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Reconsidering Uncertainties of Wave Conditions in the Coastal Areas of the Northern Baltic Sea

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ABSTRACT

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The purpose of this work is to evaluate the basic features of temporal changes of the wave properties in the northern Baltic Proper. We also aim to clarify, whether the mismatches between the existing data stem from the uncertainties of wave models and measurements, represent properties of local wave fields, or form a part of long-term changes. The study is based on instrumentally measured and visually observed long-term wave data, wave hindcast for the open part of the Baltic Sea (1966–2006) using a fetch-based model, and a shorter hindcast with the WAM wave model forced by geostrophic and MESAN winds. The models reproduce the basic features of wave fields such as the large proportion of ~0.5 m high waves, strong seasonal variation of wave activity, and an increase in the annual mean wave height from the mid-1970s to the mid-1990s, and the subsequent decrease. Neither of the models is able to systematically reproduce extreme wave conditions or spatial variability of wave fields; mostly because of insufficient quality of the historical marine wind information.

ADDITIONAL INDEX WORDS: *Wave climate, wave modelling, marine winds, WAM model.*

INTRODUCTION

The Baltic Sea is a challenging area for wave modellers. In the winter, frequent stormy winds and the presence of heavy ice often becomes a problem. Its relatively shallow areas may host extremely complex wave fields and unexpectedly high waves (SOOMERE, 2005; SOOMERE *et al*., 2008). Although storm waves in this water body are relatively steep and short, and thus comparatively dangerous for smaller craft, it has been believed that the small size of the sea together with a rare occurrence of favorable conditions for generation of high waves effectively limit the wave heights and periods.

On the one hand, this belief has been confirmed by estimates of wave energy (e.g., BERNHOFF *et al*., 2006). Additionally, existing measurements of wave properties in the NE part of the basin (where the wave heights are expected to be the largest) (KAHMA *et al*., 2003) suggest that the significant wave heights hardly exceed 8–8.5 m and that wave conditions with $H_S > 7$ m (which have occurred <10 times since 1978, SOOMERE, 2008) can be interpreted as extreme situations.

On the other hand, consequences of wave events have been most serious and at times catastrophic in the Baltic Sea. The most devastating was the loss of the passenger ferry *Estonia* in autumn 1994, which took 852 lives, owing to wave damage (KARPPINEN and LING, 1998).

There exists contradicting evidence of the temporal changes in wave properties as well. A number of extremely rough wave conditions occurred during winter storms at the turn of the millennium in the Baltic Proper (KAHMA *et al*., 2003), then in November 2001 in the Gulf of Finland (SOOMERE, 2005) and again in December 2004 – January 2005 in the entire Baltic Sea (SUURSAAR *et al*., 2006; SOOMERE *et al*., 2008). The extensive reaction of depositional shores to these events (EBERHARDS *et al*., 2006; TÕNISSON *et al*., 2008) underpinned the discussion as to whether the coastal processes in the Baltic Sea have become more intense compared to the situation a few decades ago.

Conversely, the available data suggest that the changes in the Baltic Sea wave climate have been marginal from the late 1950s until the early 1990s (BROMAN *et al*., 2006; SOOMERE and ZAITSEVA, 2007). The storminess in the Baltic Sea region was relatively high at the beginning of the 20th century, decreased at the middle of this century and then increased to the original level at the 1980s–1990s (ALEXANDERSSON *et al*., 2000). Visually observed wave data from the island of Vilsandi (Figure 1), however, suggest that these changes were not necessarily reflected in the wave activity (SOOMERE and ZAITSEVA, 2007).

The existing data, thus, lead to controversial conclusions about various aspects in changes in wave climate in the Baltic Sea. As these changes have straightforward implications on the potential intensification of beach processes, there exists an obvious necessity to re-evaluate the basic features of temporal variability of wave properties along the coasts of the northern Baltic Proper. An additional relevant issue lies in the clarification of whether the mismatches between different wave data sets stem from the uncertainties of wave models and measurements, represent properties of local wave fields, or form a part of long-term changes. The set of wave data is fairly small in this area and evidently does not reproduce spatial variability of the wave fields. Consequently, numerical reproduction of the historical wave climate is a feasible method to answer this question.

