ice-time-included statistics (type I, on the left) and by hypothetical no-ice statistics (type N, on the right). Contour lines are given at 0.25 m intervals.

are designed to use annual statistics, and there are no trivial ways to modify them to be based on monthly statistics. There is a practical need for annual statistics in ice-covered seas.

In contrast to the mean values and exceedance probabilities, the hindcast maximum values of significant wave height over the whole year are essentially free from the bias caused by

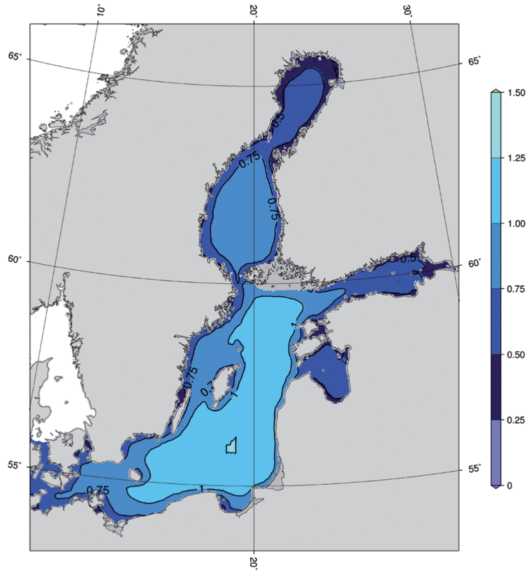

Fig. 6. Hindcast mean values of significant wave height in the Baltic Sea. Ice-time-included statistics (type I).

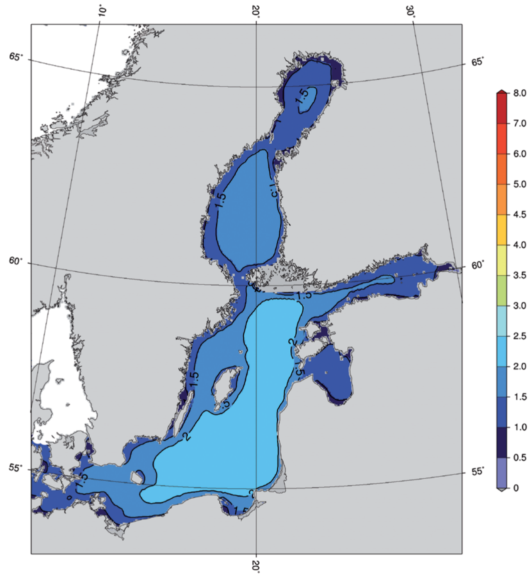

Fig. 7. Significant wave height exceeded 10% of the time in the ice-time-included statistics, type I (ca. 36.5 days in a year, type ET). According to the verification, the hindcast exceedance probabilities differ from the measured ones by ±0.25 m at most.

different ways of handling the missing values during the ice season.

In this paper, we use ice-time-included statistics (type I) in all figures except in those where the hindcast wave climate is compared with the measured wave climate. There, the ice-free-time statistic (type F) is used. In the figures showing the exceedance probabilities, the exceedances are expressed also as hours in a year (type ET), in addition to percentage of the time in a year. The former is the same for statistics types I and F. The mean values, the maximum values and the exceedance probabilities presented in this paper are valid only for the open sea areas. The wave model grid has a resolution of 6 nmi (ca. 11 km), which places the centre of each coastal grid point on the average 5 km from the shoreline.

Ice-time-included wave statistics

The ice-time-included statistics (type I) gives the mean significant wave height smaller than 1.5 m in all the areas of the Baltic Sea (Fig. 6). The Baltic Proper is an area with the severest wave climate. There, the mean values are smaller than 1.25 m and 1.5 m in the northern and southern parts, respectively. In the gulfs, the mean significant wave height is smaller than 1 m. (To give a comprehensive picture of the Baltic Sea wave climate we present exceedance probabilities (type I) of significant wave height for 10%, 5%, 3%, 1%, and 0.1% of the time in Figs. 7, 8, 9, 10 and 11, respectively.) In the Baltic Proper according to the ice-time-included statistics, the values of significant wave height, that are exceeded for 10% of the time, are smaller than 2.5 m (Fig. 7). The gulfs have a less severe wave climate. There the values of significant wave height, that are exceeded for 10% of the time, are smaller than 2 m. In the exceedance probabilities, for 5% and 3% of the time the southern Baltic Proper has a slightly more severe wave climate than the northern Baltic Proper.

Of the gulfs, the Bothnian Sea has the severest wave climate. Furthermore, at both 1% and 0.1% exceedances, the southern part of the Bothnian Sea has a more severe wave climate than the northern part. The Bothnian Bay, the Gulf of Finland, and the Gulf of Riga have quite similar wave climates, the Bothnian Bay has a slightly more severe wave climate than the other gulfs. The differences in the wave climate in the basins of the Baltic Sea are considerable but they can be

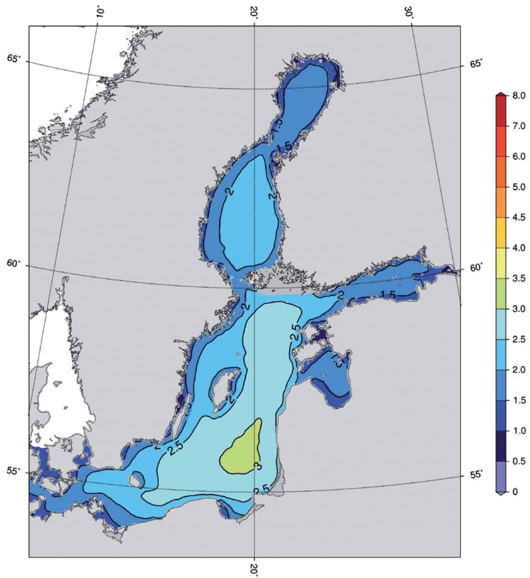

Fig. 8. Significant wave height exceeded 5% of the time in ice-time-included statistics, type I (ca. 18.3 days in a year, type ET). According to the verification, the hindcast exceedance probabilities differ from the measured ones by ±0.25 m at most.

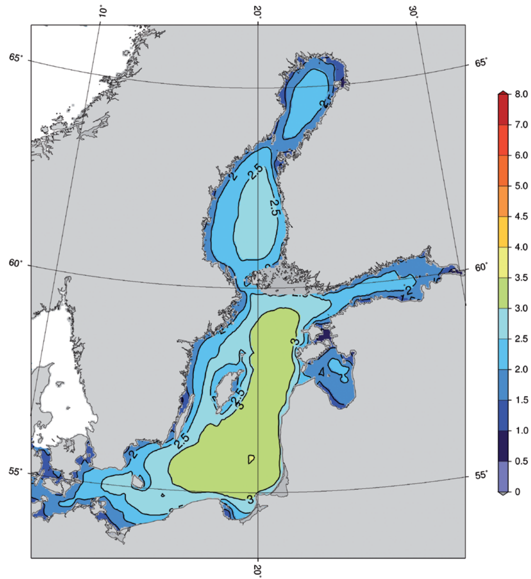

Fig. 9. Significant wave height exceeded 3% of the time in ice-time-included statistics, type I (ca. 11 days in a year, type ET). According to the verification, the hindcast exceedance probabilities differ from the measured ones by ±0.25 m at most.

