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Discussions

Wave climatology in the Arkona Basin, the Baltic Sea

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Abstract

The basic features of the wave climate in the South-Eastern Baltic Sea are studied based on available long-term measurements and simulations. The analysis of average, typical and extreme wave conditions, frequency of occurrence of different wave parameters, variations in wave heights from weekly to decadal scales, etc., is performed based on waverider measurements at the Darss Sill since 1991. The measured climatology is compared against numerical simulations with the WAM wave model driven by downscaled reanalysis of wind fields for 1958–2002 and by adjusted geostrophic winds for 1970–2007. The wave climate in this region is typical for semi-enclosed basins of the Baltic Sea. The maximum wave heights are about half of those in the Baltic Proper. The overall reliably recorded maximum significant wave height $H_S = 4.46$ m occurred during a severe S-SW storm in 1993 when the 10-min average wind speed reached 28 m s^{-1}. The long-term average significant wave height (0.75 m) shows modest interannual (about 12 % of the long-term mean) and substantial seasonal variation. The wave periods are mostly concentrated in a narrow range of 2.5–4 s and their distribution is almost constant over decades. The role of remote swell is very small. The annual wave properties show large interannual variability but no long-term trends in average and extreme wave heights can be observed.

1 Introduction

Observations, measurements and modelling of wave fields in the Baltic Sea basin go back for many decades (Soomere, 2008; Weisse and von Storch, 2010). The most systematic efforts in this direction are visual observations from ships (which have been extensively used for the compilation of older wave atlases, e.g., Rzheplinsky, 1965) and visual observations from coastal hydrometeorological stations of the former USSR along almost the entire Eastern Baltic Sea coast (Soomere and Räämet, 2011). Systematic instrumental wave measurements were probably first launched at the end of the 1970s in Swedish coastal waters (Broman et al., 2006), from the 1980s at different sites of the Northern Baltic Proper, largely focusing on sea areas surrounding Finland (Kahma et al., 2003), and from the 1990s in the Southern and South-Western Baltic Sea. These studies have been complemented by several numerical reconstructions of the wave climate (Jönsson et al., 2003; Soomere, 2005; Augustin, 2005; Räämet et al., 2010; Räämet and Soomere, 2011; Tuomi et al., 2011).

The input of wind wave research into the climatology of the Northern Baltic Proper has been extensively documented (Kahma et al., 2003; Broman et al., 2006; Soomere, 2008; Soomere and Räämet, 2011b). A comparison of the instrumentally measured and visually observed wave properties with the results of numerical simulations reveals that the Baltic Sea wind wave fields contain not only interesting spatial configurations of climatological features but also an extremely rich pattern of their changes (incl. changes to the most frequent wave propagation direction, Soomere et al., 2011) at various time scales. For example, adjacent open sea areas separated by only about 100 km may host changes of a completely different nature (Soomere and Räämet, 2011a), and the trends for average and extreme wave heights do not necessarily coincide (Soomere and Räämet, 2011b). Part of these changes apparently are related with the systematic increase in SW winds over the last 40 yr at the expense of some other wind directions in the NE part of the Baltic Sea (Jaagus, 2009). Such changes to the wave field are a probable reason for considerable variations in the evolution of coastal sections in the vicinity of Neva Bay, which was sheltered from predominant waves in the past (Ryabchuk et al., 2011).

Although the predominant SW winds usually excite the roughest wave conditions in the NE part of the Baltic Proper (Soomere et al., 2008), the wave climate in the SW region of this water body is equally important. The SW Baltic Sea hosts extremely dense ship traffic which is confined to relatively narrow fairways and is thus particularly vulnerable with respect to severe weather conditions. Also, most of the SW Baltic Sea coasts are easily erodible and, thus, any change to the wave regime may substantially affect their status and further evolution. As the spatial scales here are even smaller than in the NE Baltic Sea, the resolution of the latest wave reference books (Lopatukhin et al., 2006) and reliable global wave data sets such as KNMI/ERA-40 Wave Atlas (09.1957–08.2002, $1.5^{\circ} \times 1.5^{\circ}$) (Sterl and Caires, 2005) are far too sparse for the production of an adequate climatology of the typical and extreme wave conditions.

Information about the wave climatology in the southern part of the Baltic Sea is available mostly from numerical simulations (Gayer et al., 1995; Paplińska, 1999, 2001; Blomgren et al., 2001; Cieślikiewicz and Herman, 2002; Augustin, 2005; Cieślikiewicz and Paplińska-Swerpel, 2008), specific reconstructions (Mietus and von Storch, 1997) and from relatively short-term measurement campaigns (Mårtensson and Bergdahl, 1987). The seminal collection addressing the climate in the Baltic Sea basin (BACC, 2008) only touches the aspects of wave climate. Lately, some data have become available for the Lithuanian coast (Kelpšaite et al., 2008, 2011).

The existing information about changes to wave properties in this area is controversial. Efforts towards the reconstruction of the changes to the local wave climate undertaken until the mid-1990s (WASA Group, 1995) did not reveal any large alterations. A popular opinion in the 1980s–1990s was that the wave climate is becoming gradually more severe, following the seemingly increasing storminess (Alexandersson et al., 2000). This view was qualitatively supported by the analysis of the changes to the wind speed over this area. The National Centers for Environmental Prediction and for Atmospheric Research (NCEP/NCAR) reanalysis project revealed a significant increase in the annual mean wind speed at 850 hPa over the Baltic over the period 1953–1999 (Pryor and Barthelmie, 2003). The most of the increase was focused on the upper quartile of the wind speed distribution and in the SW of the region. The modelled wind speed showed also a clear increase in the higher percentiles of wind speed distributions at the 10 m level (Pryor et al., 2005). This increase generally means more favourable conditions for high wave generation. Somewhat surprisingly, it became evident in the wave fields neither in the Baltic Sea nor in the adjacent North Sea (WASA Group, 1998). Moreover, at some places even a long-term trend towards a reduction in severe wave conditions was found (Weisse and Günther, 2007). The discrepancy may partially reflect decadal variations in the wind properties. For example, owing to a distinct maximum in the wind speed around the mid-1990s shorter trends may substantially vary for different time intervals.