MATERIAL AND METHODS

The study is based on (i) the long-term wave hindcast for specific coastal areas of the northeastern part of the Baltic Sea using a fetch-based (SMB) model forced with coastal wind data for the period of 1966–2006, (ii) a shorter hindcast for the entire Baltic Sea with the use of a high-resolution version of the WAM wave model forced by geostrophic winds and winds from the MESAN database, and (iii) available instrumentally measured and visually observed long-term wave time series.

Wave models

The SMB-model, also called the significant wave method, is based on the fetch-limited equations of Sverdrup, Munk, and Bretschneider (e.g. SEYMOUR, 1977; HUTTULA, 1994). It calculates the significant wave height, wave period and wavelength under assumption that the wind properties are constant over the entire fetch area. As strong winds are frequently highly homogeneous in the Baltic Proper and both the reaction and memory time of a large part of the wave fields in this basin are relatively short (SOOMERE, 2005), such simple models are valuable tools for rapid estimates of the wave statistics and the first approximation of the wave time series.

Wave properties for selected time periods (entire year 1996 and several single months) for the whole Baltic Sea were also computed with the 3rd generation wave model WAM. The bathymetry was interpolated from data prepared by SEIFERT *et al.* (2001) to a regular rectangular grid with a step 3' along latitudes and 6' along longitude (239×208 grid points, resolution ~3×3 nautical miles). In order to ensure realistic wave growth rates in low wind conditions after calm situations, we used an extended frequency range in which waves with the frequency from 0.042 Hz up to about 2Hz were accounted for (SOOMERE, 2005). At each of 11545 sea points, 1008 components of the 2D spectrum (24 equally spaced directions, 42 frequencies with an increment of 1.1) were computed. Comparison with the results of the SMB model and with measured data was performed at three locations (Figure 1): Vilsandi (WAM sea point 58°24'N, 21°48'E) Almagrundet (sea point 59°09'N, 19°08'E) and the location of a wave buoy operated by the Finnish Marine Research Institute (FIMR) in the central part of the northern Baltic Proper (sea point 59°15'N, 21°00'E).

Wind data

The SMB model was forced with local wind data measured at the Vilsandi meteorological station, operated by the Estonian Meteorological and Hydrological Institute (EMHI). Predominant SW, western and NW–NNW winds in the Baltic Proper are represented satisfactorily with this data. The station is located 7 km south of the mooring site of the RDCP instrument (see below), the data from which was used to calibrate the SMB model. The wind has been measured with wind vanes in 1966–1976, automatic anemorhumbometers in 1976–2003, and MILOS-520 automatic stations since September 2003. The older data has been corrected for homogeneity (SUURSAAR and KULLAS, 2009). The time interval of meteorological observatios was 3 hours from January 1966 – August 2003. MILOS-520 provides hourly average wind speed, gust wind speed with a resolution of 0.1 m/s, and hourly prevailing wind direction with a resolution of 1°.

Typically, for larger sea areas such as the Baltic Proper, geostrophic winds or the derivatives from local atmospheric models such as the MESAN database are commonly used as substitutes of the true wind fields. In order to establish uncertainties connected with different wind data, the WAM model was run in parallel with geostrophic winds and with the MESAN data.

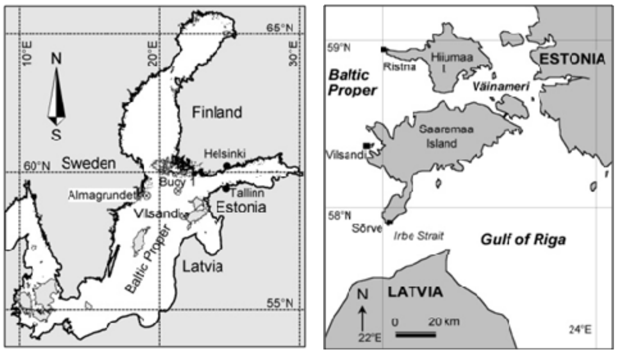

Figure 1. Location scheme of the wave and wind measurement sites in the northern Baltic Proper (left) and scheme of the SMB model calibration site near Vilsandi (right).