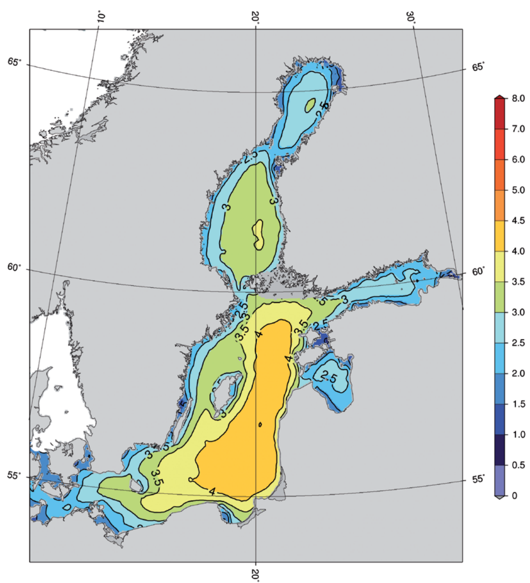

Fig. 10. Significant wave height exceeded 1% of the time in ice-time-included statistics, type I (ca. 3.7 days in a year, type ET). According to the verification, the hindcast exceedance probabilities differ from the measured ones by ±0.25 m at most.

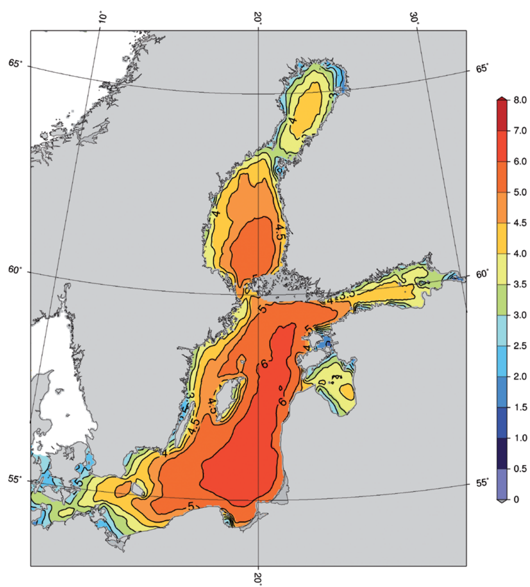

Fig. 11. Significant wave height exceeded 0.1% of the time in ice-time-included statistics, type I (ca. 8.8 hours in a year, type ET). According to the verification, the hindcast exceedance probabilities differ from the measured ones by ±0.25 m at most.

explained by the size and the shape of the areas together with the ice conditions and the prevailing wind directions. In the period 1971–2000, the prevailing wind direction, defined as the direction with the highest frequency of occurrence, is southwest on the Finnish coast of the northern Baltic Proper, the Gulf of Finland and the Bothnian Sea (Drebs *et al*. 2002). However, in the Bothnian Bay the prevailing wind direction is south. During the period presented in this paper the prevailing wind direction at FMI's coastal weather stations was from the southwest or south in the northern Baltic Proper, the Bothnian Sea and the Bothnian Bay. In the Gulf of Finland the prevailing wind directions were southwest and west.

Similar directional distributions for the northern Baltic Sea were presented by Launiainen and Laurila (1984) and Soomere (2003). On the Lithuanian coast, the predominance of westerly winds was shown e.g. by Dailidienė *et al*. (2006). However, the wind direction in high wind situations may differ from these. For instance, during the period in question in the southern part of the Bothnian Sea, winds with speeds of over 21 m s^{-1} were most often from the north and northwest. Also Launiainen and Laurila (1984) and Soomere (2003) showed that the highest wind speeds may be from other than the prevailing directions. This is the reason behind the slightly higher 1% and 0.1% of the time exceedance values in the southern part of the Bothnian Sea. The southern Baltic Proper has a long fetch from both the west and north, whereas the northern Baltic Proper has a long fetch only from the south. This together with the prevailing wind directions explains the slightly higher values of significant wave height of the exceedance probabilities 5% and 3% of the time as well as the more widespread area of higher values of significant wave height in the southern part of the Baltic Proper as compared with those in the northern part. Wave growth in the Gulf of Finland is limited by the narrowness of the Gulf. In a narrow fetch geometry, the growth of waves is reduced as compared with a broad fetch geometry (Kahma and Pettersson 1994, Pettersson 2004).

The exceedances of significant wave height for selected points at 0.25-m intervals in hours during a year are given in Table 1 (statistics type ET). In addition to the model points closest to the measurement locations NBP and HKI, we show the exceedance hours for model points having the highest maximum values in the southern Baltic Proper, the northern Baltic Proper, and the southern and northern part of the Bothnian Sea, the Bothnian Bay and the Gulf of Finland (locations of these points are shown in Fig. 1).

The comparison of the hindcast against buoy measurements showed that the hindcast significant wave height is slightly underestimated in the northern Baltic Proper. The comparison between the hindcasts and altimeter measurements showed that the behaviour of the hindcast significant wave height is similar in the Baltic Sea as a whole. To clarify the effect of this bias on the wave statistics, we compared exceedance probabilities from NBP and HKI buoy measurements with the model point closest to the measurement location (Figs. 12 and 13). Exceedance probabilities are calculated only for the periods when measurements were available (type M). Underestimation of the hindcast significant wave height can be seen in the cumulative curves at both sites. The underestimation is smaller than 0.25 m and exists up to 0.6% exceedance values at HKI, and smaller than 0.25 m up to 0.1% exceedance values at NBP. In other areas of the Baltic Sea, the difference in the hindcast and measured exceedance values is expected to be of the same magnitude as that at the HKI and NBP sites based on the comparison between hindcast and altimeter data. However, it is possible that the exceedance values of significant wave height may also be overestimated in some areas of the Baltic Sea. Therefore, we did not include a systematic correction in Figs. 7–11. As mentioned earlier, the highest measured significant wave height, 5.2 m, at HKI is missing from Fig. 13, because only the measurement values coinciding with the hourly hindcast values are taken into account in this comparison.

The highest values of hindcast significant wave height were over 9 m during the period in question (Fig. 14). The highest value, 9.7 m, was hindcast in the northeastern part of the Baltic Proper during a storm in January 2005. This corresponds with the estimate, 9.6 m, (Soomere *et al*. 2008), reported as the maximum significant wave height during this storm based on validated wave forecasts by German Weather Forecast Service, Danish Meteorological Institute and Finnish Institute of Marine Research. The maximum values in all open sea areas of the Baltic Sea were over 4 m. The problem in evaluating the accuracy of the highest significant wave height values in the Baltic Sea is that the high sea states are quite rare. According to hindcast statistics, significant wave height of 4 m is

Table 1. Exceedance time statistics (type ET) of significant wave height (hours during a year) in eight locations in the Baltic Sea. Locations having the highest maximum values in these areas were selected. In addition, the values for the model points closest to the NBP and HKI wave buoys are given (marked with DWR).

