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Locally calibrated wave hindcasts in the Estonian coastal sea in 1966–2011

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Abstract. Wave parameters were studied in four differently exposed fetch-limited Estonian coastal sea locations: the Harilaid Peninsula facing W–NW, Letipea N–NE, Matsi SW and Kõiguste SE. Based on high-quality measurements of waves with the bottom-mounted Recording Doppler Current Profiler in 2006–2011, a model for significant wave height was calibrated separately for those locations. Using wind forcing data from Estonian coastal meteorological stations, a set of hindcasts was obtained over the period of 1966–2011. The wave heights showed some quasi-periodic cycles with a high stage in 1980–1995, and probably also from 2007; a prevailing overall decrease in the mean wave height; an increase in high wave events at the windward coasts of West Estonia but a decrease at the northern and southeastern coasts. The spatially contrasting results for differently exposed coasts reflect the corresponding variations in local wind, which are probably caused by changes in large-scale atmospheric pressure patterns above Northern Europe and a poleward shift of cyclones' trajectories. Although featuring outstanding calibration results, the long-term wave hindcast may be impacted by possible inhomogeneities in the older wind data.

Key words: wave modelling, wave measurements, fetch, wind climate, climate change, Baltic Sea.

INTRODUCTION

Data on surface waves and their long-term regimes – wave climates – are increasingly needed both in environmental investigations and engineering applications. Wave climate has a strong influence not only on various aspects of human activities but also on the development of seacoasts and on ecological conditions in the coastal zone. According to numerous studies (Jaagus et al. 2008; Suursaar & Kullas 2009; Keevallik 2011; Lehmann et al. 2011), the wind climate above the Baltic Sea has experienced some seasonally contrasting and important changes over the last 50–100 years. These changes should be somehow reflected in the wave climate.

Continuous wave measurement is a demanding task and no long-term instrumental wave measurements (like the Swedish wave-buoy at Almagrundet in the NE Baltic Proper, see e.g. Broman et al. 2006) exist in the Estonian coastal sea. Regular instrumental measurements of waves have just begun in some Estonian ports. However, several modelling studies have addressed the wave climate in the northeastern (NE) section of the Baltic Sea and particularly in the Estonian coastal sea in the last ten years. The Estonian coastal sea is also covered in a few Baltic Sea hindcasts (Jönsson et al. 2002; Tuomi et al. 2011). Depending on the data source and analysis method, these studies use three principally different approaches, each having its strengths and limitations.

Firstly, T. Soomere introduced the WAve Prediction Model (WAM) (e.g. Komen et al. 1994) for calculating the patterns and statistics of wave properties during extreme weather conditions in the Estonian coastal sea (Soomere 2001, 2003; Soomere et al. 2008). Later on, an array of long-term calculations and estimates of different spatial aspects of the Baltic Sea wave climate appeared (Räämet et al. 2009; Räämet & Soomere 2010; Soomere & Räämet 2011). These calculations were forced by 6 × 6 nautical miles (nm) or even coarser gridded geostrophic model winds (from the Swedish Meteorological and Hydrological Institute), by HIRLAM (stands for High Resolution Limited Area Model) or MESAN (Operational Mesoscale Analysis System) winds. The BaltAn65+ re-analysis of meteorological data for the Baltic Sea region are available now for 1965–2005 (Luhamaa et al. 2011). Minor shortcomings of this otherwise up-to-date method seem to be a somewhat limited reproduction of local wave properties in a shallow rugged coastal sea, which is generalized by a 3 × 3 nm grid size, and questionable representativeness of gridded large- or medium-scale model winds in local applications. The model winds tend to smooth out some local variations (Keevallik et al. 2010; Räämet & Soomere 2010).

Secondly, visual observations made at several coastal hydrometeorological stations (Vilsandi, Narva-Jõesuu, Pakri) have recently been digitized (Soomere & Zaitseva 2007; Zaitseva-Pärnaste et al. 2009, 2011). Indeed, the obtained time series and statistics, in some cases covering the period from 1954 to 2009, express certain long-term parameters of wave fields. However, the large number of gaps, inexact nature of such measurements and imprint of subjectivity may lower the value of the findings.

Thirdly, locally calibrated wave hindcasts using a semi-empirical wave model were presented for the Harilaid-Vilsandi region in 1966–2006 (Suursaar & Kullas 2009), Kunda-Letipea for 1966–2008 (Suursaar 2010) and Neugrund (Suursaar et al. 2011). Determining the model parameters and an appropriate procedure for the fetch length is usually complicated in such models, since good measurement data are not always available. The calibrations discussed in this article were based on our wave measurements using the Recording Doppler Current Profiler (RDCP) oceanographic complex, which were conducted in different locations in the Estonian coastal sea during a total of about 800 days in 2003–2011. The long-term hindcasts apply the wind data measured at the ground-based weather station nearest to the specific RDCP measurement/wave modelling site. Given the computational cost of the contemporary spectral wave models and extensive problems with the resolution and accuracy of modelled wind speeds over the Baltic Sea, the developed simple technique has presumably its niche in wave science alongside with the WAM and other rather demanding third-generation models. It can be effectively used for express estimates of the present and past wave climates at particular locations.

The objectives of the study are as follows:

- to summarize our experience with the locally calibrated wave hindcasts;
- to update the previously published two hindcasts until the end of 2011 and to introduce two new study sites in the Gulf of Riga. One is a southeasterly exposed area at the entrance to Kõiguste Bay and the other lies at the southwesterly exposed Matsi coast (Fig. 1);
- to present the details of the calibration procedure and to discuss the strong and weak aspects of the proposed method;
- to discuss the climatological background of the obtained findings in wave properties at differently exposed coasts of Estonia.

MATERIAL AND METHODS

RDCP measurements of waves

The instrument, referred to by different manufactures as, e.g., Acoustic Doppler Current Profiler (ADCP), Doppler Current Meter (DCM), Acoustic Doppler Profiler (ADP) or Acoustic Doppler Velocimeter (ADV), applies the Doppler effect to measure flow velocity. Since obtaining our first measuring complex of this kind in 2003, the RDCP-600 manufactured by Aanderaa Data Instruments, we have recorded high-resolution oceanographic data during twelve campaigns. The primary tasks of these deployments varied from monitoring the influence of dredging in the Port of Muuga, a study on dilution conditions of pulp mill effluents near Kunda, to wave