Wave climate reconstructions based on adjusted geostrophic winds revealed a possible increasing trend in wave heights in the Arkona Basin since about 1970 (Räämet et al., 2010). This trend may represent an increase in the geostrophic wind speed (GWSP) in wintertime (December–February) for the southern and central parts of the Baltic Sea by about 1.5 $\mathrm{m\,s^{-1}}$ in 1989–2007 compared to that in 1970–1988 (Lehmann et al., 2011). The spring season (March–May) hosts an overall increase in the GWSP by 0.5–1 $\mathrm{m\,s^{-1}}$ in the Baltic together with a change in the wind direction from SW to west. During autumn, however, the GWSP decreased by about 1.5–2 $\mathrm{m\,s^{-1}}$ for the western and central parts of the Baltic Sea. Although there seems to be no overall increase in the GWSP in this region, the turn in the wind direction more to the west apparently favours the increase in wave heights in the SW Baltic Sea. The wave properties are often fetch-limited in this area and therefore frequently depend as much on the wind direction as on the wind strength.

In this paper we make an attempt to establish the basic features of the wave climate and its changes for the SW part of the Baltic Sea, the Arkona Basin and specifically the Darss Sill region. The analysis is based on waverider measurements at the Darss Sill covering 20 yr (1991–2010). The recorded wave properties are compared against numerical wave simulations performed in the Institute of Coastal Research, Helmholtz-Zentrum Geesthacht for 1958–2002 (Augustin, 2005) and against experiments performed in the Institute of Cybernetics at Tallinn University of Technology using geostrophic winds for 1970–2007 (Räämet and Soomere, 2010). We start with the description of the instrumentally recorded and numerically simulated data sets. The wave climatology is discussed based on the distributions of the frequency of occurrence of different wave heights and periods. The temporal changes to the wave properties are analysed on daily, weekly, annual and decadal scales. The comparison largely focuses on the time interval of 1991–2002 covered by all the data sets.

2 Recorded and modelled data

Since 29 January 1991, wave measurements in the SW Baltic Sea have been carried out at a station located at 54°41.9′ N, 12°42.0′ E in the area of the Darss Sill (with the GKSS Research Centre, now the Helmholtz-Zentrum Geesthacht as the operator), and since 2002 at a station northwest of Cape Arkona (54°52.9′ N, 13°51.5′ E) by the Federal Maritime and Hydrographic Agency of Germany (BSH) (Fig. 1). A short analysis of the data is available in the form of HELCOM information sheets[1]. The latter data set covers a relatively short time interval and is not considered in this paper.

The waves at the Darss Sill are measured with surface following buoy (Seawatch Directional Waverider, Barstow et al., 1994) approximately every hour. The significant wave height is calculated onboard the buoy over 1600 s time series of surface displacement. The largest gaps, with no measurements at all for periods longer than a few days are from 30 July–11 August, 16–18 August, 14 October–27 November 1991, 17 December 1991–23 April 1992, 1 February–1 May 1996 (caused by ice formation), 10 January–13 February 1997, May 2000, February 2006, October 2009, March–May and December 2010 (Fig. 2). During the time interval of 1991–2010 (7305 calendar days altogether), covered in this paper, there were 6198 days with at least one sensible recording per day whereas 1107 days had no data.

The gaps in data are distributed unevenly over the calendar year (Fig. 3). There are very few gaps in the summer season, from June to August when usually measurements from only one year are missing. The end of November–beginning of December is equally well represented. The lowest percentage of days covered by measurements is in January and October and, somewhat surprisingly, in April and May when typically 15 yr out of 20 are represented.

The number of measurements per day varies over time. It is 9–10 during the first

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[1] See e.g. Pettersson, H., Lindow, H., Schrader, D.: Wave climate in the Baltic Sea 2009. HELCOM Indicator Fact Sheets, 2010, http://www.helcom.fi/BSAP_assessment/ifs/ifs2010/en_GB/waveclimate2009/.

years of measurements, decreases to about 8 by the end of 1991, increases to about 48 from April 1999, fluctuates very strongly between almost zero and 50 in 2001–2002 and up to March 2003, after which it stabilises on the level of 48 measurements per day. As each measurement cycle covers 1600 s, each day can only host maximally 54 independent measurements. For this reason, measurements with overlapping time interval are left out from the further analysis in which maximally 50 measurements a day are accounted for (Fig. 2). The total amount of recorded wave conditions is 190 608 in 1991–2010, that is, about 26 measurements per day. A few measurements were obviously distorted and 190 305 records contain consistent data considered below. From a variety of measured parameters we mostly consider the significant wave height (called simply wave height below) and the period T_{-1}, called mean period in what follows.

The measured wave data are compared with two numerically simulated wave data sets. For the period 1958–2002 numerical simulations with the third generation wave model WAM (Komen et al., 1994) covering the entire Baltic Sea were performed (Augustin, 2005) as part of a consistent met-ocean hindcast for the area (Weisse et al., 2009). The model was driven by atmospheric wind fields derived from an atmospheric reconstruction using a regional atmosphere model (Feser et al., 2001) driven by the hourly winds from the NCEP/NCAR weather reanalyses (Kalnay et al., 1996; Kistler et al., 2001). At the lateral boundaries wave fields from a corresponding North Sea hindcast (Weisse and Günther, 2007) were used. The spatial resolution was about three nautical miles (about 5.5 km × 5.5 km). The wave spectra were computed with a directional resolution of 15° and using 28 frequency bins ranging from about 0.05 to 0.66 Hz. Two-dimensional wave spectra were stored every 3 h, whereas integrated wave parameters such as significant wave height, mean wave direction, and different wave periods are available every hour.