The near-surface wind (10 m) used as the input to the WAM model, was calculated from the geostrophic wind by a standard procedure in which the wind speed was multiplied by 0.6 and the direction turned 15 degrees to the left (BUMKE and HASSE, 1989).

MESAN (operational Mesoscale Analysis System) has been developed at the Swedish Meteorological and Hydrological Institute (SMHI) to produce hourly gridded wind information on a 22 km grid since October 1996 (HÄGGMARK *et al.*, 2000). The 10 m wind from HIRLAM is used as the first guess field. It is processed by means of optimal interpolation of wind measurements from automatic stations and manual observations into the wind field. This process uses spatially variable structure functions that depend on horizontal distance between the grids of the first guess field and the measurement locations. Accounting for surface roughness and the fraction of land and water in each grid area makes it possible to describe local wind variations in rough landscapes and coastal areas (HÄGGMARK *et al.*, 2000).

Calibration of the SMB model

The long-term calculations of wave parameters with the use of the SMB model were performed for the region of Vilsandi. The location of the case study of hydrodynamic measurements and modelling (58°28'N, 21°49'E) was 1–1.5 km off the coast of the Harilaid Peninsula (Figure 1). For comparison and calibration of the SMB-model, an oceanographic measuring complex RDCP-600 from AADI Aanderaa Instruments was deployed at a seabed depth of 14 m between 20 December 2006 and 23 May 2007. During this 5-month calibration period, the SMB model reproduced the wave parameters at the single point with acceptable accuracy. The model output required very moderate calibration to yield as high correlation coefficient as 0.88, low RMSE (0.233) and nearly equal average and maximum values of calculated and measured wave properties (SUURSAAR and KULLAS, 2009). The calibrated model was further used in multiyear wave hindcast.

Observed and instrumentally measured wave data

The data from Almagrundet (1978–2003, 59°09' N, 19°08' E, Figure 1, BROMAN *et al.*, 2006) form the longest instrumentally measured wave time series in this region. An upward-looking echo-sounder placed at a depth of about 30 m produced wave data over 640 s long samples once an hour in 1978–1995. An analogous device, installed for 1992–2003 in a neighbouring location, had certain quality problems and the data are not used below. Single waves were identified based on the classical zero-downcrossing method. An estimate of the significant wave height was found from the 10th highest wave in a record under the assumption that the wave heights are Rayleigh distributed.

Visual wave observations were performed at Vilsandi starting from 1954 up to three times a day. The interval between subsequent observations is often much longer than the typical saturation time of rough seas in the northern Baltic Proper or the duration of wave storms. The data, however, match the general features of the Baltic Sea wave fields well. The results represent the properties of about 3% of the highest waves, but are at times interpreted as estimates of the significant wave height and mean period (SOOMERE and ZAITSEVA, 2007).

A directional waverider was deployed by the FIMR in the northern Baltic Proper at a depth of about 100 m (buoy 1 in Figure 1, 59°15' N, 21°00' E) in September 1996 and has since then been operated during the ice-free seasons (KAHMA *et al.*, 2003). This device, as well as spectral wave models, estimate the significant wave height from the zero-order moment of the wave spectrum (the total variance of the water surface displacement).

RESULTS

Modelled and measured wave statistics

The results of calibration runs of the SMB model (SUURSAAR and KULLAS, 2009) show that this simple model forced with Vilsandi wind data reasonably reproduces not only the basic statistics of the wave properties (such as relatively low overall wave activity, large proportions of wave conditions with wave heights about 0.5 m (Figure 2), short wave periods, or substantial seasonal variation of wave conditions with larger wave activity in fall and winter (BROMAN *et al.*, 2006; SOOMERE and ZAITSEVA, 2007)) but also the time series of the basic wave conditions at the calibration site. The model failed to reproduce remote swell and extreme wave conditions. Both these shortcomings are natural for this type of model (SUURSAAR and KULLAS, 2009).