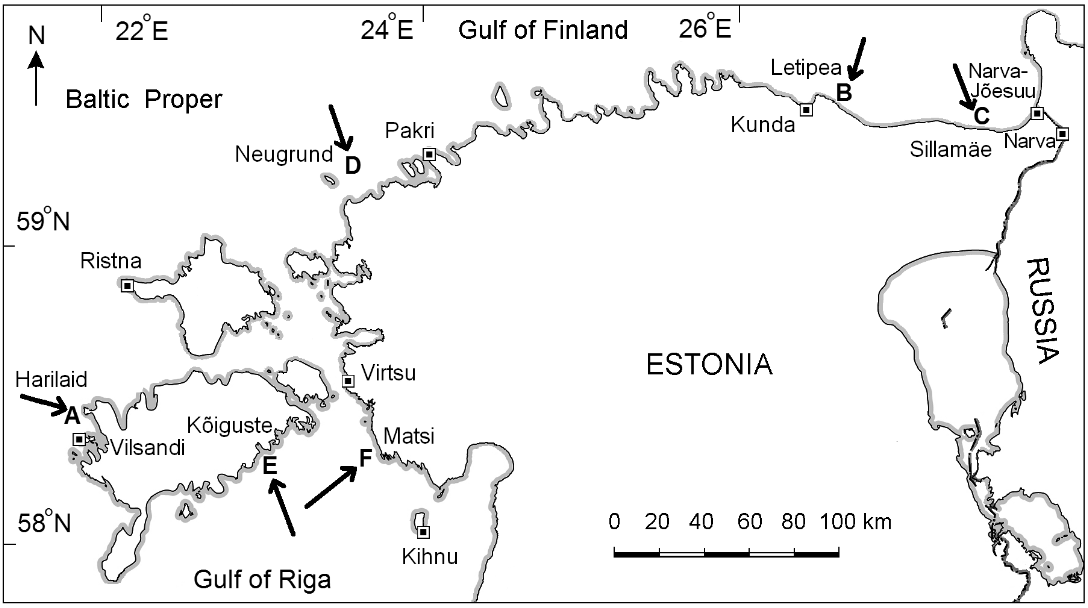

Fig. 1. Map of the study area. Wave measurement and modelling locations are denoted with letters (see also Table 1) accompanied by arrows which indicate the directions of the longest fetches. The locations of the EMHI weather stations used in calibrations or hindcasts are marked with ▣.

studies near the geomorphically active gravel spit of the Harilaid Peninsula and a study of upwelling-related coastal jets (Suursaar & Aps 2007; Suursaar et al. 2008; Suursaar 2009; 2010). The RDCP-600 is also equipped with temperature, conductivity, oxygen and turbidity sensors. The high-accuracy quartz-based pressure sensor (resolution 0.001% of full scale) enables the measurement of wave parameters. The first deployments in 2003–2006 were too short for real wave climate studies. Then, a 39-day-long record at the Letipea Peninsula in the autumn of 2006 and a 154-day record off the Harilaid Peninsula in winter 2006/2007 ultimately led to the wave hindcasts (Suursaar & Kullas 2009; Suursaar 2010). Since then, wave studies have become one of the most important outcomes of these rather diverse measurements. In this article we also neglect all the other measurements and concentrate on only wave data.

We discuss six mooring locations (Fig. 1) with the actual measuring periods somewhat longer than shown in Table 1 (which only indicates the calibration periods): Letipea–Kunda site (59°34′N, 26°40′E, four moorings on 10 August–14 September 2006, 16 October–25 November 2006, 13 August–17 September 2008, 15 November 2008–9 June 2009), Harilaid–Vilsandi site (58°28′N, 21°49′E, 20 December 2006–23 May 2007), Sillamäe (59°25′N, 27°48′E, 29 July–10 September 2009), Neugrund (59°20′N, 23°30′E, 20 November 2009–24 April 2010), Kõiguste (58°19′N, 23°01′E, 2 October 2010–11 May 2011) and Matsi (58°20′N, 23°43′E, 13 June–2 September 2011).

The self-contained upward-looking instrument was deployed at the seabed by divers about 1–3 km off the nearest coast (except for Neugrund). The mooring depth varied between 10 and 15 m. Although shorter recording intervals of 10 or 20 min were used in earlier measurements, the interval was always set to 1 h in the long-term measurements discussed in the current article. One hour is conveniently also the interval for the routinely measured meteorological data used in the wave model calibrations and hindcasts. In the RDCP, significant wave height (H_S), which is the most commonly used wave parameter, is calculated based on the energy spectrum. It coincides almost exactly with the average height of the 1/3 highest waves for Rayleigh-distributed wave fields and matches well the visually observed 'average wave height'. The instrument also records the maximum wave height (which usually is approximately 1.5 times H_S) and produces several estimations for wave periods. The wave model calibration and the following hindcasts were performed only for H_S.

Wind forcing data

For supplying wave models with wind speed and direction, we acquired data from the meteorological stations operated by the Estonian Meteorological and Hydrological Institute (EMHI). For each wave measuring/modelling site we used the wind data from the closest station as the first choice (Tables 1, 2). The Vilsandi station is not only closest (7 km) to the Harilaid Peninsula, but also one of the best Estonian weather stations in terms of reproduction of marine winds (Soomere 2003; Keevallik et al. 2007). Situated at the western coast of the Island of Vilsandi, the station has an open location and the highest average wind speed (6.15 m s^{-1} in 1966–2011; see also Table 2) of all the Estonian weather stations.

The Kunda station is closest to the Letipea measuring site, just 10 km west of it (Fig. 1). For wind measurements, the site is somewhat sheltered by land from southerly directions but the marine wind from northerly sectors

Table 1. Wave model calibration results at different locations (see Fig. 1) of the Estonian coastal sea. The verdict (++ very good, + ok, – unusable) is further explained in the text

Location	Modelling location	Wind forcing	Distance between, km	Calibration period	Measured H_S		r	RMSE	RMSE, %	Verdict, application
					Avg.	Max.				
A	Harilaid	Vilsandi	7	20.12.06–23.05.07	0.57	3.16	0.880	0.233	7.4	++ 1966–2006
A2	Harilaid	Vilsandi	7	20.12.06–23.05.07	0.57	3.16	0.900	0.227	7.2	++ 1966–2011
B	Letipea	Kunda	10	16.10.06–24.11.06	0.50	2.91	0.923	0.223	7.8	++ 1966–2011
C	Sillamäe	Narva-Jõesuu	18	29.07.09–10.09.09	0.19	1.29	0.772	0.141	10.9	–
D	Neugrund	Pakri	30	20.11.09–30.12.09	0.46	2.04	0.810	0.227	11.1	+/– 2003–2011
D2	Neugrund	Ristna	90	20.11.09–30.12.09	0.46	2.04	0.613	0.319	15.6	–
D3	Neugrund	Vilsandi	140	20.11.09–30.12.09	0.46	2.04	0.514	0.348	17.1	–
E	Kõiguste	Kihnu	58	4.10.10–14.11.10	0.42	1.76	0.926	0.167	9.4	++ 1966–2011
E2	Kõiguste	Virtsu	38	4.10.10–14.11.10	0.42	1.76	0.931	0.159	9.0	+ 1966–2011
F	Matsi	Kihnu	29	13.06.11–12.08.11	0.27	1.51	0.911	0.135	8.9	++ 1966–2011
F2	Matsi	Virtsu	26	13.06.11–12.08.11	0.27	1.51	0.850	0.172	11.4	+ 1966–2011

Table 2. Information on meteorological stations used or discussed in the study. Wind speed in 2011 is based on hourly one-hour sustained data

Station	Latitude (N)	Longitude (E)	Altitude, m	Period	Wind speed, m s^{-1}
Vilsandi	58°22′58″	21°48′51″	6	1966–2011	6.07
Kunda	59°31′04″	26°32′43″	2	1966–2011	3.35
Narva-Jõesuu	59°27′47″	28°02′44″	6	2000–2011	2.64
Pakri	59°23′22″	24°02′24″	23	2003–2011	4.57
Ristna	58°55′15″	22°03′59″	7	1966–2011	3.74
Virtsu	58°34′22″	23°30′49″	2	1966–2011	3.59
Kihnu	58°05′55″	23°58′12″	3	1966–2011	5.65

are properly represented. This is also the main direction for waves and the overall quality of the wind data is considered to be rather good (Keevallik et al. 2007). Another weather station at Narva-Jõesuu is located approximately 80 km from the Letipea site and 18 km from the Sillamäe wave measuring site. However, the station is more sheltered than the Kunda station. Moreover, its location was changed from Narva to Narva-Jõesuu in 2000, so the data set is not homogeneous.