Another set of long-term time series of reconstructed wave properties is extracted from simulations performed for 1970–2007 for the entire Baltic Sea (Räämet and Soomere, 2010) using the wave model WAM with the same spatial and directional resolution but driven by adjusted geostrophic winds with temporal resolution of 3 or 6 h. Differently from the above simulations, wave propagation from the North Sea into the Baltic Sea was ignored and an extended frequency range up to about 2 Hz (wave periods down to 0.5 s, 42 frequencies) was used to ensure realistic wave growth rates in low wind conditions after calm situations (Soomere, 2005). For the comparisons below, we use simulated data from both sets for a grid point with coordinates 54°42′ N, 12°42′ E. The simulations will be referred to as AW and RS in what follows. The presence of ice was accounted for in the AW simulations as monthly ice coverage from the BSH observations but ignored in the RS simulations

3 Wave climatology

The median of the entire data set of measured wave heights is 0.64 m and the thresholds for 10 %, 5 % and 1 % of the highest wave heights are 1.43, 1.68 and 2.22 m, respectively. The relevant values for the data set of daily average wave heights differ insignificantly and are 0.68, 1.36, 1.58 and 2.02 m, respectively. Therefore, wave conditions in which $H_S > 2$ m are already very severe in this area and occur during about 1 % of the time, or during approximately 100 h a year. Note that a similar threshold for the open Baltic Proper is 4 m (Kahma et al., 2003). Waves higher than 3 m occur with a probability of about 0.15 %, that is, during some 13 h a year. Waves higher than 4 m were measured in three storms during the 20 yr under study. In a long wave storm on 10–11 January 2010 the wave height was close to 4 m during about 30 h. The largest reliably recorded wave height (4.46 m) occurred on 3 November 1995 in a strong NE storm when the maximum simulated wave height was 3.92 m. The maximum numerically simulated wave height 6.23 m in 1958–2002 occurred on 26 January 1990 before the measurements started.

The large number of available measurements makes it possible to estimate the diurnal variations in the measured wave heights. Such variations play a great role in areas affected by strong breeze and may lead to an increased level of cross-seas and pose a certain danger to smaller vessels (Vethamony et al., 2011). The number of measurements at the Darss Sill is distributed practically evenly over the day (Fig. 4a). Only the main synoptic times (around 00:00, 03:00, 06:00, 09:00, 12:00, 15:00, 18:00 and 21:00) contain more measurements because during the first years of measurements the recordings mostly exist for these times. This difference in recordings does not become evident in the diurnal course of the wave height (Fig. 4b). On average, the largest wave heights occur at the Darss Sill between 10:00 and 15:00 whereas a clearly visible minimum exists for late evening and night (21:00–01:00). The average amplitude of this diurnal variation over all seasons is 2.6 cm, that is, almost 3.5 %. In June and July the amplitude is much larger, about 11 % and 14.5 %, respectively. The diurnal variation is reversed, with higher waves present in the evening time in November and December.

The most frequently used parameter of surface waves, the long-term average significant wave height over all available data, is 0.760 m for the measurements, 0.836 m for the AW simulations (1958–2002) and 0.800 m for the RS simulations (1970–2007). As no long-term trend in simulated wave heights exists at the study site (see below), the differences in this parameter basically reflect the adequate quality of the wave hindcasts for the Arkona Basin. The slight overestimation of the wave height evidently stems from the particular choice of wind information. Comparisons of the RS simulations with visually observed wave data from coastal sites in the Northern Baltic Proper and at the entrance to the Gulf of Finland (Räämet and Soomere, 2010) suggested that these simulations underestimate wave heights by about 15 %. Therefore, the adjusted geostrophic wind speed used to drive these simulations is slightly underestimated for the open Baltic Proper. The almost perfect match of the long-term wave height at the Darss Sill indicates, however, that the resulting driving wind speeds are adequate for the SW Baltic Sea.

The quite substantial diurnal variation in wave heights suggests that the changing number of wave measurements per day and during different seasons or longer time intervals may affect the estimates of the climatological properties of wave fields. It is possible to remove the associated inhomogeneity in the time series (and especially quite diverse coverage of different calendar days) by means of using either daily average wave heights or wave heights averaged over certain shorter intervals that have more or less the same coverage over the entire measurement time. The long-term average wave height, however, is almost the same when calculated from all measurements in a straightforward way (0.7603 m) and from daily mean wave heights (0.7608 m).

The distribution of the occurrence of different wave heights at Darss Sill (Fig. 5) resembles those for the open parts of the Baltic Proper (Kahma et al., 2003; Broman et al., 2006). As expected, the data set of daily mean wave heights has a clearly smaller frequency for the lowest and the largest wave heights, and a somewhat larger frequency of waves in the range of about 0.5–1.25 m. For all measurements the waves are most frequent in the range of 0.25–0.375 m whereas wave situations with the daily mean heights of 0.25–0.625 m occur with an almost equal frequency. The difference in the shapes of these two distributions becomes evident in terms of the parameters of the relevant Weibull distribution: $k = 1.6550$, $b = 0.8505$ for the entire data set and $k = 1.8112$, $b = 0.8552$ for the daily mean wave heights. This dissimilarity would lead to obvious differences in estimates for the probabilities of occurrence of severe seas. Interestingly, the parameter b is almost the same for the AW (1958–2002) and RS (1970–2007) simulations ($b = 0.8416$ and $b = 0.8320$, respectively) whereas the parameter k is much smaller ($k = 1.4906$ and $k = 1.3774$, respectively).

A comparison of the distributions of the occurrence of different wave heights estimated from measurements with those extracted from numerical reconstructions for the time interval of 1991–2002, which is covered by all the data sets (Fig. 6), shows certain deviations of the modelled wave statistics from the measured data. The modelled data sets adequately reproduce the frequency of moderately high wave fields (0.5–2 m). Simulations by RS overestimate low wave heights (0.125–0.375 m) whereas simulations by AW underestimate the frequency of such wave conditions. The largest discrepancy between the model results occurs for the range of wave heights of 0.25–0.375 m. Still, both the models adequately reproduce the overall proportion of wave fields with $H_S < 0.5$ m: the measured data contain 49 % of such fields while the RS hindcast has

52 % of waves with $H_S < 0.5$ m. The AW hindcast result for such wave fields (44 %) is close to the value in terms of daily mean wave heights (48 %). Both models tend to overestimate the proportion of relatively rough wave fields with Hs > 1.5 m. This feature may partly reflect several longer gaps in the measured data pool (see Sect. 2). Notice that the distributions of the measured wave heights for 1991–2010 and for 1991–2002 almost exactly coincide. This feature suggests that these distributions are relatively insensitive to changes in the wind field over the area in question during the latter decades reported in Lehmann et al. (2011).

The distribution of the occurrence of different measured mean wave periods (T_{-1}, Fig. 7) has a general bell shape, slightly skewed towards shorter waves. Waves with periods of about 3 s are the most frequent. About 50 % of all waves are within the period range of 2.7–3.6 s and about 70 % in the range of 2.6–4 s. Waves with periods below 2 s occur with a probability of 0.02 %, waves with periods exceeding 4, 5, 6, and 7 s with probabilities of 10.85 %, 0.55 %, 0.075 % and 0.007 %, respectively. The frequent presence of waves with periods 3–4 s is not unexpected as such waves are typical for coastal areas of the Baltic Sea (Soomere, 2008; Soomere and Räämet, 2011). Both the modelled and measured distributions have a two-peak appearance, with the secondary peak for periods of about 3.5 s. This feature may be associated with a superposition of two wave regimes in the Darss Sill region: locally generated waves with typical periods of about 3 s and wave systems with periods of > 3.5 s generated in the Baltic Proper.