The year 1996 was chosen to compare the results of the SMB and WAM models, because this year exhibited unusually large wave activity in June–July (Figure 3, Table 1). Also, there was enough wave data from Vilsandi and Almagrundet for comparisons. Both models reproduced the seasonal course of wave heights near Vilsandi in this atypical year and produced an almost equal annual average wave height and the threshold height of waves occurring with the probability of 1% (Table 1). The WAM model hindcasts somewhat smaller variability of wave heights and a lower threshold for waves with the probability of 90%. As the WAM model realistically accounts for wave generation and propagation, it is not unexpected that it would predict somewhat larger annual maximum of wave heights.

Table 1: Comparison of statistics of wave simulations (m) and corresponding wind forcing (m/s) in 1996 for the SMB model forced with Vilsandi wind data, WAM model forced with geostrophic wind, and visual wave observations at Vilsandi.

Characteristic		SMB	WAM	Observed
Wind	Average	5.5	6.1	
	St.dev.	3.2	3.3	
	90%	10.0	10.6	
	99%	14.0	15.5	
	max	18.0	21.8	
Significant wave height	Average	0.47	0.50	0.84
	St.dev.	0.39	0.34	0.62
	90%	1.09	0.88	1.70
	99%	1.77	1.74	2.31
	max	2.55	3.30	2.60

A remarkable mismatch between the modelled and observed wave properties was found for the period in question (Table 1). Namely, observed values of average wave properties (except for the annual maximum wave height) substantially exceed the modelled values. The reasons for such a large mismatch are not clear. Partially, it may stem from the observation procedure that actually records either the maximum wave height or the average height of the five largest waves (SOOMERE and ZAITSEVA, 2007).

Modelled and measured time series

The match between hindcasts with the use of the WAM model forced with different wind data and the measured data was found to be sensitive with respect to the particular location. In coastal areas of Sweden, simulations using MESAN winds reasonably matched qualitative course of the observed wave properties and in many cases also satisfactorily reproduced the instantaneous wave height (Figure 4). In this region, the wave heights calculated using geostrophic winds were generally much less (e.g. by 23 cm in the mean in October 2000).

On the contrary, at the FIMR wave buoy in the central part of the northern Baltic Proper (Figure 1), hindcasts using geostrophic winds frequently gave more adequate results than simulations with the use of MESAN winds (Figure 5). Wave heights obtained with the use of geostrophic winds generally exceeded (in average by 20 cm) those calculated based on the MESAN winds.

Wave hindcast with the use of WAM systematically underestimated the factual wave heights both at Almagrundet and at the FIMR wave buoy. The monthly bias, typically, was in the range of 20–40 cm and reached 60–70 in windy months such as December 1999. Still the temporal course of wave heights was qualitatively reproduced. The timing of the roughest wave

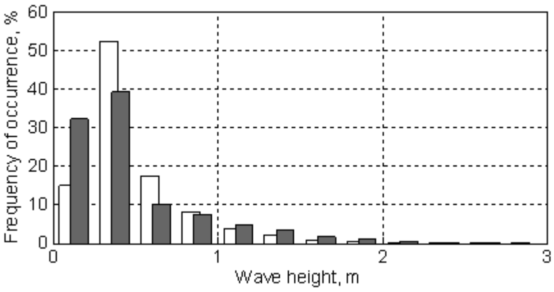

Figure 2. Frequency of occurrence of wave heights at Vilsandi 1996 according to the WAM (white bars) and SMB models (grey bars).

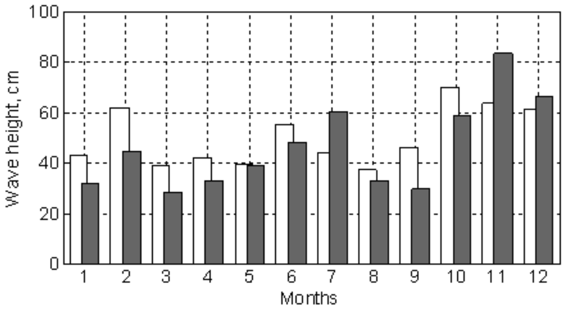

Figure 3. Monthly mean wave height at Vilsandi 1996 according to the WAM (white bars) and SMB models (grey bars).