The Pakri meteorological station is located about 30 km east of the Neugrund mooring site. Opinions about this station, regarding the openness and the adequacy of representation of marine wind properties, are somewhat mixed (Keevallik & Soomere 2009). One reason may be the influence of the North Estonian Klint (limestone escarpment). Unfortunately, the position of the station on the Pakri Peninsula has changed three times, most recently in September 2003.

For the Gulf of Riga, we studied wind data from the Kihnu and Virtsu stations (Tables 1, 2). Although the Virtsu station is somewhat closer to both wave measuring sites, it is far more sheltered and, unlike the Kihnu station, it does not adequately represent marine winds.

Most of the listed weather stations have been operational for a century or even longer but the digitized wind data have been available since 1966. The completeness of the data sets varies between 98% and 100%. Hardly any values were missing in the database for Kunda, Pakri and Kihnu. At Vilsandi, only 1.6% of the measurements are missing over the period of 1966–2011. For long-term trend analysis, a few missing records in 1990, 1991, 2003 and 2005 were replaced by averages from the seasonal cycle. At Virtsu, besides some smaller gaps, the data for the entire year 1984 are missing and remain in a gap.

Regarding the potential homogeneity issue, three sub-sets of wind data can be distinguished over the study period. Wind speed was measured with a wind vane of Wild's design during 1966–1976, with a recording anemorhumbometer (ARM) during 1976–2003 and using the MILOS-520 automatic weather station from September 2003. While the automatic weather station provides hourly wind data, the data from January 1966 to August 2003 have a time interval of 3 h. The latest change in measuring equipment in 2003 did not introduce any substantial discrepancies into the data sets according to, e.g., Keevallik et al. (2007). An important change from wind vanes (weathercocks) to automatic ARMs took place in November 1976. Back then, some parallel measurements were performed during a few years. It turned out that the ARMs systematically underestimated strong (>10 m s^{-1}) winds in comparison with the visual readings from weathercocks. Therefore, during data pre-treatment, we adjusted the strong wind data from 1966–1976 with corrections provided by a professional handbook (Gidrometeoizdat 1990). The procedure (which slightly reduces winds over 10 m s^{-1}) was shortly described also in Suursaar & Kullas (2009). For example, a wind speed of 11 m s^{-1} measured by the ARM corresponds to the previous 12 m s^{-1}, and 20 m s^{-1} measured by the ARM was set equivalent to the previous 23 m s^{-1}.

The older data are also less exact: the step for the wind speed is 1 m s^{-1} from 1966 until September 2003 and 0.1 m s^{-1} thereafter. Wind directions for 1966–1976 were given in the 16-rhumb system (later converted into degrees in the EMHI database), while the directional resolution of the ARMs data was 10° until 2003 and the currently used MILOS-520 weather stations provide 1° resolution output. The 1-h averaged hourly wind data were used in 2003–2011, as they yielded marginally better wave calibration results than the 10-min average data recorded once an hour. In general, the difference between these two wind instrument outputs is very small, especially when compared to the earlier equipment changes.

For statistical purposes we also calculated the u (east–west, positive to the east) and v (north–south, positive to the north) components of the wind velocity vector. Their use enables somewhat different interpretation in addition to the more traditional windrose approach.

Wave modelling

Wave parameters in this study, like in the previous ones (Suursaar & Kullas 2009; Suursaar 2010), were calculated using a semi-empirical SMB-type wave model. The model is based on the fetch-limited equations of Sverdrup, Munk and Bretschneider, where the significant wave height H_S (below called simply wave height) is a function of wind speed, fetch length and water depth. Nowadays, the associated set of prediction graphs and models is more known as the SPM prediction method (e.g. Massel 1996). It stems from the *Shore Protection Manual* (SPM) by the Coastal Engineering Research Center of the U.S. Army Corps of Engineers, originally published in 1974 and consecutively updated (e.g. USACE 1984, 2002). In fact, the manuals and handbooks include a wide choice of such equations and procedures with slightly different empirical coefficients and terms, which should take into account different wind conditions, water depths and shallow-water effects. The version for waves in shallow water and for 'intermediate' depth used by us is the same as used by Huttula (1994, eqs (1)–(3)). It probably originates from the SPM 1974 (now hard to access), was reviewed by Bishop et al. (1992) and reads in metric units as follows:

$$H_S = 0.283 \frac{U^2 A_h}{g} \tanh\left[\frac{0.0125}{A_h}\left(\frac{gF}{U^2}\right)^{0.42}\right], \qquad (1)$$

where

$$A_h = \tanh\left[0.53\left(\frac{gh}{U^2}\right)^{0.75}\right],$$

U (m s^{-1}) is the wind speed, F (m) is the effective fetch, h (m) is the water depth and g (m s^{-2}) is the acceleration due to gravity. The original formulae also include equations for wave period (T_S) and length. However, no wave periods and lengths are calculated here, because it is not possible to calibrate the model regarding H_S and T_S at the same time. The RDCP has a cut-off period of about 4 s for our mooring depth and cannot provide proper calibration data for wave periods, i.e. the RDCP and wave models represent somewhat different aspects of the wave spectrum.

This class of semi-empirical equations has been widely used since the 1970s for local wave forecasts and engineering purposes (e.g. Seymour 1977; Samad & Yanful 2005). As the role of remotely generated waves (swell) is small and the memory time of the wave fields in the Baltic Sea is relatively short (Soomere 2001; Leppäranta & Myrberg 2009), this relatively simple method can deliver reasonably good and fast results for its semi-enclosed medium-sized sub-basins. In practical applications, the main problem for such models seems to be wind stress parameterization and the choice of fetch length because of the irregular coastline and rugged bathymetry of a water body. As a rule, a set of fetches is prescribed as the headwind distances from the nearest shores for different wind directions. Specific algorithms are applied to take into account the properties of the basin in a wider wind sector (Massel 1996; USACE 2002). Our idea was to calibrate the wave model using high-quality wave measurements, so that afterwards the model can act as a 'virtual' extension of the fixed-point measurements both for hindcasts and forecasts. We admit that in doing so, the exact model version did not necessarily have to be the one we used for hindcasts. Instead, the site-dependent calibration procedure became crucially important for the model set-up.

Our first effort was based on hourly Vilsandi wind data and the hourly RDCP calibration data of waves obtained near the Harilaid Peninsula, which yielded the hindcast for 1966–2006 (Table 1; Suursaar & Kullas 2009). We calculated a set of slightly different H_S time series taking into account different basin depths and angular distributions of fetches, and chose the best combination for further applications. The procedure also included a slight final correction of model results for the highest waves using a simple polynomial to yield a correlation coefficient (r) as strong as 0.880, low root means square error (RMSE) and nearly equal average and maximum values of the calculated and measured wave properties.

Starting from the Kunda–Letipea hindcast (Suursaar 2010), a new iterative calibration scheme was introduced. It was supposed to find the best set of fetch distributions and other parameters, and in a way, even compensate for local wind impediments. The results and lessons from the procedure are more thoroughly discussed in the following chapter.