Other specific features of this distribution are that (i) the wave periods are concentrated in quite a narrow range and (ii) waves with very short periods (about 1–2 s, which are frequent in coastal areas) are almost missing. Partly these features stem from the inaccuracy in the representation of wave periods both in measurements and modelling efforts: in both cases the typical wave periods for steep seas are overestimated. This distortion evidently is the source of the predomination of waves with periods just below 3 s. On the other hand, the very small share of remote swell is typical for the Baltic Sea and becomes evident also here.

The largest discrepancy between the modelled and measured distributions appears for the wave fields with periods > 3 s. The modelled periods have also most often values close to 3 s. Their distributions reveal, however, much more frequent presence of larger periods: the hindcast values for the frequency of wave fields with periods about 5 s substantially exceed those extracted for measurements and even periods over 6 s occur with appreciable frequency according to simulations. Waves with such periods cannot be generated locally by predominant westerly winds because of limited fetch. The large proportion of long waves, however, does not necessarily mean a considerable level of associated wave energy; for example, it may simply reflect that, according to the model, low remote swell often enters the sea area in question.

Although both the measured and simulated (AW) distributions show a rapid decrease in the number of wave fields when the mean period is below 3 s, the almost total absence of waves with mean periods below 2.2 s is not realistic for the Baltic Sea wave fields in nearshore regions. The RS simulations suggest that the proportion of waves with periods of 2–2.5 s apparently is considerable in the study area. The most probable reason for the discrepancy of the two models stems from the difference in the spectral coverage: the AW simulations account for waves with periods > 1.5 s while the RS simulations use the frequency range up to 0.5 Hz (periods starting from about 0.5 s).

The similarity of the distributions of measured periods for 1991–2010 and 1991–2002 (Fig. 6) suggests that the structure of this distribution is extremely stable. The same conclusion is true for the modelled distribution of periods for 1957–2002 and for 1991–2002 (not shown): the differences between the two distributions are below 5 % for single frequency bins. Consequently, the distribution of wave periods, either measured or calculated, is very stable on a decadal scale. This conjecture matches the similar conclusion of (Soomere and Räämet, 2011) about very limited changes to the modelled wave periods in different regions of the Baltic Sea.

The distribution of the occurrence of measured combinations of wave heights and periods (Fig. 8; sometimes called scatter diagrams) has a shape generally characteristic of the Baltic Sea conditions: wave situations are typically concentrated along the area corresponding to the saturated wave fields with a Pierson-Moskovitz (PM) spectrum. Differently from the relevant diagrams for the open Baltic Proper (Soomere, 2008), waves in the Darss Sill region are mostly steeper than those with the PM spectrum. This feature is particularly apparent for relatively severe wave fields, with $H_S > 2\,\mathrm{m}$. It evidently stems from the relatively small size of the Belt Sea and the Arkona Basin where most of the wave fields develop in fetch-limited conditions and, therefore, the properties of wave fields should generally follow the properties of waves with a JONSWAP spectrum (Komen et al., 1994).

The branch of low and long waves, usually the dominant one in the open ocean, is almost missing in Fig. 8. This feature of the wave statistics suggests that the penetration of swells excited in the Baltic Proper into the area in question occurs infrequently and the waves here are mostly of local origin. Remotely excited waves are only represented as a few cases with $H_S < 1.2\,\mathrm{m}$ and with periods of 5.5–6 s. The relevant storms are evidently localised in the southern part of the Baltic Proper because storms covering the entire Baltic Sea usually excite swells with periods of 6–8 s (Soomere, 2008; Soomere and Räämet, 2011).

Notice that the distribution of the measured wave heights and periods in Fig. 8 also reflects several limitations of the measurement device and/or procedures. As discussed above, the measured data pool does not contain short waves with periods below 2 s. While the wave height apparently is estimated more or less correctly in such cases, the wave period evidently is overestimated. Another limitation of the device seems to become active for higher but relatively steep wave conditions so that the resulting diagram in Fig. 8 has a more or less straight edge of the truncation line in the space of wave properties. Comparison of the recorded wave properties with the ones reconstructed in the AW simulations for the overlapping interval 1991–2002 suggests that the simulated distribution is wider and somewhat shifted to longer and less steep waves than the measured one. The AW simulations apparently represent more adequately the proportion of wave fields with periods below 3 s but still do not capture situations with peak periods below 2 s. The wave periods in the RS simulations (not shown) do extend down to about 1.5 s, but the accuracy of the reconstruction of wave properties for particular time instants is poor because of a low resolution of the driving winds in both space and time.

The modelled extreme wave heights are somewhat larger than the measured ones. The model in the AW simulations suggests that in a few cases swell with periods of 6–7 s and steepness smaller than for similar wave systems with a PM spectrum has entered the area in question. Both the distributions are actually very similar in the region of severe seas with $H_S > 2$ m and suggest that in such cases one should expect fresh and steep seas with a minimum amount of longer wave components. Both the distributions also mirror a relatively large amount of seas with a mean period of 3–4 s and wave heights below 1 m. The absence of modelled wave fields with periods below 2 s evidently stems, as discussed above, from the limited coverage of the WAM model in the frequency space (only periods > 1.5 s accounted for) in the AW simulations. In reality, it is natural to expect a considerable amount of waves with periods of 1–1.5 s in this sea area. This limitation calls for an increase in the range of spectral components used in the model. Such an increase would also make it easier to adequately represent wave growth curves under low winds and after long-term calm situations.

The diagrams in Fig. 8 suggest that, according to the measurements, the roughest seas at the Darss Sill site, which occurred once in 20 yr, may have wave heights slightly exceeding 4 m and the mean period of about 7 s. The AW simulations suggest that in one “population” of strongest storms eventually corresponding to the relatively steep seas excited by SW winds, the wave height may reach about 4.5 m and the mean period of also 7 s. The most severe representative of the another “population” of storms would apparently have slightly lower wave heights, about 4.3 m but the mean period would be about 8 s.