H_s	Southern Baltic Proper 54°54´N, 19°24´E	Northern Baltic Proper (DWR) 59°12´N, 21°00´E	Northern Baltic Proper 58°18´N, 21°36´E	Gulf of Finland (West) 59°24´N, 23°48´E	Gulf of Finland (DWR) 60°00´N, 25°12´E	Bothnian Sea (South) 61°00´N, 20°24´E	Bothnian Sea (North) 62°30´N, 20°00´E	Gulf of Bothnia 65°00´N, 23°24´E
9.75	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
9.50	0.0	0.0	0.3	0.0	0.0	0.0	0.0	0.0
9.25	0.0	0.0	0.5	0.0	0.0	0.0	0.0	0.0
9.00	0.2	0.0	0.5	0.0	0.0	0.0	0.0	0.0
8.75	0.5	0.0	0.7	0.0	0.0	0.0	0.0	0.0
8.50	1.0	0.0	0.7	0.0	0.0	0.0	0.0	0.0
8.25	1.2	0.3	0.8	0.0	0.0	0.0	0.0	0.0
8.00	1.5	0.5	0.8	0.0	0.0	0.0	0.0	0.0
7.75	2.0	0.7	1.0	0.0	0.0	0.0	0.0	0.0
7.50	2.0	1.2	1.0	0.0	0.0	0.0	0.0	0.0
7.25	2.3	2.7	1.3	0.0	0.0	0.0	0.0	0.0
7.00	3.2	3.7	1.5	0.0	0.0	0.2	0.0	0.0
6.75	4.2	4.2	2.0	0.0	0.0	0.5	0.0	0.0
6.50	5.8	5.0	2.5	0.2	0.0	0.7	0.7	0.3
6.25	8.0	6.5	4.0	0.3	0.0	1.0	1.0	0.3
6.00	9.8	8.8	6.7	0.8	0.0	2.8	1.3	0.3
5.75	13.3	10.5	10.0	1.3	0.0	5.0	2.0	0.8
5.50	17.2	13.2	14.0	2.0	0.0	7.0	3.2	1.3
5.25	21.8	19.5	18.2	5.3	0.0	10.5	4.0	2.0
5.00	26.5	27.5	23.2	8.7	0.0	15.2	5.8	2.5
4.75	34.0	38.8	29.8	11.3	1.3	19.2	7.3	3.3
4.50	45.2	49.5	44.2	14.3	2.2	25.5	11.0	4.7
4.25	63.3	65.5	58.5	17.5	3.2	38.0	18.0	7.3
4.00	90.4	94.4	76.9	21.8	5.8	50.7	30.5	12.5
3.75	122.0	124.9	97.7	28.5	11.7	67.0	45.3	20.0
3.50	170.4	167.5	133.0	35.8	23.2	85.5	63.8	32.5
3.25	233.7	231.2	182.4	48.2	37.7	111.4	98.5	49.8
3.00	316.6	318.6	256.2	68.0	58.2	152.0	146.9	78.0
2.75	422.4	427.8	355.2	106.9	87.9	216.0	222.7	120.4
2.50	562.6	592.5	501.8	159.5	137.2	300.2	325.6	180.4
2.25	762.5	846.4	693.3	244.4	204.2	434.1	472.4	274.2
2.00	1021.9	1170.3	968.1	357.2	326.2	645.1	701.5	409.9
1.75	1386.5	1608.2	1361.8	544.6	514.5	947.5	1021.7	600.8
1.50	1918.3	2190.5	1869.3	839.5	805.5	1391.2	1479.5	867.5
1.25	2645.3	2964.7	2535.1	1300.1	1262.5	2037.6	2143.2	1272.3
1.00	3640.0	3956.4	3468.0	2051.5	1971.1	2980.8	3007.4	1863.3
0.75	5012.6	5253.9	4758.1	3138.9	3094.9	4289.1	4243.5	2675.1
0.50	6844.6	6955.1	6451.1	4844.4	4775.8	6074.4	5970.0	3812.2
0.25	8582.1	8446.8	8238.0	7400.5	7052.1	8009.7	7882.1	5546.4
0.00	8766.0	8766.0	8766.0	8766.0	8766.0	8766.0	8766.0	8766.0

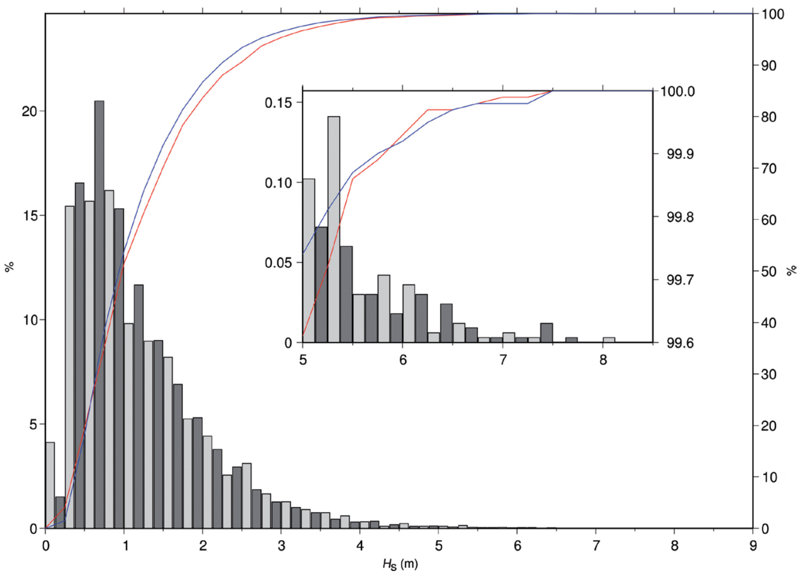

Fig. 12. Distribution of significant wave height at the northern Baltic Proper wave buoy location. Percentage of total amount of data as bars (hindcast dark gray, measurements light grey) on the left *y*-axis. Percentage for cumulative curves (measured red, hindcast blue) on the right *y*-axis. H_s classes at 0.25 m intervals on the *x*-axis. In the insert, the high values of significant wave height are shown.

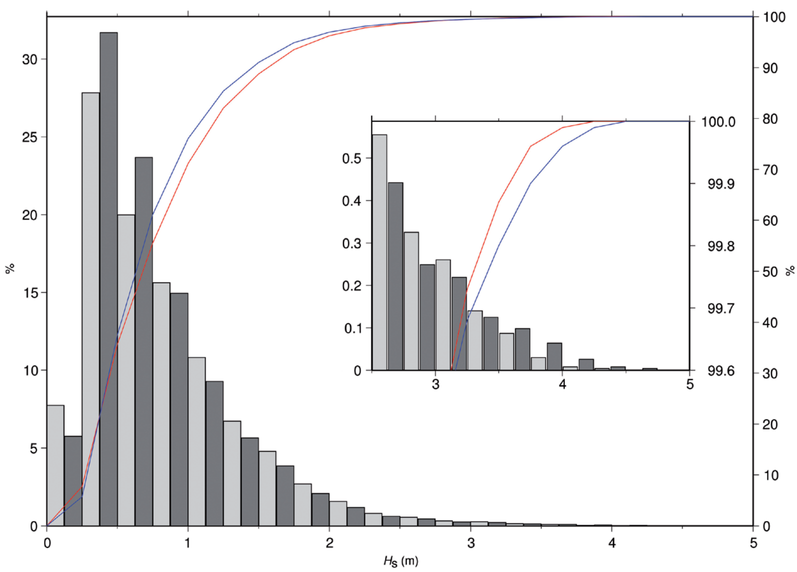

Fig. 13. Distribution of significant wave height at the Helsinki wave buoy location. Percentage of total amount of data as bars (hindcast dark gray, measurements light grey) on the left *y*-axis. Percentage for cumulative curves (measured red, hindcast blue) on the right *y*-axis. H_s classes at 0.25 m intervals on the *x*-axis. In the insert, the high values of significant wave height are shown.