RESULTS AND DISCUSSION

Results of model calibrations

Although the calibration also includes a search for the appropriate depth and a certain correction factor could be applied for wind speeds, these options can be compensated for in the process of prescribing fetch length to different wind directions. However, certain initial values should be established. An empirically established wind correction factor ranging between 1.0 and 1.4 was found for stations, but not for the stations which more or less adequately represent 'marine' winds like Vilsandi or Kihnu (Table 2). Basically the correction could be viewed as the factor by which the long-term average wind speed at these stations is lower than at the corresponding wave measuring location. Considerable damping of marine winds occurs already in the coastal zone (e.g. Launiainen & Laurila 1984; USACE 2002) and continues over the land terrain (see also average wind speeds in Table 2). The height of the wind-recording instrument is important in terms of wind measurement quality standards but it is not relevant in the calibration procedure.

The SMB model assumes that the basin has a constant depth. The water depth in the model should thus represent both the depth of the actual mooring (i.e. 10–15 m) and the average depth of the sub-basin (37 m in the Gulf of Finland and 26 m in the Gulf of Riga). Increase in the depth also increases wave heights, but slightly more so in high wind speed conditions, whereas the lengthening of fetches influences wave heights more uniformly. Our calibrations included depths between 19 m (Kõiguste) and 33 m (Neugrund).

The most important item, however, was prescribing the fetch for different sectors, which was performed with a step of 20°. After measuring the fetches from nautical charts for a specific location (Fig. 2), the comparison statistics between the measured and modelled hourly time series were typically not good enough. It was difficult to guess the exact influence of islands, shoals and coastline on waves. Also, the wind forcing is usually far from ideal, which should mean 'open terrain' or full openness to every direction. New distributions of fetches were created by maximizing the correlation coefficient and minimizing the root square error by means of consecutively adjusting the fetch in all 20° wide sectors (Fig. 2). For example, at Letipea the geographical (measured) fetch distances vary between 1.5 (S, SW) and 140 km (NE). To compensate for the wind impediment of the southerly directions at the Kunda station, the procedure somewhat enhances the fetches from corresponding directions. For calibrating Matsi waves forced with Virtsu winds, westerlies should be enhanced but northerlies and northeasterlies should be reduced (Fig. 2). The best site-dependently obtained calibration results are summarized in Table 1 and Fig. 3.

We always tried to have the maximum and average wave heights equal in the modelled and reference series, which usually covered 40–60 days of hourly data. The 'quality' of the calibration could not be judged by only r or RMSE but also by the standardized RMSE (Table 1). The latter shows that the prognostic value of the calibration is higher when it covers a broader range of values. For instance, at Sillamäe (C, Table 1), the measurements used in calibration were relatively short and the period did not include strong winds, which are necessary for full range calibration. Therefore, the waves above 1.3 m are probably extrapolations and not so reliable. Also, weak winds usually include considerable local imprint, which does not extend over the longer distance and therefore leads to relatively low values of r. Relocation of the weather station from Narva to Narva-Jõesuu in 2000 was the final reason, why no long-term forecast was constructed for the Sillamäe wave measurement site.

In general, the distance between modelling and forcing locations is important. The proximity is as good as 7–10 km in case of A and B, but also 30–60 km can deliver acceptable results (Table 1). The Neugrund case is quite instructive. The present location and openness of the Pakri weather station is quite good but relocations of the station in 1969, 1992 and 2003 introduced inhomo-

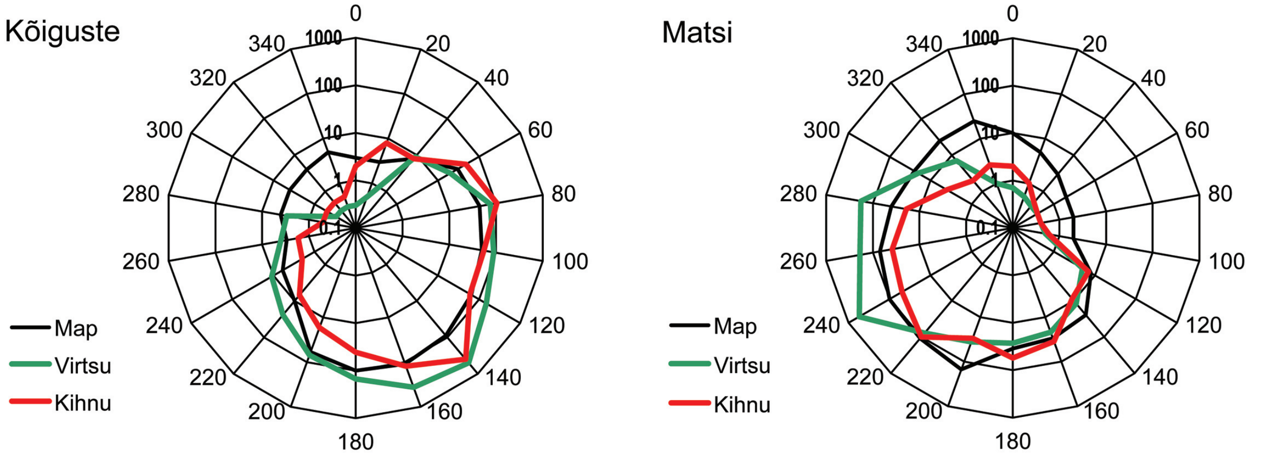

Fig. 2. Directional distributions of fetches used in the model at Kõiguste and Matsi. The initial values ('map') are shown together with calibration results, which were independently obtained using Virtsu and Kihnu winds. The fetch is expressed on a logarithmic scale and varies between 0.5 and 500 km.