4 Seasonal variations in wave heights

It is also interesting to compare seasonal variations in the measured and modelled wave data for daily mean values of significant wave height (Fig. 9). The overall good performance of the two data sets in reproductions of the variations on weekly scales, especially during windy months such as November–December, once more confirms the adequacy of the WAM wave model and the NCEP/NCAR weather reanalyses for the site in question. The AW simulation reproduces qualitatively similar variations also during the relatively calm season except for a few cases (e.g. at the end of August when the model shows a local minimum instead of the recorded maximum) but in many occasions does not fully follow the measured data. This feature suggests that most of the differences between the model output and measurements are connected with problems with the reproduction of high seas and probably with single strong storms. As waves are almost always fetch-limited in this region and saturation of wave fields usually occurs within a few hours after an increase in wind speed, this actually means that the properties of wind fields in strong storms (or the duration of the storm peaks) are not exactly represented in the underlying atmospheric models.

Comparison of the annual course of daily mean wave heights over a longer time scale (Fig. 9) demonstrates that most of the variations on weekly scales do not persist over longer time intervals. For example, extensive variations at the end of January–beginning of February in 1991–2002 are completely lost in data covering four decades and the amplitude of the variations during the calm period is much smaller. As in many weeks this course of wave height is already in antiphase, the variations on weekly scales apparently are smoothed out over a longer time series of observations. Still, an interesting feature is the relatively low period of wave activity in December, which becomes also evident in visually observed data sets from the NE Baltic Sea (Soomere et al., 2011). Also, Fig. 9 demonstrates that while the monthly mean wave height evidently well represents the wave activity during windy (November–February) and calm (May–July and partially August) months, there exist systematic variations in the wave activity within the transitional months (March–April and September–October).

Recent research has shown substantial changes to the seasonal distribution of strong winds. There has been a major shift of stormy winds from late autumn to winter months (Lehmann et al., 2011) accompanied by a certain change to the wind direction. In order to establish whether and how these changes become evident in the measured wave fields, we calculate monthly mean wave heights for five 4-yr intervals proceeding from daily mean wave heights (Fig. 10). The overall annual course of wave intensity follows a similar course of wind speed in the area in question, with a calm period in April–August and November–February as windy months. The seasonal course of monthly mean wave heights is most similar to the monthly course of the percentage of high winds at Lighthouse Kiel (Lehmann et al., 2011) with the highest waves present in January and February and even a minor local maximum in wave heights in June clearly evident. While there are certain fluctuations in the wave heights for different 4-yr periods, wave activity has been continuously high in February. Interestingly, the distributions of wave heights for 1991–1994 and 2007–2011 are most similar to the distributions of high winds of (Lehmann et al., 2011), while for several other periods the average wave heights in November and December exceed those in January.

5 Long-term variations

The measured annual mean wave heights vary from 0.68 m (−12 % of the average) up to 0.89 m (+16 % of the average) (Fig. 11). The modelled (AW) annual mean wave heights vary even in a smaller range, from 0.74 m to 0.94 m, that is, about ±12 %. Such a small variation apparently characterises the particular location of the measurement site: it is sheltered from many storms that occur in the Baltic Proper and wave properties here are mostly determined by local wind speed and fetch length; and these do not vary substantially. There has been a very weak increase (about 9 mm/decade) in the modelled wave heights. The increase was somewhat larger since about 1970 until 2002 (14 mm/decade) but is still much lower than reported in (Soomere and Räämet, 2011). The RS simulations using adjusted geostrophic winds show a considerable increase (about 50 mm/decade) in the wave heights for 1970–1990 and a comparable decrease since then. Although both the simulations reproduce the annual mean wave heights with an error of < 15 %, neither of them adequately represents the interannual variations in the measured wave heights. In general, the AW simulation appears to reproduce the large interannual variations somewhat more exactly than the RS simulation. The latter seems to be in antiphase with respect to measured data for a few years (e.g., 1996 and 1997).

The temporal behaviour of the basic annual characteristics of modelled and measured wave data (annual mean wave heights and the higher quantiles of the wave heights – thresholds for 10 % and 1 % of the highest waves; also called 90 % and 99 % percentiles, respectively) is mostly very similar except for the year 1995 when their course was somewhat different (Fig. 11). The measured wave heights seem to undergo a quasiperiodic change, with relatively high waves around 1995 and 2005, and with a lower wave activity at the turn of the century. In essence, such a manner of variations matches the variation derived from visual observations at the Lithuanian coast (Zaitseva-Pärnaste et al., 2011). The formal trend for measured wave heights is decreasing (18 mm/decade).

The behaviour of the 90 % and 99 % percentiles is, not surprisingly, qualitatively very similar to that of the annual average wave height (Fig. 11b). These quantities only show a larger interannual variability and relatively higher peaks with respect to their average values. While the threshold for the highest 10 % of wave heights shows a very weak increase (14 mm/decade), the threshold for the highest 1 % of wave heights reveals a comparably weak decrease with a comparable rate (–18 mm/decade). Interestingly, the 90 % and 99 % percentiles show a different trend for both modelled and measured waves. While these characteristics saw almost no changes in the modelled data over 1958–2002, the 90 %-tile decreased at a rate of 57 mm/decade and the 99 %-tile even at a rate of 72 mm/decade. Notice that the latter rate would have been considerably larger without the evident peak in 2010 (Fig. 11b). In general, the modelled thresholds have almost the same long-term average while the relevant values for particular years differ considerably. The modelled thresholds for 10 % of the highest waves very slightly exceed the values estimated from the measurements. Both models tend to generally overestimate the 99 %-tile (by up to 40 % for some years) although in some other years (e.g. 1993 or 1995) the modelled and measured estimates of this threshold almost coincide.

6 Conclusions and discussion

The climatological wave properties in the Darss Sill area resemble to some extent those in the Baltic Proper. Still they have several interesting features that do not become evident in analogous sub-basins in the Baltic Sea. On one hand, a considerable diurnal variation in the wave height, especially in the summer season, suggests that the seas here are strongly influenced by coastal effects. On the other hand, the proportion of low waves ($H_S < 0.25$ m) is quite small and thus the site cannot be considered as a coastal one (in which calm conditions are frequent even at the coasts of the Baltic Proper). The qualitative appearance of the distributions of the frequency of occurrence of different wave heights is more characteristic for the open sea wave climatology. However, the most typical (0.64 m) and long-term average wave heights (0.76 m) as well as the most frequent wave periods (2.5–4 s) are still characteristic to the coastal conditions. A specific feature of the Darss Sill area is the predominance of relatively short wave periods: much longer waves may frequently occur in other large subbasins of the Baltic Sea such as the Gulf of Finland, Gulf of Riga or Bothnian Sea. Finally, the extreme wave heights, of the order of $H_S \approx 4$ m once a decade, are similar to those that occur in these sub-basins.