exceeded less than 1% of the time in the Baltic Proper, and 6 m less than 0.1% of the time. Also the highest maximum values in the different areas of the Baltic Sea are often hindcast to locations in which measurements are not available, or for the time of the year when the wave buoys have been recovered due to risk of ice. The permanent wave buoy locations as well as the locations of wave buoys in measurement campaigns are selected to serve various purposes, and are not necessarily in the areas to catch the highest waves. Altimeter measurements have a wider spatial coverage than buoy measurements, but very limited temporal coverage. This is even more so in enclosed sea areas like the Baltic Sea. During the 6-year period of hindcasts presented in this study, only one extreme sea state was captured by the Jason-1 altimeter. This was in the southern Baltic Proper in November 2005. At the NBP site, the highest hindcast significant wave height, 8.5 m, was from February 2002, when the wave buoy had already been recovered. At this time, the Finnish coastal weather stations in the northern Baltic Proper and the

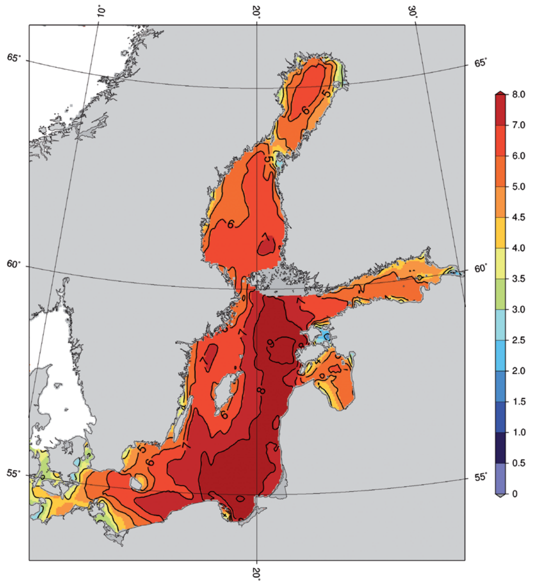

Fig. 14. Hindcast maximum values of significant wave height in the Baltic Sea during November 2001–October 2007.

western part of the Gulf of Finland measured high values of wind speed: the highest at Utö was southerly wind at 28 m s^{-1} (10 minutes average). This was higher, and of longer duration, than the highest wind speed, 26 m s^{-1}, measured in Utö in December 2004, when the NBP wave buoy measured the maximum value of significant wave height 8.2 m. At that time, the model underestimated the significant wave height by predicting the maximum to be 7.4 m.

During the period in question the highest hindcast maximum values were along the eastern coast of the Baltic Proper. The lack of instrumental measurements in these areas makes the comparison of these maximum values difficult. The only continuous wave measurements made in the eastern coastal areas of the Baltic Proper are the visual observations made for instance on the Estonian and Lithuanian coasts. These visual observations were recently analysed for instance by Soomere and Zaitseva (2007), and by Kelpšaitė *et al*. (2008), but as the observations are made in shallow waters near the coastline, they do not represent open sea conditions, and thus are not useful in the evaluation of the accuracy of the hindcast maximum values presented in this paper.

As we showed earlier, heterogeneity in the quality of the forcing wind fields has a greater effect on the high values of significant wave height. The comparisons against buoy data at NBP and HKI showed that, despite the different quality in the accuracy of the forcing wind fields, most of the high values of significant wave height that could be verified are within 1 m of the measured values. In addition, the 6-year period is relatively short for evaluating the maximum values of significant wave height. The locations of the highest maximum values represent individual high wind situations, and are not necessarily in the areas of the highest exceedance probabilities. This can be seen for example in the exceedance time statistics (Table 1) when comparing the locations with the highest maximum values in the southern and the northern Baltic Proper. Although the northern Baltic Proper has a higher maximum value than the southern Baltic Proper, the exceedance hours of significant wave height of over 6 m have greater values in the southern Baltic Proper. Moreover, in the northern Baltic Proper the model point closest to the Directional Waverider has higher exceedance hours of significant wave height of over 6 m than the location with the highest maximum value.

For designing offshore structures and ships, it would be useful to compile combined statistics of significant wave height and peak wave period. Such statistics have been presented from measured data in Kahma *et al*. (2003) for the northern Baltic Proper, and from model results in the southern Baltic Sea by Gayer *et al*. (1995). However, wave models at present cannot be tuned to predict the peak periods in the Baltic Sea with sufficient accuracy. There is a large scatter in the hindcast wave periods by WAM when compared with the measurements at the HKI site (Fig. 15). Especially the high peak periods of over 10 s measured by wave buoy are considerably underestimated. The underestimation of peak periods has also been noticed by Gayer *et al*. (1995), who presented scatter diagrams from the HYPAS model predictions for the Warnemünde harbour entrance. They concluded that the reason was the location of the wave buoy, which was more exposed to long waves entering the bay than the corresponding wave model grid point. The underestimation of high peak periods by WAM at the HKI site cannot be explained by a different exposure to longer waves of the model and the measuring site. One reason for this underestimation could be that even though WAM can predict the amount of energy in the wave spectrum with good accuracy, the distribution of the energy between wind waves and swell in the wave spectra is not equally well predicted (e.g. Alves and Banner 2003, Tuomi 2008). The underestimation of the peak periods is largest when the significant wave height is smaller than 2 m (not shown here). Therefore, it might be possible to present combined statistics starting from significant wave heights of over 2 m. Since further research is needed to fully understand the predictability of the peak periods, the combined statistics are not presented in this paper.

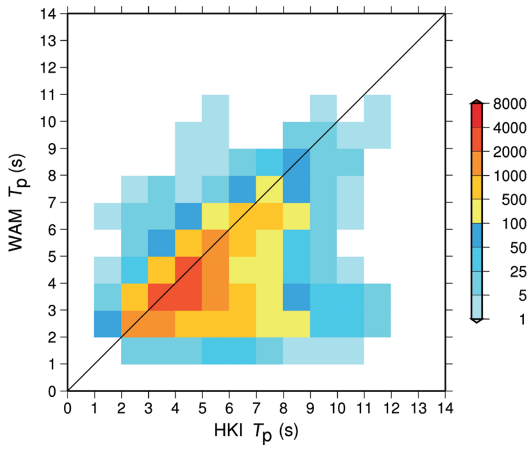

Fig. 15. Hindcast peak period (T_p) compared with measured values at the HKI site (bias = –0.82 s, rms = 1.66 s). The colours present the numbers of entries within 1 s.