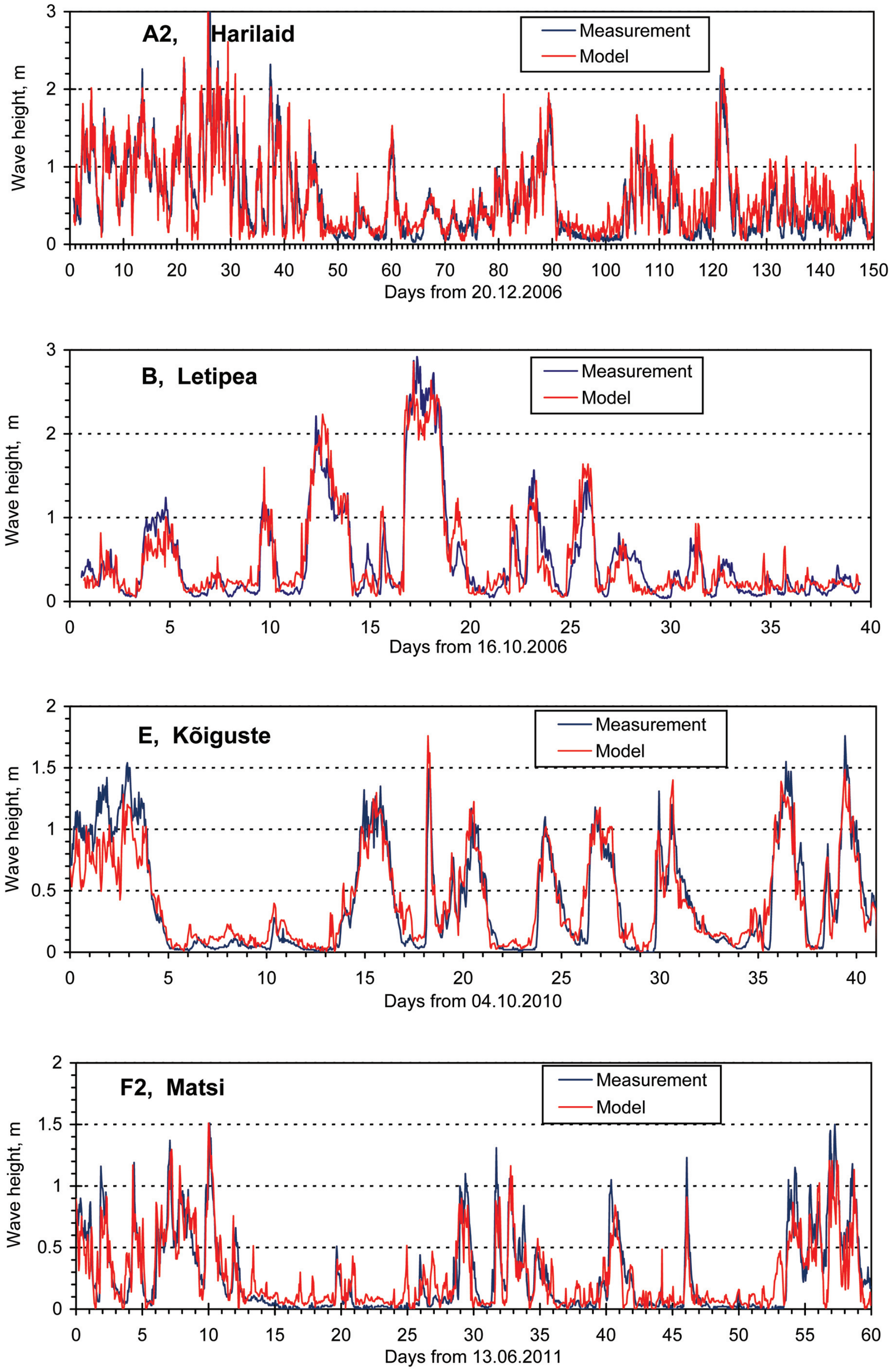

Fig. 3. Measured and modelled wave series in four calibration examples (see also Table 1 for all calibrations and additional information).

geneities both in the wind data (Keevallik & Soomere 2009) and wave hindcasts (Suursaar et al. 2011). In pursuit for more distant but homogeneous wind series, the calibration using Ristna wind data (90 km away) and Vilsandi station data (140 km away) yielded poor results with $r = 61$ and $r = 51$, respectively (Table 1). We can assume that data from neither of the Finnish stations of Hanko (70 km) or Utö (140 km) would help us out. It is interesting to note that the calibration quality for Pakri (30 km) was always lower than in our previous efforts near Harilaid and Letipea. The modelling quality was probably lower due to some islands (e.g. Osmussaar) and shallow banks which constitute the present-day Neugrund meteorite impact structure, as the highly homogeneous offshore wind-wave fields may be occasionally 'contaminated' by refraction, breaking and other shallow-water effects. In that sense, sub-basins like the eastern Gulf of Finland (Letipea site) and Gulf of Riga (Kõiguste and Matsi) are more promising for the particular model.

Despite somewhat larger distances, the calibrations were slightly more successful at Kõiguste than at Matsi (Fig. 3, Table 1), probably because of larger wave heights during the calibration. Although Virtsu forcing also delivered rather good hindcasts, we consider the results of Kihnu forcing more reliable. Namely, it is better if the weather station and the coastal study site have similar exposure and openness. Whereas Kihnu is restricted only from the N–E (the same directions as at Matsi), the Virtsu station is fully open to the north and NE and more or less restricted in all other directions. It means that the calibration procedure has to amplify southerly to westerly winds, and fetch lengths as long as 500 km can be found after calibration (Fig. 2). This number may seem large but a 500 km long fetch actually produces (also depending on depth and wind speed) only about 20% higher waves than a 100 km long fetch can do. Also, as the average overall wind speed at Virtsu is smaller (4.14 m s^{-1} versus 5.66 m s^{-1} at Kihnu in 1966–2011; see also Table 2), a correction factor for wind speed should be used as well. Using selectively and strongly elongated or shortened fetches is not necessarily bad. However, it may reduce the prognostic value of a specific calibration in very long hindcasts. Strictly speaking, the calibration is fully valid for the conditions during the calibration but may appear inadequate for older data.

We have also performed some validations of the site-specific calibrated model. For instance, at Letipea (see fig. 3 in Suursaar 2010) the comparison during another (independent) period showed remarkably good agreement between measurements and calculations but the comparison statistics were slightly lower than in the calibration period. We can assume that moving backwards away from the calibration time, the results get gradually worse. Even if the location of a weather station has not changed over the study period, some changes have probably occurred in the vegetation and constructions surrounding the station. Also, the measuring equipment in most of the stations has changed at least twice, in 1976 and 2003 (see also the 'Material and Methods' chapter, and Jaagus & Kull 2011). An interesting 'validation' option is presented in Fig. 4. Ideally, the parallel hindcasts using independent calibrations with Kihnu and Virtsu forcings should yield similar results. Both at Kõiguste and Matsi, the series are reasonably similar from 1976 onwards but Virtsu forcing seems to be inadequate for Matsi in 1966–1976 (Fig. 4). Some important changes might have taken place. Taking into account the lowering of the wind instruments height at Virtsu (10 m since 1976 and 13 m before) and the missing year of 1984, we can conclude that the results obtained with Kihnu forcing should be more trustworthy.

Spatially different wave climates of 1966–2011

Two examples of wave calculations in 2011 are shown in Fig. 5. They both include 8760 data points (24 h multiplied by 365 days). The graphs represent significant wave heights H_S. A small number of waves can always be up to 1.6 times higher. Each point on the long-term graphs (Figs 4, 6, 7) represents different summary statistics (e.g. average, standard deviation, 90 percentile, 99 percentile and maximum H_S) calculated from such annual samples. Being differently exposed (Letipea mostly to the N–NE, Matsi to the S–SW), the locations reveal rather different time series. As a rule, both average wave heights and higher percentiles show clear seasonal variations (Soomere & Zaitseva 2007; Suursaar & Kullas 2009), confirming that rough seas in the Baltic Sea tend to prevail in autumn and winter and calm conditions are more likely in spring and summer.