Analysis of the modelled and measured wave data from the Darss Sill measurement site in SW Baltic Sea reveals that there have been no substantial changes in the long-term wave climatology in this area since the 1950s. Somewhat surprisingly, the wave measurement site is almost perfectly sheltered from storm waves excited in the Baltic Proper and the role of remote swells is negligible in this area. This feature together with the small size of the sea area allows for considerable simplification of the reproduction of wave properties for engineering applications: in many cases the wave field properties are determined by the local wind and fetch length.

The described combination of wave properties explains why both numerical simulations and in situ wave recordings obviously distort the shape of the joint distribution of wave heights and periods by systematically overestimating periods if they are < 3 s. This shortcoming can be removed by using an extended range of frequencies, up to about 1 Hz, to properly resolve short-wave situations in further simulations. The limitations of the waverider are apparently deeper and some other means should be used for wave measurements in order to properly resolve the short-wave domain.

In the context of a number of studies showing an increase in the wind speed in the SW Baltic Sea (e.g., Pryor and Barthelmie, 2003) it is remarkable that both the modelled and measured wave data show a decrease in both mean and especially severe wave conditions. This feature by no means contradicts the phenomenon of increasing wind speed. More importantly, it demonstrates that wave properties in semi-sheltered sea areas such as the Baltic Sea depend on the wind properties in a complicated manner and frequently are more strongly affected by (changes to) the wind direction (Soomere and Räämet, 2011b). The reported results support the outcome of several other wave studies in the Baltic Sea basin that have demonstrated that the temporal course of wave height is frequently decoupled from the course of the mean wind speed. Last but not least, it is interesting to mention that the shift in high wind speeds from November–December to January–March (Lehmann et al., 2011) apparently has largely occurred at the turn of the century or even during the latter decade.

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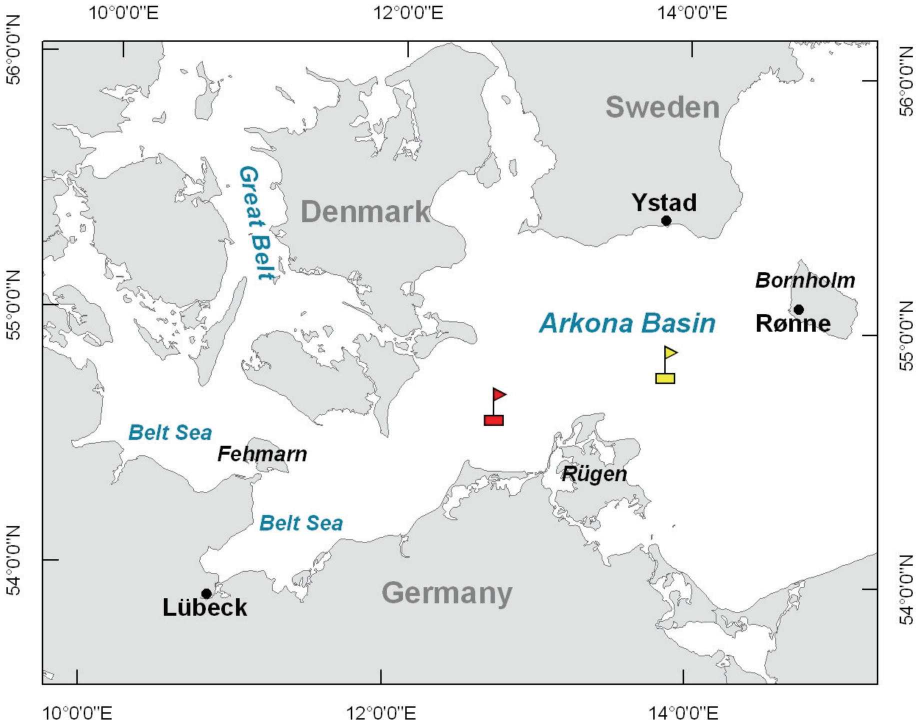

Fig. 1. Location scheme of the wave measurement sites at the Darss Sill and to the north of Cape Arkona.

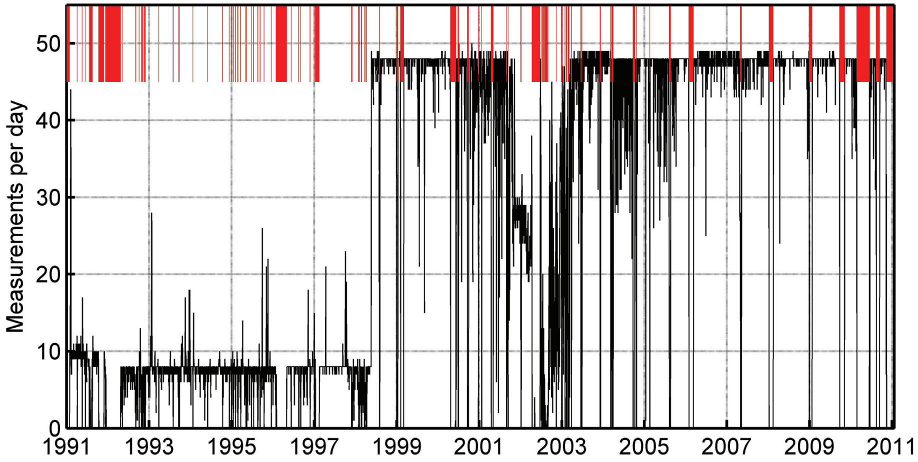

Fig. 2. Number of measurements recorded per day at the Darss Sill in 1991–2010 in the data pool used for this research. The red lines at the top of the panel indicate days with no measurements.