Seasonal statistics

The seasonal mean values of significant wave height in the ice-time-included statistics (type I) were greatest during the winter and smallest during the summer, excepting the ice-covered areas, where the highest mean values are reached in the autumn and the smallest in the spring (Fig. 16). The effect of the ice conditions on the wave statistics can be seen also in the seasonal mean values. For example, in the northernmost part of the Bothnian Bay, in the eastern part of the Gulf of Finland, and in the Gulf of Riga the mean values by statistics type I are smaller in the winter and the spring than in the summer, although in the Baltic Proper the mean values in the summer are smaller than in any other season.

The seasonal maximum values of significant wave height are highest in the autumn and winter (Fig. 17). Nonetheless, high values of significant wave height are also hindcast in the spring and summer. In the summer and autumn, the highest maximum values are in the southern Baltic Proper. Also in the spring it is one of the areas with highest maximum values. Only in the winter is the highest maximum value in the northern Baltic Proper. As pointed out earlier, the shortness of the hindcast period has a large effect on the distribution of the seasonal maximum values in the different areas of the Baltic Sea.

We evaluated the accuracy of the hindcast seasonal mean and maximum values by comparing the hindcast and measured monthly mean and maximum values at NBP and HKI sites (Fig. 18). The monthly means are well hindcast during summer and slightly underestimated in autumn at both sites. During winter and spring there is too little data from the measurements to make a reliable comparison. Even so, in winter and spring the hindcast significant wave height values show behaviour similar to the measured values. The hindcast maximum values are generally higher than measured maximums during winter and spring, since in those seasons there is wave buoy data only from a few months. During most of the summer and autumn months the hindcast maximum values are slightly underestimated as compared with the measurements.

Summary

We calculated wave statistics for the Baltic Sea using six years of wave hindcasts. The hindcasts were run using the wave model WAM with wind forcing from FMI's atmospheric model HIRLAM. Special features of the Baltic Sea such as the complex structure of the coastline, the archipelago and ice during the winter, were taken into account when making the wave hindcasts. To estimate quality of the statistics we compared

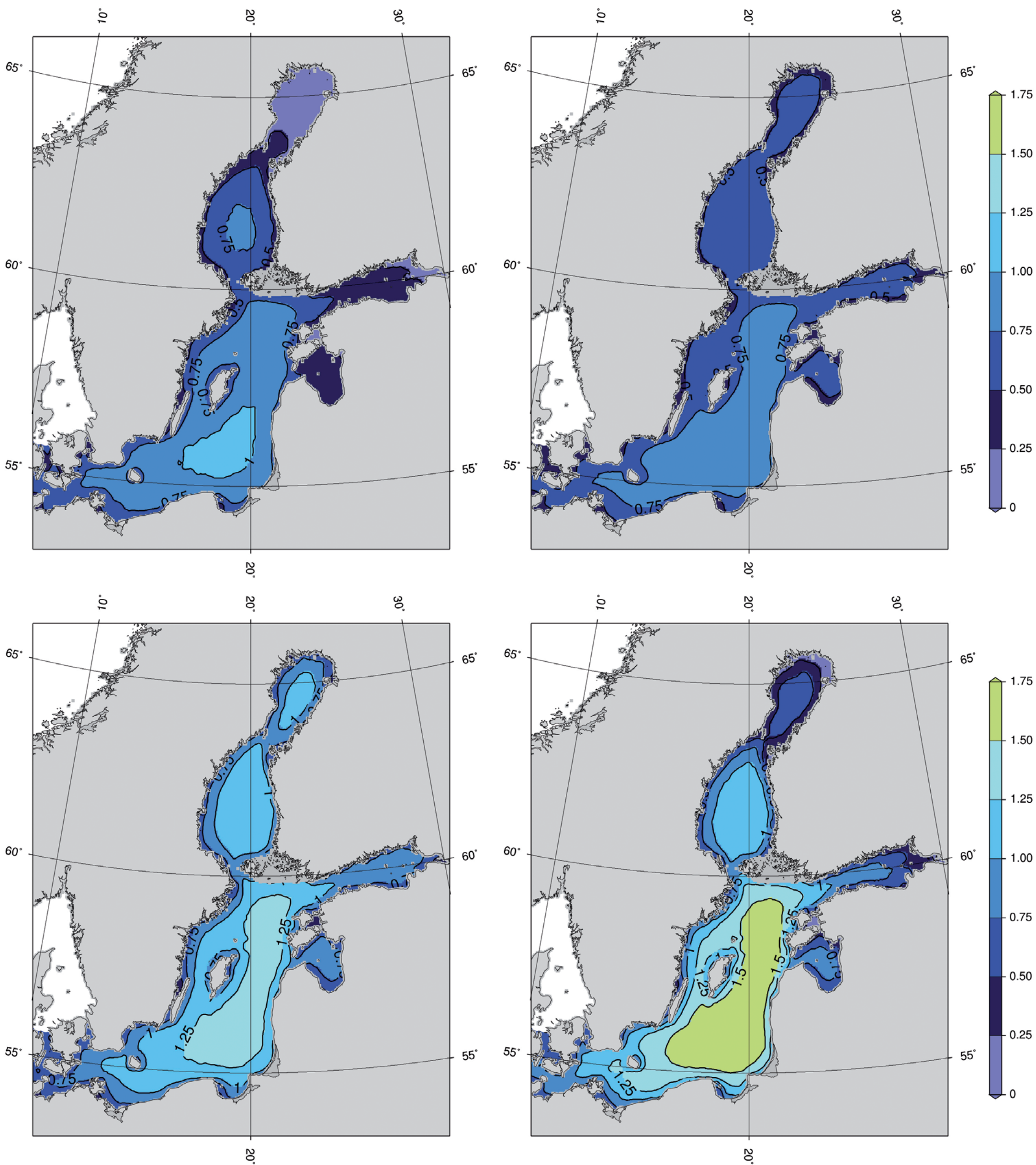

Fig. 16. Hindcast seasonal mean values of significant wave height in the Baltic Sea. Ice-time-included statistics (type I). Spring (upper left), summer (upper right), autumn (lower left) and winter (lower right).

the wave hindcasts against measured data from two buoys in the northern Baltic Sea, and from the Jason-1 altimeter. Verification showed that the model slightly underestimated the significant wave height in the open sea areas of the Baltic Sea with the exception of the highest values of significant wave height, which show a tendency to be overestimated by the model. The bias between the hindcast and measurements was further analysed by comparing the hindcast and measured exceedance probabilities. Based on this comparison the error in the hindcast exceedance probabilities is expected to be less than 0.25 m in all the open sea areas of the Baltic Sea. Due to the rare occurrence of high sea states, the accuracy of the maximum values of significant wave