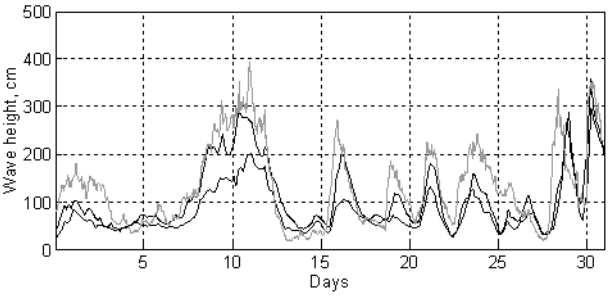

Figure 4. Wave heights (grey line) at Almagrundet (A), October 2000. Bold and solid lines show the hindcast of WAM model forced with MESAN (M) and geostrophic (G) wind. The biases and rms deviations (cm) are: $Bias_{M-G}$ = 23.4; $Bias_{A-M}$ = 24.1; $Bias_{A-G}$ = 47.4; RMS_{M-G} = 37.7; RMS_{A-M} = 48.3; RMS_{A-G} = 72.1.

conditions was almost perfect at Almagrundet. The overall timing was also acceptable at the FIMR wave buoy, but the simulations failed to reproduce the duration of rough seas.

The largest mismatch between simulated and measured data usually occurred during extreme wave events. The timing and qualitative course of wave heights hindcast by the WAM model usually acceptably matched measured data. In several cases the model almost exactly reproduces the wave height during the wavestorm maximum. This happened more frequently for the FIMR buoy and the geostrophic winds (e.g. on 13.01.2005, Figure 6). A severe underestimation occurred on 09.01.2005.

Finally, hindcasts of both wave models reasonably matched each other and, to some extent, visually observed wave data at Vilsandi in terms of timing and maximum of wave heights during rough sea events (Figure 7). As expected, the SMB model, which does not account for realistic wave growth, hindcasts somewhat earlier appearance of high waves.

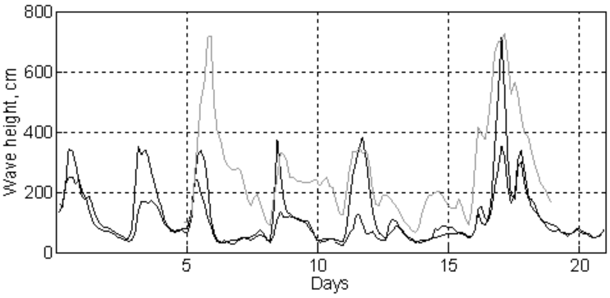

Figure 5. Wave heights (grey line, www.fimr.fi/en/tietoa/veden_liikkeet/en_GB/aaltoennatyksia/) at the location of the FIMR wavebuoy (wb) in December 1999. Notations are the same as for Figure 4. The biases and rms deviations (cm) are: $Bias_{G-M}$ = 11.7; $Bias_{wb-M}$ = 77.0; $Bias_{wb-G}$ = 68.0; RMS_{M-G} = 75.1; RMS_{wb-M} =205; RMS_{wb-G} = 192.

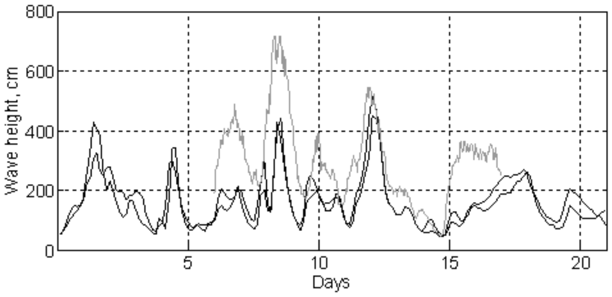

Figure 6. Wave heights (grey line, SOOMERE *et al*., 2008) at the location of the FIMR buoy in January 2005. Notations are the same as for Figure 4. The biases (cm) are: $Bias_{M-G}$ = 7.3; $Bias_{wb-M}$ = 51.7; $Bias_{wb-G}$ = 46.0.