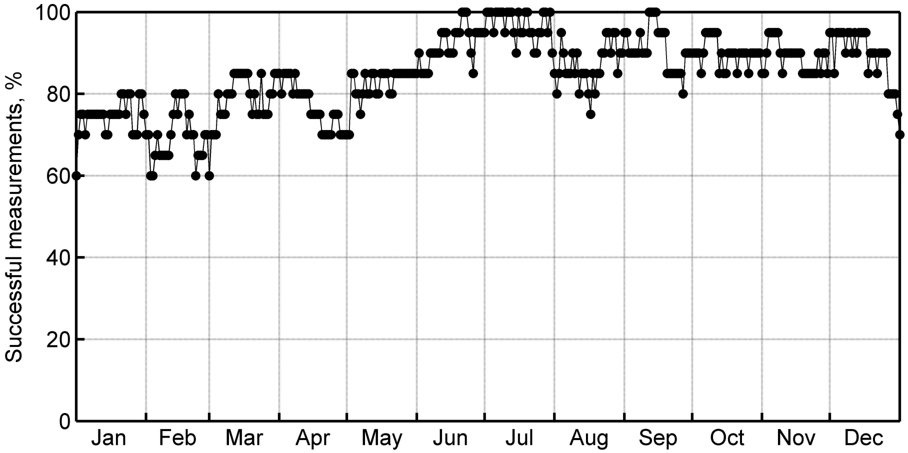

Fig. 3. Percentage of calendar days with at least one successful measurement in 1991–2010.

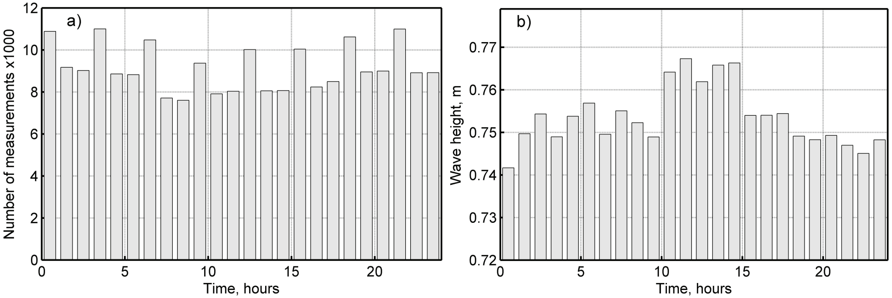

Fig. 4. **(a)** Number of measurements each hour; **(b)** diurnal variations in the average wave height at the Darss Sill in 1991–2010.

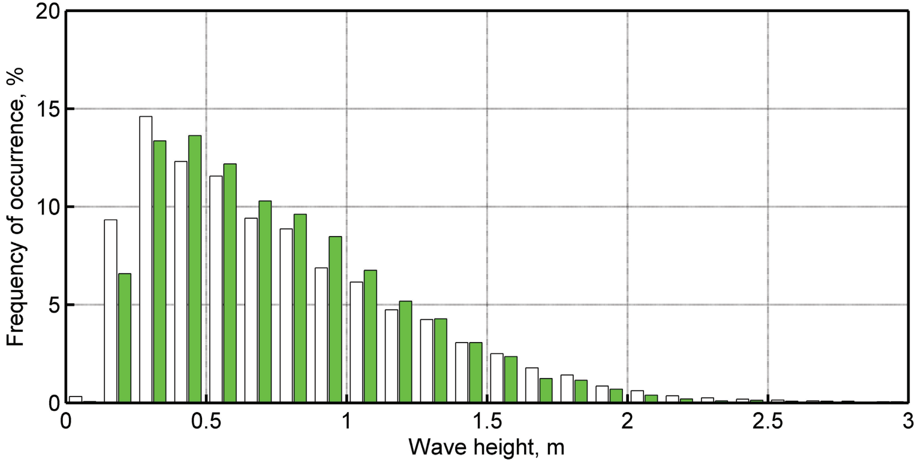

Fig. 5. Frequency of occurrence of different wave heights based on all measurements (white) and daily average wave heights (green) in 1991–2010.

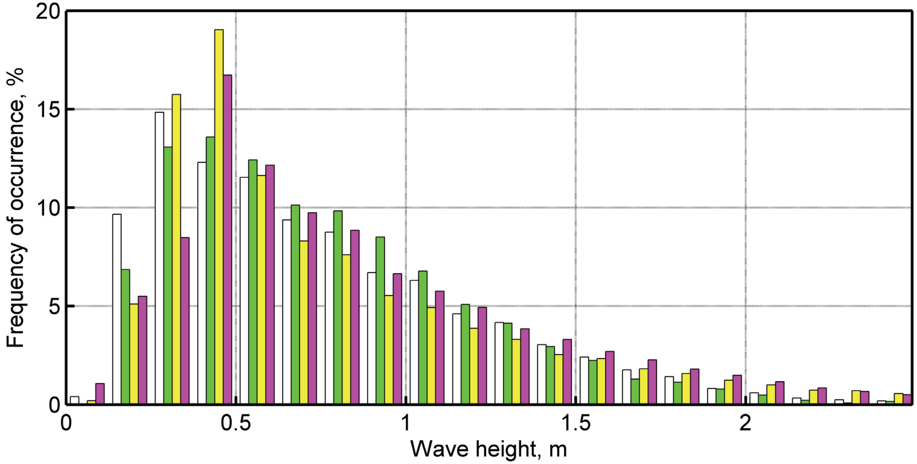

Fig. 6. Frequency of occurrence of different wave heights based on all measurements (white), daily average wave heights (green), simulations by RS (yellow) and by AW (magenta) for 1991–2002.

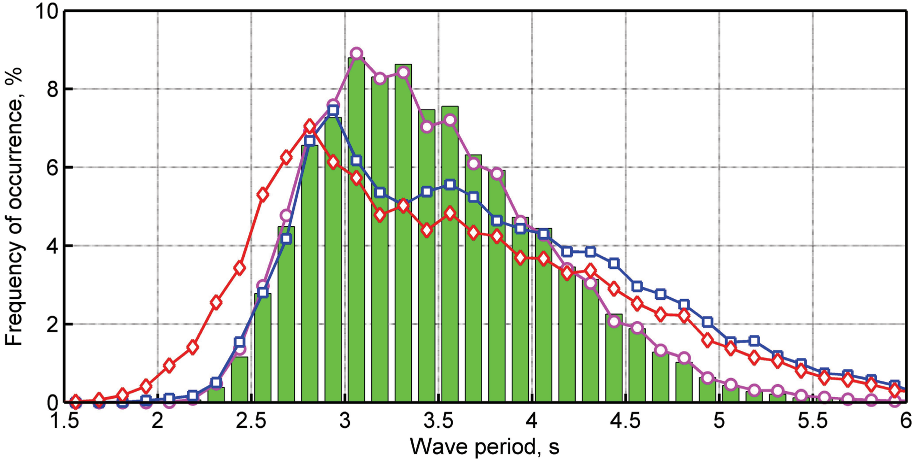

Fig. 7. Frequency of occurrence of different mean wave periods (T_{-1}) based on measurements for 1991–2010 (bars) and for 1991–2002 (magenta circles) and modelling results by AW (blue squares) and RS (red diamonds) for the years of 1991–2002.