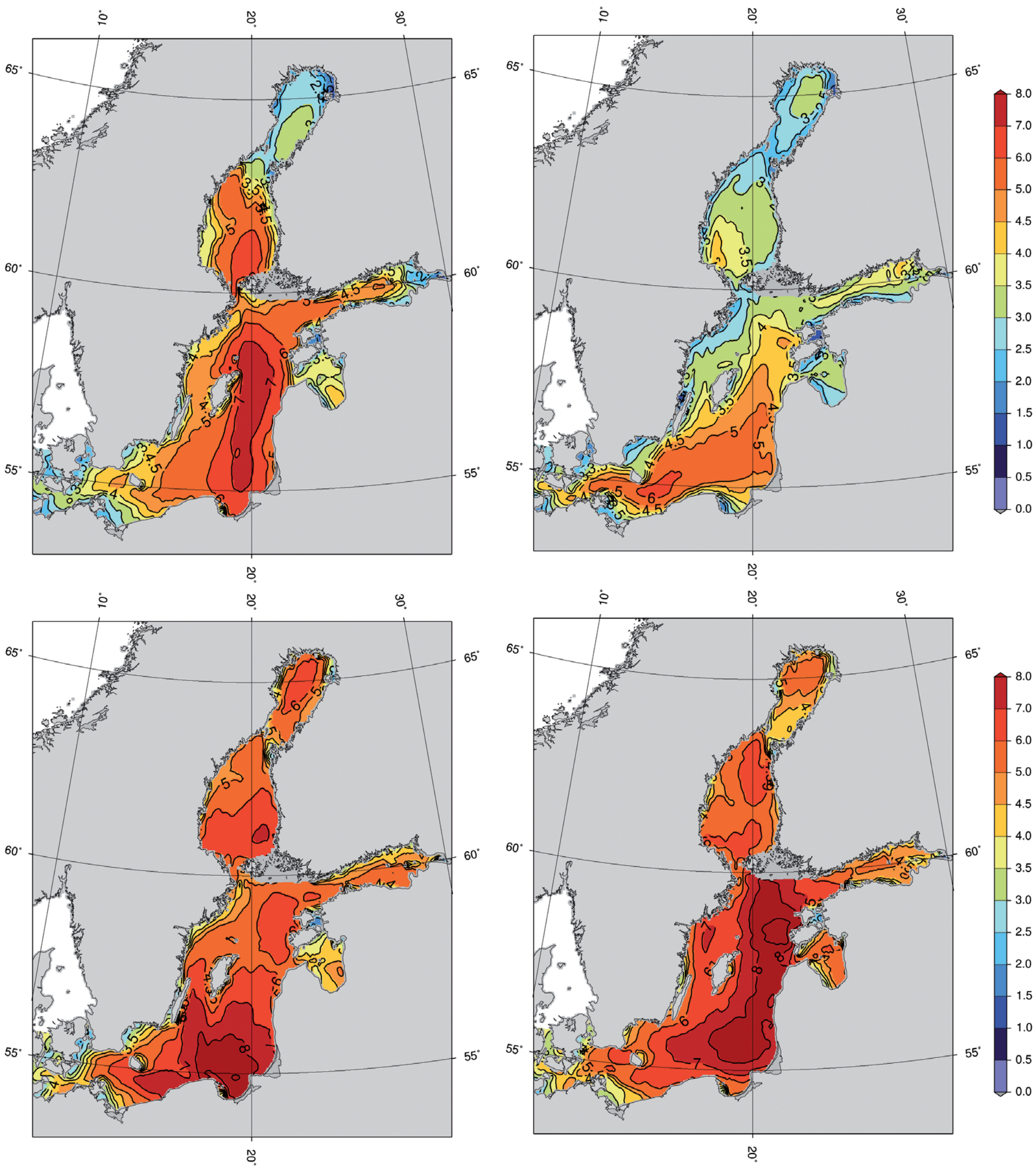

Fig. 17. Hindcast seasonal maximum values of significant wave height in the Baltic Sea. Spring (upper left), summer (upper right), autumn (lower left) and winter (lower right).

height was more difficult to verify. However, we can give an estimate based on the highest values that could be analysed against buoy data, that the hindcast maximum values are expected to be within 1 m of the measured values.

We discussed the problems related to the formulation of statistics in seasonally ice-covered seas, and introduced five different types of statistics, namely measurement statistics, ice-time-included statistics, ice-free-time statistics, exceedance time statistics, and hypothetical no-ice statistics. The mean values of significant wave height were smaller than 1.5 m in all the areas of the Baltic Sea according to ice-time-included statistics. The mean values are highest in the Baltic Proper. In the gulfs mean values of significant

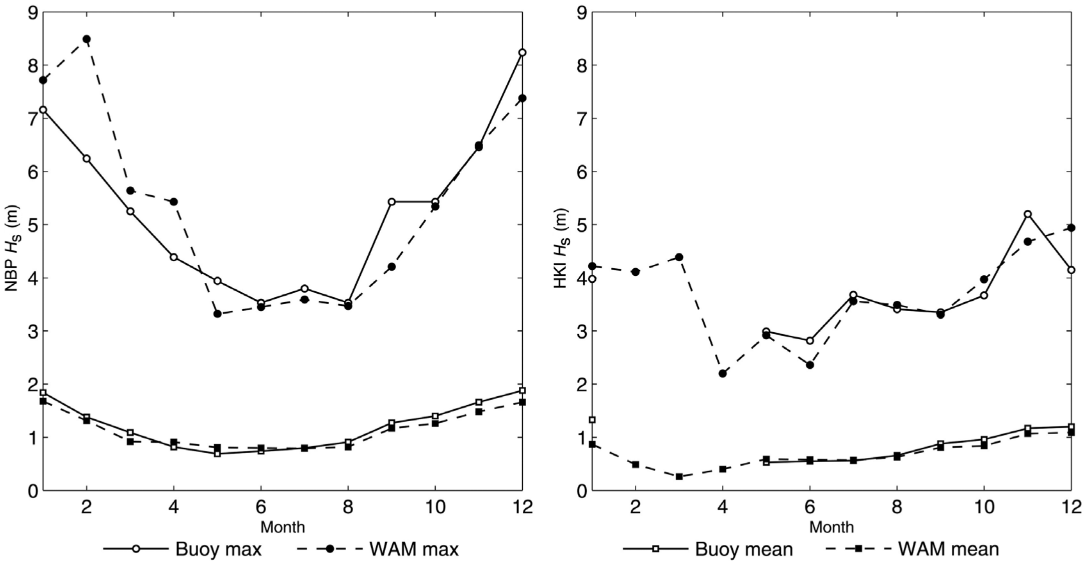

Fig. 18. Monthly mean and maximum values of significant wave height at the NBP site (left-hand-side panel) and the HKI site (right-hand-side panel). Hindcast values (statistics type F) dashed line and measured values (statistics type M) solid line.

wave height were smaller than 1 m. The exceedance probabilities were again highest in the Baltic Proper, the values being slightly higher in the southern part than in the northern part.

In severe storms, the significant wave height can reach over 9 m. The hindcast maximum value of significant wave height was 9.7 m. The measured maximum value in the Baltic Sea is 8.2 m, measured by the northern Baltic Proper wave buoy. For determining the maximum values of significant wave height in all the open sea areas of the Baltic Sea, the 6-year hindcast period is relatively short. Re-analyses of the Baltic Sea maximum values of significant wave height should be done as soon as re-analysed wind fields are available with a resolution sufficient for the Baltic Sea area.