Leaving aside Neugrund (which has too short reliable time series; see Table 1), we can properly consider four differently exposed coastal sea locations. In addition to the previously mentioned Letipea and Matsi sites, Harilaid has the best openness to the W–NW and Kõiguste to the SE (Fig. 1). The changes according to formal linear trends (Table 3) were calculated for a 46-year period. However, these estimates are indicative only, as they depend on the choice of initial and terminal points of the time series. Owing to the large interannual variability, only a few of the linear trends calculated from the annual summary statistics of waves were statistically significant (i.e. the regression line slopes were different from zero) on the $p < 0.05$ level (Table 3; Fig. 6F–H). According to different statistics (Fig. 6), the wave height showed some quasi-periodic cycles with high stages in 1980–1995 and also probably from about 2007 onwards. The

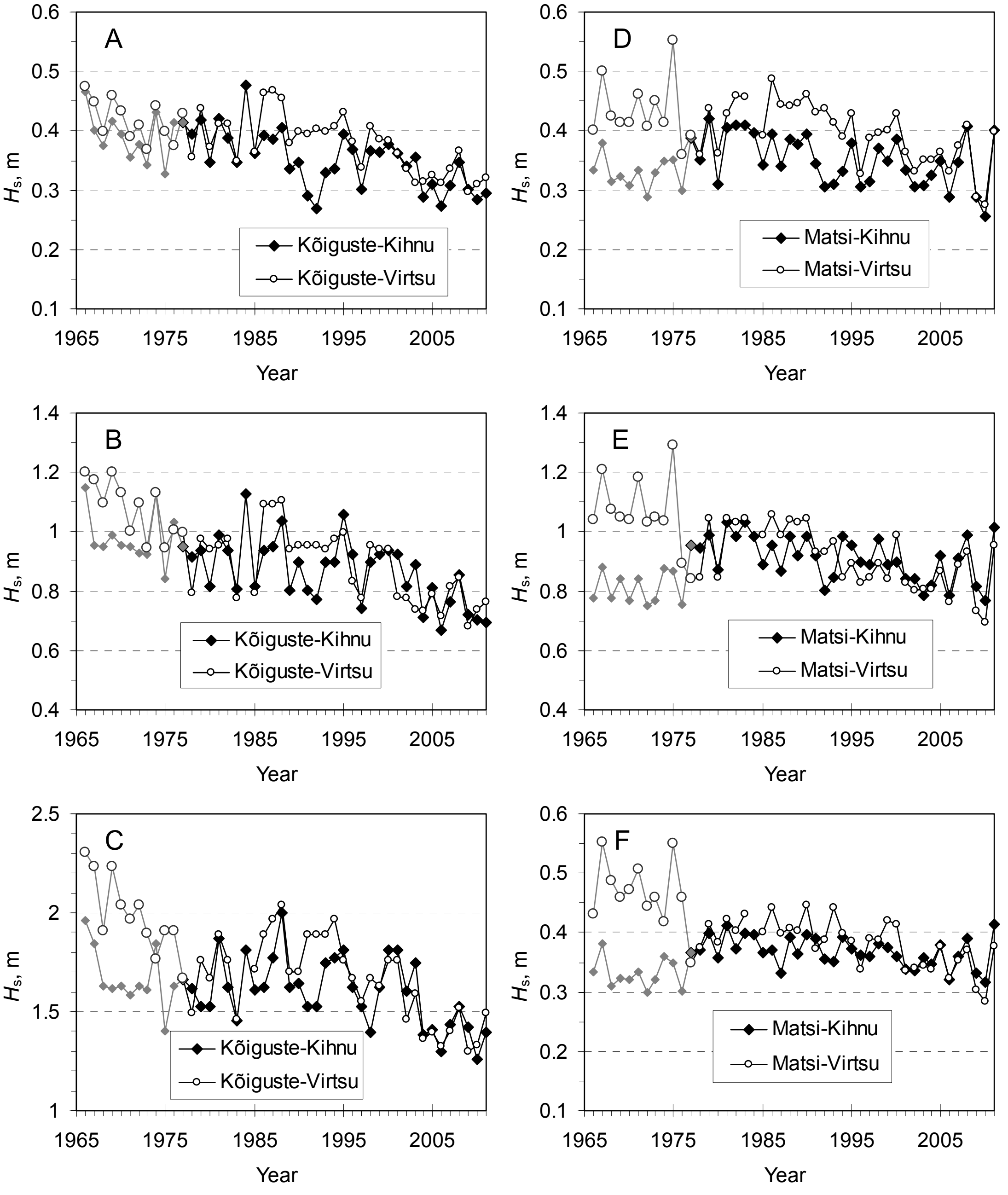

Fig. 4. Hindcasts of significant wave height (H_S) at Kõiguste and Matsi obtained with two different wind forcings (Virtsu and Kihnu). The time series composed from statistics of annual data samples represent annual average wave heights (A, D), 90%-iles (B, E), 99%-iles (C), and standard deviations (F). The years 1966–1976 are probably less representative.

cycles are somewhat shifted with respect to each other in westerly and northerly exposed locations, and basically follow the ones in atmospheric processes (Fig. 7; see also Jaagus & Kull 2011; Keevallik 2011). The average wave height has likely decreased at all locations. While at the windward (i.e. exposed to the SW, W or NW) Vilsandi and Matsi sites the overall linear trend was just very slightly decreasing in 1966–2011, the trend was significantly decreasing near Letipea and Kõiguste. However, the trends for the annual maxima and higher quantiles (90%, 99%) were increasing near Vilsandi and Matsi but still decreasing near Letipea and Kõiguste (Fig. 6). The Letipea results were also corrected with ice conditions (Suursaar 2010), which insignificantly altered the trends. For Neugrund, lying geographically in the midway between Harilaid and

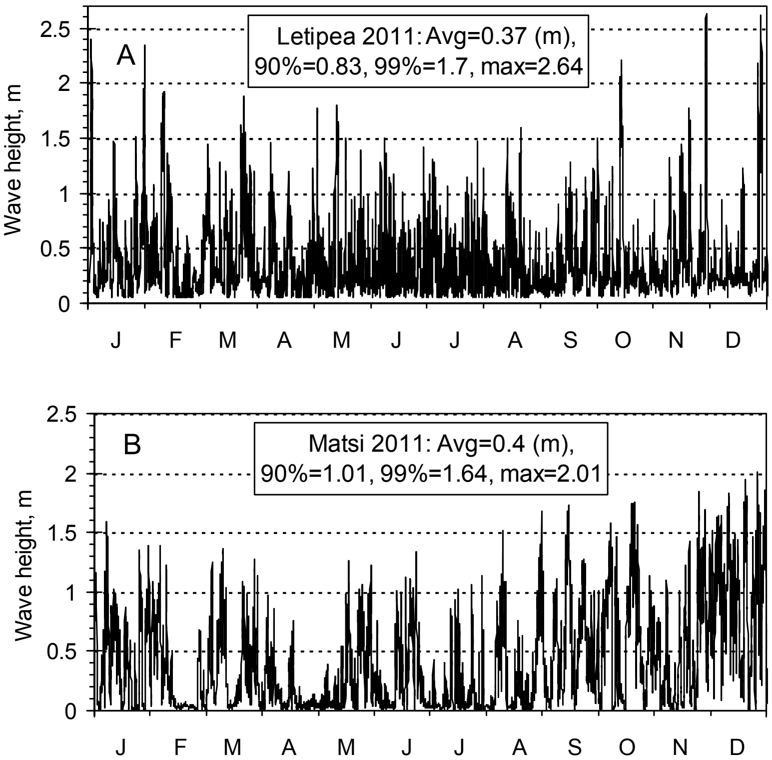

Fig. 5. Modelled hourly wave heights at the Letipea Peninsula and off the Matsi coast in 2011.

Kunda, the shorter hindcasts gave mixed results (Suursaar et al. 2011).