Long-term changes

Although the rapid increase of the wave activity in the 1990s in the northern part of the Baltic Proper (BROMAN *et al*., 2006; SOOMERE and ZAITSEVA, 2007) matches the similar trend in the North Sea (GULEV and HASSE, 1999), a decrease of the annual mean wave height has occurred since 1997, and in 2004–2005 wave activity was equal to the global minimum that occurred in the beginning of the 1980s. The decrease, although somewhat unexpected (because the average wind speed in the northern Baltic Sea increased between 1990–2007 (BROMAN *et al*., 2006)), is mirrored by a certain decrease of the intensity and duration of severe wave heights in the North Sea since about 1990–1995 (WEISSE and GÜNTHER, 2007). Figure 8 shows that the discussed course of the overall wave activity is, at least, qualitatively reproduced by the SMB model for coastal areas of Vilsandi. Interestingly, there is almost no change in the annual standard deviation of the wave height. This feature suggests that the extreme wave heights may have not decreased since about 1990.

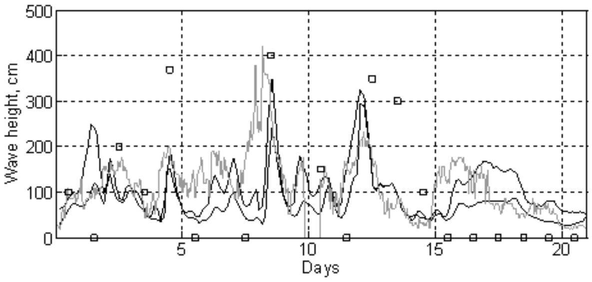

Figure 7. Wave heights at Vilsandi hindcast using the SMB model (grey line), WAM model forced with MESAN (bold line) and geostrophic wind (solid line) and observed wave heights (squares), respectively. The biases (cm) are: $Bias_{M-G}$ = 24.6; $Bias_{SMB-M}$ = 25.3; $Bias_{SMB-G}$ = 0.7.

CONCLUSIONS AND DISCUSSION

The large number of mismatches and controversial estimates suggests that reconsidering the potential uncertainties of reproduction of the wave properties is a necessary step towards understanding changes in wave-induced processes in the Baltic Sea basin. The models in use adequately reproduce the basic features of seasonal and qualitative features of decadal variations of wave fields in the northern Baltic Proper (such as an increase of wave heights until the mid-1990s and their decrease since then). Even the simplest, one-point, fetch-based models perform well in this water body when supplied with correct wind information.

Major problems, however, become evident in reproduction of spatial patterns of wave fields. The comparison of forcing data and

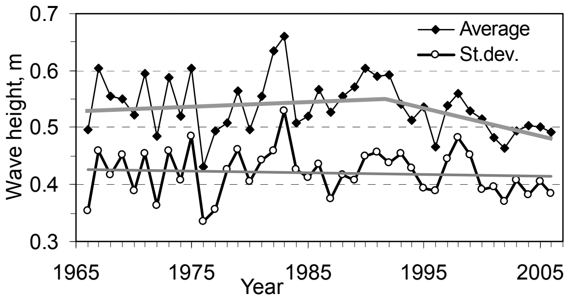

Figure 8. The modeled annual average and standard deviation of the wave height and their trends at Vilsandi based on 8 daily values. The wave height increased by 0.16 cm/year until 1990 and decreased by 0.57 cm/year since then.

model output (Figures 4–7, Table 1) and, specifically, the difference in the wave hindcast for Swedish coastal areas and for the central part of the Baltic Proper using different wind data, suggests that the central source of uncertainties in estimates of the wave climate of the past is the quality of marine wind data.

All models in use tend to underestimate the maximum wave heights in strong storms whereas the mismatch considerably varies for different storms. This feature once more suggests that the marine wind data available to date do not allow reproduction of the course and properties of extreme wavestorms of the past, a feature which severely restricts the possibilities of reconstructions of past wave climate in the Baltic Sea.

However, an adequate qualitative match of the modeled and measured wave data (in particular, in terms of wave statistics) suggests that the existing models and wind information can be used for establishing other long-term changes in wave properties such as the annual mean wave height or seasonal course of wave conditions even with the use of fairly simple wave models.

An unexpected feature is that the accuracy of different wind data seems to largely vary in different regions of the Baltic Proper. While the MESAN database seems to be more accurate (and only leads to minor underestimation of wave heights) in the coastal areas of Sweden, the use of geostrophic wind (which produces more realistic wave fields in the middle of the basin) seems to be justified for simulation of wave fields in the entire Baltic Proper.

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