Acknowledgements: We are grateful for the inspiring working environment at the former Finnish Institute of Marine Research, at which most of the work for this paper was done, and for the continuity the Finnish Meteorological Institute has provided for our work. The supply of ice information for the wave hindcasts by Mr. Jouni Vainio (presently at FMI), the wave buoy data handling by Mr. Hannu Jokinen (presently at FMI) and the altimeter data handling by Mr. Tuomas Niskanen (presently at FMI) are gratefully acknowledged. The wave measurements at HKI site are operated in cooperation with the Finnish Maritime Administration and the Port of Helsinki. The altimeter data used in this study was extracted from the RADS altimeter database hosted by TuDelft, Netherlands.

References

Alves J.H.G.M. & Banner M.L. 2003. Performance of a saturation-based dissipation-rate source term in modeling the fetch-limited evolution of wind waves. *J. Phys. Oceanogr*. 33: 1274–1298.

BACC Author Team 2008. *Assessment of Climate Change for the Baltic Sea Basin*. Springer Verlag, Heidelberg.

Blomgren S., Larsson M. & Hanson H. 2001. Numerical modeling of the wave climate in the southern Baltic Sea. *J. Coastal Res*. 17: 342–352.

Broman B., Hammarklint T., Rannat K., Soomere T. & Valdmann A. 2006. Trends and extremes of wave fields in the north-eastern part of the Baltic Proper. *Oceanologia* 48: 165–184.

Caires S., Sterl A., Komen G. & Swail V. 2004a. The web-based KNMI/ERA-40 global wave climatology atlas. *WMO Bulletin* 53: 142–146.

Caires S., Sterl A., Bidlot J.-R., Graham N. & Swail V. 2004b. Intercomparison of different wind-wave reanalyses. *J. Climate* 17: 1893–1913.

Cieślikiewicz W. & Paplińska-Swerpel B. 2008. A 44-year hindcast of wind wave fields over the Baltic Sea. *Coastal Eng*. 55: 894–905.

Dailidienė I., Davulienė L., Tilickis B., Stankevičius A. & Myrberg K. 2006. Sea level variability at the Lithuanian coast of the Baltic Sea. *Boreal Env. Res*. 11: 109–121.

Drebs A., Nordlund A., Karlsson P., Helminen J. & Rissanen

P. 2002. *Climatological statistics of Finland 1971–2000*. Finnish Meteorological Institute, Helsinki.

Gayer G., Günther H. & Winkel N. 1995. Wave climatology and extreme value analysis for the Baltic Sea area off the Warnemünde harbour entrance. *Deutsche Hydrographische Zeitschrift* 47: 109–130.

Høyer J.L. & Nielsen J.W. 2006. Satellite significant wave height observations in coastal and shelf seas. In: Danesy D. (ed.), *Proceedings of the Symposium on 15 Years of Progress in Radar Altimetry, 13–18 March 2006, Venice, Italy (July 2006)*, ESA Special Publication SP-614, ESA Publications Division, Noordwijk, The Netherlands, paper no. 812.

Järvenoja S. 2005. A new meso-β-scale HIRLAM system at FMI. *Hirlam Newsletter* 47: 91–106.

Järvenoja S. & Tuomi L. 2002. Coupled atmosphere-wave model for FMI and FIMR. *Hirlam Newsletter* 40: 9–22.

Jönsson A., Broman B. & Rahm L. 2003. Variations in the Baltic Sea wave fields. *Ocean Engineering* 30: 107–126.

Kahma K. 1976. Preliminary results of wind wave measurements in the southern part of the Bothnian Sea. In: *Proceedings of the 10th conference of the Baltic Oceanographers*, Part 1, Göteborg, Sweden, paper no. 1.

Kahma K.K. 1981. A study of the growth of the wave spectrum with fetch. *J. Phys. Oceanogr.* 11: 1503–1515.

Kahma K.K. & Pettersson H. 1993. Aaltohavaintoja Suomenlahdelta 1982–1985. Wave statistics from the Gulf of Finland. *Finnish Institute of Marine Report. Internal Report* 1/1993. [In Finnish with English summary].

Kahma K.K. & Pettersson H. 1994. Wave growth in a narrow fetch geometry. *Global Atmos. Ocean Syst.* 2: 253–263.

Kahma K., Rantanen E. & Saarinen J. 1983. *Aaltohavaintoja eteläiseltä Selkämereltä 1973–1975, 1981* [*Wave data from the southern Bothnian Sea 1973–1975, 1981*]. Finnish Institute of Marine Research, Internal report 1/1983. [In Finnish with English summary].

Kahma K., Pettersson H. & Tuomi L. 2003. Scatter diagram wave statistics from the northern Baltic Sea. *MERI — Report Series of the Finnish Institute of Marine Research* 49: 15–32.

Kahma K., Pettersson H., Stipa T., Högström U., Smedman A.S. & Bergström H. 1997. *Comparison of wind stress hindcast by a coupled atmospheric-wave model (ECAWOM) and the measured wind stress at Östergarnsholm*. Technical Report, MAST 2 Project ECAWOM, Finnish Institute of Marine Research, Helsinki.

Kangas M. & Sokka N. 2005. Operational and RCR HIRLAM at FMI. *Hirlam Newsletter* 48: 14–20.

Kelpšaitė L., Hermann H. & Soomere T. 2008. Wave regime differences along the eastern coast of the Baltic Proper. *Proc. Estonian Acad. Sci. Eng.* 57: 225–231.

Kistler R., Kalnay E., Collins W., Saha S., White G., Woollen J., Chelliah M., Ebisuzaki W., Kanamitsu M., Kousky V., van den Dool H., Jenne R. & Fiorino M. 2001. The NCEP-NCAR 50-year reanalysis: monthly means [CD-ROM and documentation]. *Bull. Amer. Meteor. Soc.* 82: 247–268.

Komen G.J., Cavaleri L., Donelan M., Hasselmann K., Hasselman S. & Janssen P.A.E.M. 1994. *Dynamics and modelling of ocean waves*. Cambridge University Press, Cambrigde.

Launiainen J. & Laurila T. 1984. Marine wind characteristics in the Northern Baltic Sea. *Finnish Marine Research* 250: 52–86.

Longuet-Higgins M.S., Cartwright D.E. & Smith N.D. 1963. Observations of the directional spectrum of sea waves using the motion of a floating buoy. In: *Ocean Wave Spectra: Proceedings of a Conference on Ocean Wave Spectra, Easton, Maryland, 1–4 May 1961*, Prentice-Hall, Engelwood Cliffs, N.J., pp. 111–132.

Pettersson H. 1992. Estimates of the highest wind generated waves in the Gulf of Finland. In: P*roceedings of the 18th Conference of the Baltic Oceanographers, St. Petersburg, 23–27 November, 1992*, vol. 2, St. Petersburg, Russia, pp. 88–95.

Pettersson H. 1994. *Aaltohavaintoja eteläiseltä Selkämereltä — suuntamittauksia 1992* [*Directional wave statistics from the southern Bothnian Sea 1992*]. Finnish Institute of Marine Research, Internal report 5. [In Finnish with English summary].

Pettersson H. 2001. Aaltohavaintoja Suomenlahdelta: suuntamittauksia 1990–1994 [Directional wave statistics from the Gulf of Finland 1990–1994]. *MERI — Report Series of the Finnish Institute of Marine Research* 44: 1–37. [In Finnish with English summary].