The spatially contrasting results for westerly and northerly–easterly exposed coastal sections are probably related to the changes in atmospheric pressure patterns above North Europe and a poleward shift of cyclone trajectories over the last decades (Pinto et al. 2007; Jaagus et al. 2008). According to Lehmann et al. (2011), the number and pathways of deep cyclones changed considerably in line with an eastward shift of the North Atlantic Oscillation centres of action. There is a seasonal shift of strong wind events from autumn to winter and early spring, while at the same time easterly wind situations decrease. Regarding waves and storm surges, it is important that more cyclones bypass Estonia from the north, creating strong westerly winds along the western coast of Estonia (Suursaar & Sooäär 2007; Suursaar 2010), however, fewer cyclones cross over Estonia and create strong northerly and easterly winds in their course.

The prevailing overall decrease in mean wave parameters, an increase in high wave events at selected locations and their relationship with wind regimes were already noticed in 2009–2010 (Suursaar & Kullas 2009; Suursaar 2010; Soomere & Räämet 2011). Following the calculated trends (Table 3), mean wind speed has decreased in the studied stations, high winds have either slightly decreased or been more or less level, and the westerly (u) component has probably increased at Vilsandi and Kihnu. The resulting flow directions, calculated from hourly wind speed components, not from the wind rose (Fig. 7E–H), have turned towards the west in all cases (except Virtsu), which basically coincides with the results by Keevallik (2011) and Jaagus & Kull (2011). In this study we do not discuss the seasonality in trends but the above-mentioned works and some previous papers (Suursaar & Sooäär 2007; Jaagus et al. 2008; Keevallik 2011; Lehmann et al. 2011) pinpoint the crucial role of wintertime changes. It is also interesting that changes in the average of the v-component are small. At the same time it is known that the decrease in wave heights at Letipea appears mainly as a result of a decrease in northerly winds at Kunda (Suursaar 2010). Indeed, a decomposition of the v-component into northerly and southerly events shows that both magnitudes have decreased, yet retaining their balance. While the fate of southerly winds is quite irrelevant to the waves at Letipea, the actual decrease in northerly winds obviously influences the wave statistics. Roughly the same is valid for other nearshore locations: the tendencies in winds blowing

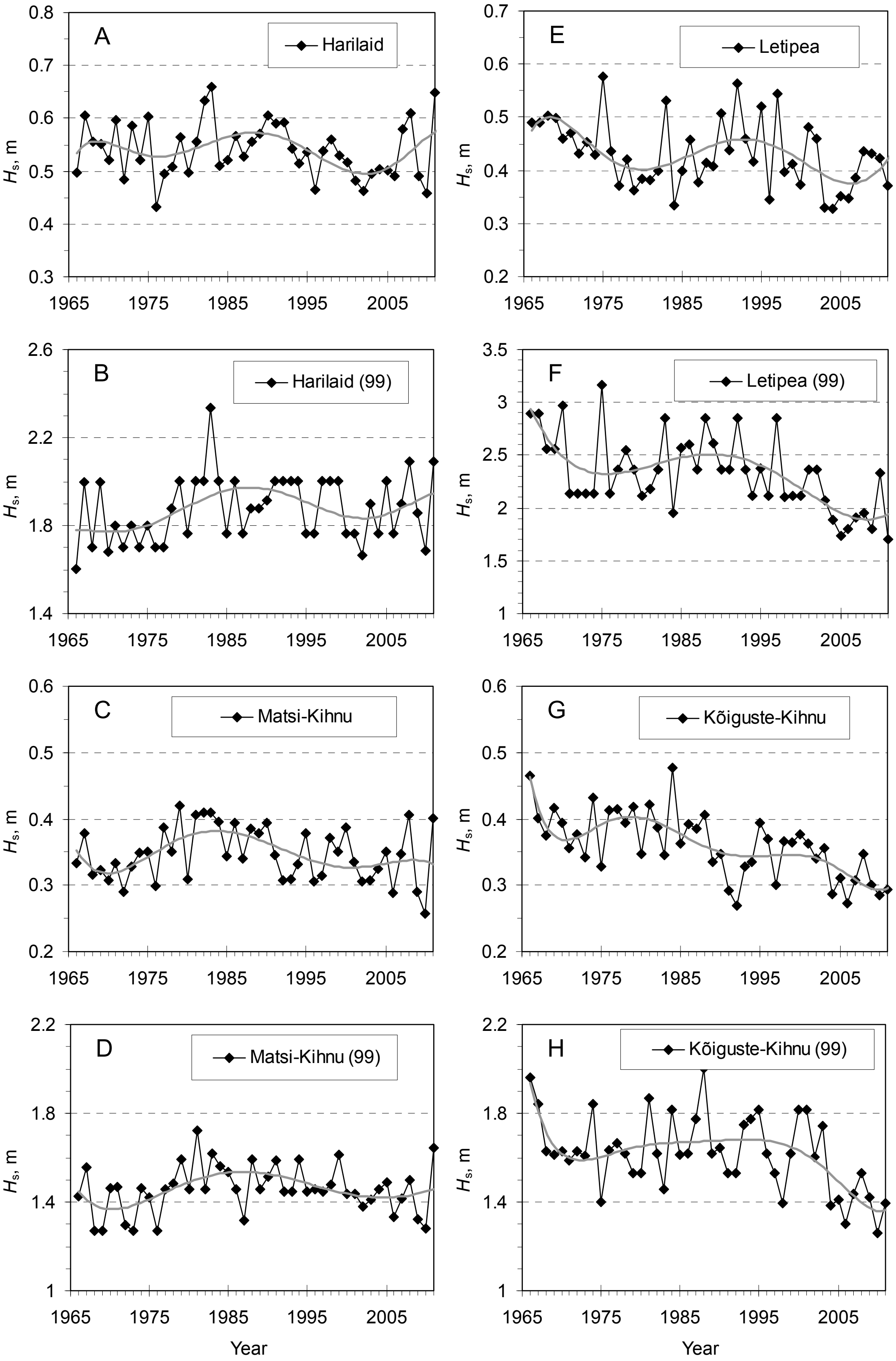

Fig. 6. Annual average (A, C, E, G) and 99%-ile (B, D, F, H) wave height at four modelling locations in 1966–2011. Matsi and Kõiguste time series are calculated using Kihnu winds. Sixth-order polynomial trendlines are added for visualization of quasi-cyclicity; for statistics according to linear trendlines see Table 3.