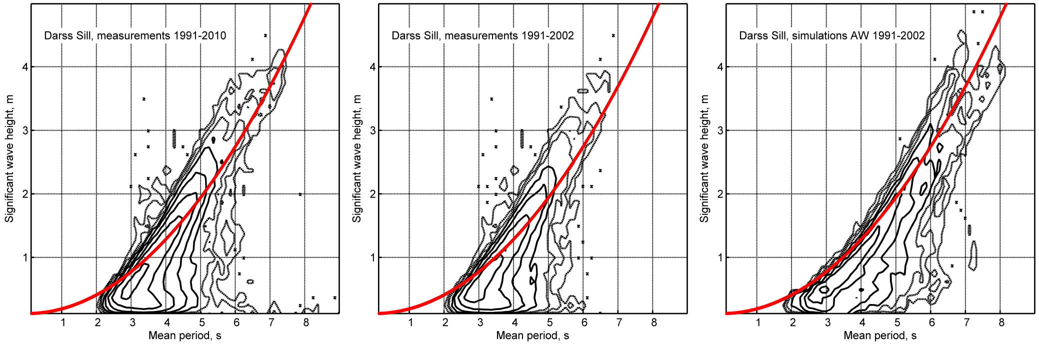

Fig. 8. Probability of occurrence of different combinations of wave heights and mean periods based on measured data from the Darss Sill in 1991–2011 and in 1991–2002, and AW simulations for 1991–2002. The red line indicates the parameters of wave fields with a Pierson-Moskowitz spectrum. The contour lines are drawn for 1, 3, and 10 cases (dashed) and 33, 100, 330, 1000 and 3300 cases (solid). The resolution for both wave heights and periods is 0.125.

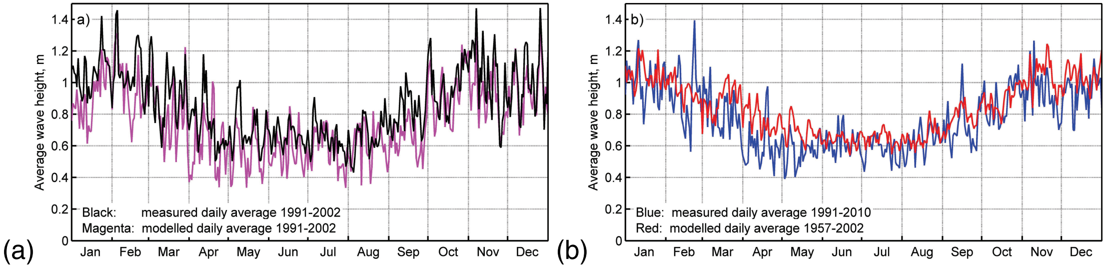

Fig. 9. Variations on a weekly scale of **(a)** measured and modelled (AW) wave heights at the Darss Sill for 1991–2002 and **(b)** of all measurements in 1991–2010 and model results for 1957–2002.

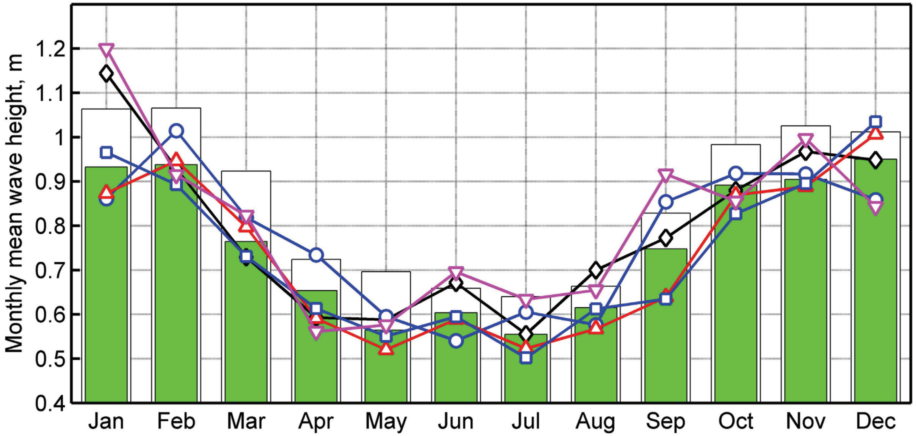

Fig. 10. Recorded (green bars) and modelled (empty bars, AW) monthly mean wave heights at Darss Sill for 1991–2002 and recorded montly mean wave heights for four-year intervals (diamonds 1991–1994, circles 1995–1998, triangles 1999–2002, squares 2003–2006 and downward-looking triangles 2007–2010).

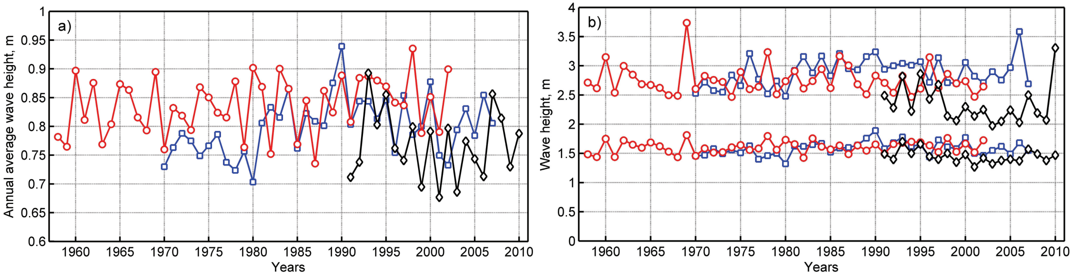

Fig. 11. Annual mean modelled (circles: AW, squares: RS) and measured (diamonds) wave heights **(a)**; thresholds for the highest 10 % (lower set of markers) and 1 % (upper set of markers) of wave heights **(b)** at the Darss Sill.