Pettersson H. 2004. Wave growth in a narrow bay. *Finnish Institute of Marine Research, Contributions* 9: 1–33.

Pettersson H. & Jönsson A. 2005. *Wave climate in the Northern Baltic Sea 2004*. HELCOM Indicator Fact Sheets 2005, available at http://www.helcom.fi/BSAP_assessment/ifs/archive/ifs2005/en_GB/Waveclimate/.

Pettersson H., Hammarklint T. & Schrader D. 2007. *Wave climate in the Baltic Sea 2006*. HELCOM Indicator Fact Sheet 2007, available at http://www.helcom.fi/BSAP_assessment/ifs/archive/ifs2007/en_GB/waveclimate/.

Pettersson H., Kahma K.K. & Tuomi L. 2010a. Wave directions in a narrow bay. *J. Phys. Oceanogr.* 40: 155–169.

Pettersson H., Lindow H.T. & Schrader D. 2010b. *Wave climate in the Baltic Sea 2009*. HELCOM Indicator Fact Sheet 2010, available at http://www.helcom.fi/BSAP_assessment/ifs/ifs2010/en_GB/waveclimate2009/.

Pettersson H., Graber H.C., Hauser D., Quentin C., Kahma K.K., Drennan W.M. & Donelan M.A. 2003. Directional wave measurements from three wave sensors during the FETCH experiment. *J. Geophys. Res.* 108: 8061–8076.

Ponce de León S. & Guedes Soares C. 2008. Sensitivity of wave model predictions to wind fields in the western Mediterranean sea. *Coastal Eng.* 55: 920–929.

Queffeulou P. 2004. Long-term validation of wave height measurements from altimeters. *Mar. Geod.* 27: 495–510.

Räämet A. & Soomere T. 2010. The wave climate and its seasonal variability in the northeastern Baltic Sea. *Estonian J. Earth Sci.* 59: 100–113.

Räämet A., Soomere T. & Zaitseva-Pärnaste I. 2010. Variations in extreme wave heights and wave directions in the north-eastern Baltic Sea. *Proc. Estonian Acad. Sci. Eng.* 59: 182–192.

Schrama E., Scharroo R. & Naeije M. 2000. *Radar Altimeter Database System (RADS): Towards a generic multi-satellite altimeter database system*. USP-2 report 00-11, BCRS/SRON, Delft, Netherlands.

Seinä A. 2007. Ice seasons 2005–2006. *MERI — Report Series of the Finnish Institute of Marine Research* 59: 7–11.

Seinä A. 2008. Ice season 2006/2007. *MERI — Report Series of the Finnish Institute of Marine Research* 62: 51–56.

Seinä A. & Peltola J. 1991. Duration of the ice season and statistics of fast ice thickness along the Finnish coast 1961–1990 [Jäätalven kestoaika ja kiintojään paksuustilastoja Suomen merialueilla 1961–1990]. *Finnish Marine Research* 258: 1–46. [In Finnish and English].

Seinä A., Eriksson P., Kalliosaari S. & Vainio J. 2006. Ice seasons 2001–2005 in Finnish sea areas [Jäätalvet 2001–2005 Suomen merialueilla]. *MERI — Report Series of the Finnish Institute of Marine Research* 57: 1–94. [In Finnish and English].

Soares C.G.2008. Hindcast of dynamic processes of the ocean and coastal areas of Europe. *Coastal Eng.* 55: 825–826.

Soomere T. 2003. Anisotropy of wind and wave regimes in the Baltic Proper. *J. Sea Res.* 49: 305–316.

Soomere T. 2005. Wind wave statistics in Tallinn Bay. *Boreal Env. Res.* 10: 103–118.

Soomere T. & Zaitseva I. 2007. Estimates of wave climate in the northern Baltic Proper derived from visual wave observations at Vilsandi. *Proc. Estonian Acad. Sci. Eng.* 13: 48–64.

Soomere T., Behrens A., Tuomi L. & Nielsen J.W. 2008. Wave conditions in the Baltic Proper and in the Gulf of Finland during windstorm Gudrun. *Nat. Hazards Earth Syst. Sci.* 8: 37–46.

Swail V.R. & Cox A.T. 2000. On the use of NCEP–NCAR reanalysis surface marine wind fields for a long-term North Atlantic wave hindcast. *J. Atmos. Oceanic Techol.* 17: 532–545.

Tuomi L. 2008. The accuracy of FIMR wave forecasts in 2002–2005. *MERI — Report Series of the Finnish Institute of Marine Research* 63: 7–16.

Tuomi L. & Sarkanen A. 2008. Wave forecasts for the Baltic Sea using ECMWF wind fields as forcing data. In: *US/EU-Baltic International Symposium, 2008 IEEE/OES*, doi: 10.1109/BALTIC.2008.4625529.

Undén P., Rontu L., Järvinen H., Lynch P., Calvo J., Cats G., Cuxart J., Eerola K., Fortelius C., Garcia-Moya J., Jones C., Lenderlink G., McDonald A., McGrath R., Navascues B., Nielsen N., Odegaard V., Rodriguez E., Rummukainen M., Rõõm R., Sattler K., Sass B., Savijärvi H., Schreur B., Sigg R., The H. & Tijm A. 2002. *HIRLAM-5 Scientific Documentation*. Swedish Meteorological and Hydrological Institute, Norrköping.

Uppala S.M., Kållberg P.W., Simmons A.J., Andrae U., da Costa Bechtold V., Fiorino M., Gibson J.K., Haseler J., Hernandez A., Kelly G. A., Li X., Onogi K., Saarinen S., Sokka N., Allan R.P., Andersson E., Arpe K., Balmaseda M.A., Beljaars A.C.M., van de Berg L., Bidlot J., Bormann N., Caires S., Chevallier F., Dethof A., Dragosavac M., Fisher M., Fuentes M., Hagemann S., Hólm E., Hoskins B. J., Isaksen L., Janssen P.A.E.M., Jenne R., McNally A.P., Mahfouf J.-F., Morcrette J.-J., Rayner N.A., Saunders R.W., Simon P., Sterl A., Trenberth K E., Untch A., Vasiljevic D., Viterbo P. & Woollen J. 2005. The ERA-40 re-analysis. *Q. J. R. Meteorol. Soc.* 131: 2961–3012.

Wahl G. 1973a. *Vågstatistik från svenska kustfarvatten: fyrskeppet Fladen: visuella observationer och vågregistreringar*. Allmän rapport från Statens skeppsprovningsanstalt Nr. 35.

Wahl G. 1973b. *Vågstatistik från svenska kustfarvatten: fyrskeppet Svenska Björn: visuella observationer och vågregistreringar*. Allmän rapport från Statens skeppsprovningsanstalt Nr. 36.

Wahl G. 1973c. *Vågstatistik från svenska kustvatten: fyrskeppet Falsterborev: visuella observationer och vågregistreringar*. Allmän rapport från Statens skeppsprovningsanstalt Nr. 38.

WAMDI 1988. The WAM model — A third generation ocean wave prediction model. *J. Phys. Oceanogr.* 18: 1775–1810.