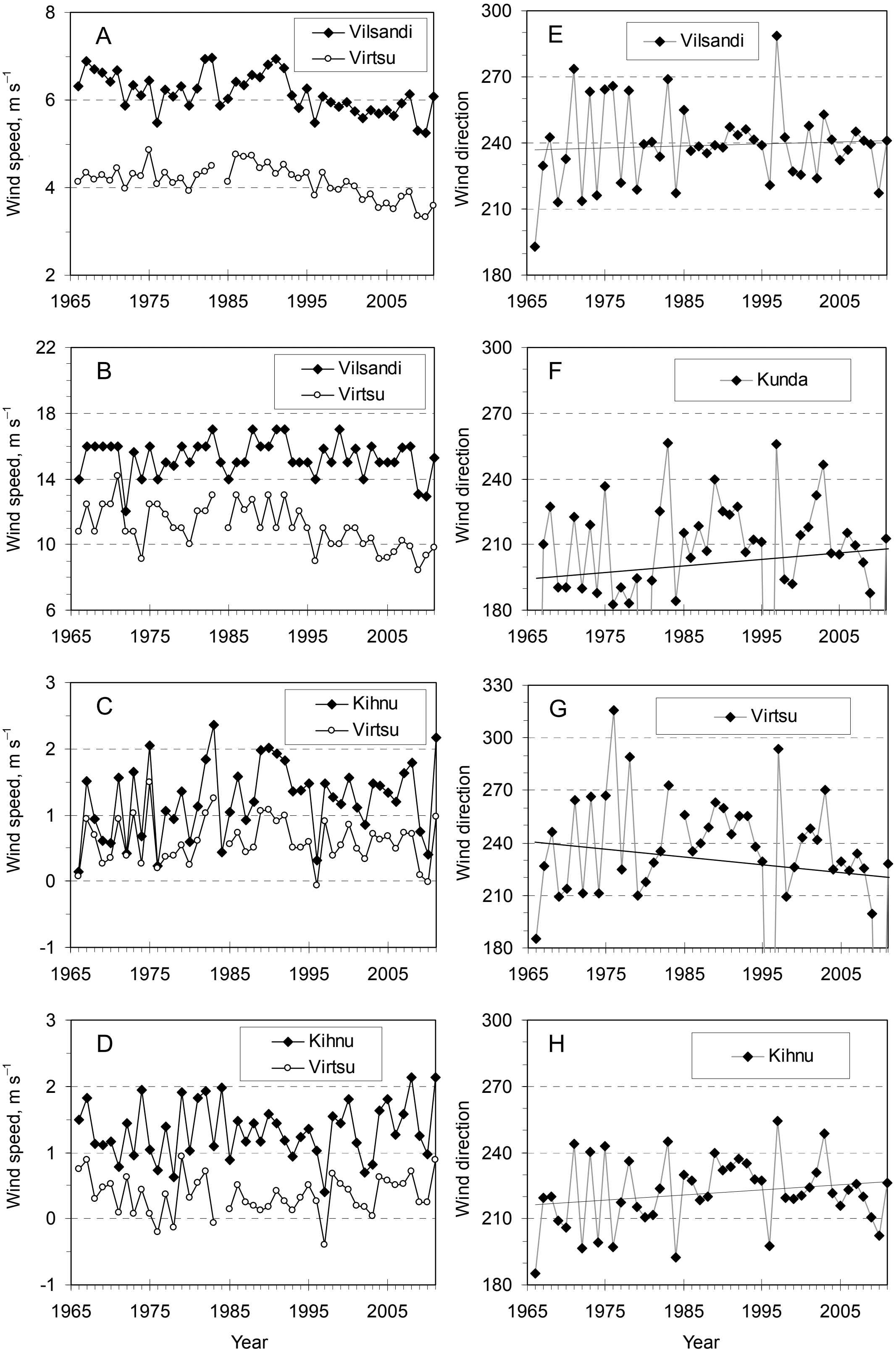

Fig. 7. Annual average (A) and 90%-ile (B) of the wind speed, annual mean zonal (u) (C) and meridional (v) wind component (D), and annual resulting wind direction calculated from the wind velocity components (E, F, G, H).

Table 3. Average changes according to linear trendlines calculated from modelled wave time series at the Harilaid Peninsula (Ha), Letipea (Le), Kõiguste (Kõ), Matsi (Ma), and wind time series at Vilsandi (Vi), Kunda (Ku), Virtsu (Vu) and Kihnu (Ki) in 1966–2011 (see also Figs 6, 7). The values divided by 46 (years) give average annual change rates. Positive trend values are highlighted in bold. Results with significantly differing from zero trend slopes (on $p < 0.05$ level) are marked with an asterisk

Statistic	Waves, m				Wind speed, m s^{-1}			
	Ha	Le	Kõ	Ma	Vi	Ku	Vu	Ki
Max.	**0.14**	−0.69*	−0.23	−0.18	**0.56**	−1.76	−3.17*	−3.23*
99%	**0.11**	−0.66*	−0.24*	**0.03**	−0.27	−2.81*	−2.55*	−1.80*
90%	**0.07**	−0.48*	−0.25*	**0.04**	−0.37	−2.63*	−2.10*	−0.33
Avg.	−0.02	−0.08	−0.11*	−0.01	−0.84*	−1.37	−0.73*	−0.07
u-comp.					**0.29**	−0.05	−0.05	**0.45**
v-comp.					**0.02**	−0.32*	**0.03**	**0.10**

from the directions with longer fetches are far more important than those in winds with short fetches. This is also the main reason for the different behaviour of time series in the four differently exposed locations.

Uncertainties

Quite understandably, the different forcing data, locations and methods occasionally deliver somewhat different results and some disagreements may occur in trend values (e.g. Soomere & Zaitseva 2007; Räämet et al. 2009; Suursaar 2010; Soomere & Räämet 2011). Additional difficulties in taking into account seasonal ice conditions in the Baltic Sea were reviewed by Tuomi et al. (2011).

In large and complex marine areas, the local wave properties may appear as a mixture of several wave fields and relationships between forcing and outcome may sometimes be obscure (e.g. Weisse & Günther 2007). However, in the medium-sized semi-enclosed marine areas this is mainly a question of the quality or inherent properties of the wind forcing used. Although somewhat selectively in coastal areas, a wave model still reflects winds. Assuming that wave models are all more or less adequate within their limits, the different results largely reflect differences in wind forcing. We do not discuss here the geostrophic, HIRLAM or MESAN winds that are used in WAM models. The main developments in measured wind series from Estonian coastal meteorological stations include an overall decrease in average values, an increase in the westerly wind velocity component (or an increase in the frequency of SW and W winds), seasonality in trends, an increase in wintertime extreme events at some westerly exposed stations (e.g. Keevallik & Soomere 2009; Suursaar 2010; Jaagus & Kull 2011; Keevallik 2011).

Being closely related to large-scale variations in atmospheric conditions (Pinto et al. 2007; Lehmann et al. 2011), including the North Atlantic Oscillation Index, these general patterns both in wave and wind statistics are probably valid. However, the main concern expressed here is: are the time series homogeneous enough throughout 1966–2011? Regarding changes in instrumentation, they probably are more or less homogeneous at least since 1976. Then, the second issue is the potential change in surface roughness and weather station openness. Obviously some changes have inevitably occurred but they are not similar in different locations and their influence is difficult to take into consideration. The changes in obstacles are relatively small at Vilsandi and Kihnu, but may be notable at Virtsu, Pakri and Kunda. Jaagus & Kull (2011) have made an attempt to correct them using the WAsP (stands for Wind Atlas Analysis and Application Program) model in their study of changes in wind directions during 1966–2008. However, some investigations are still needed. Can the once measured data be changed retrospectively? How high is the reliability of older data in the context of long-term changes? Is it possible that the decreasing trend (which is visible in most of the Estonian wind time series) is a result of inhomogeneities in data and should actually be less pronounced? At the same time, the marine wind speed at Utö, Northern Baltic Proper, has probably increased over a similar period (Räämet & Soomere 2010). However, these long-term data may include some inhomogeneities as well.

CONCLUSIONS

A fetch-based calibration scheme for simple wave models is presented. We calibrated a model for significant wave heights (it could be any version of them) against good-quality wave measurements and calculated the hindcasts as ‘extensions of in situ measurements’ at differently exposed locations in the Estonian coastal sea. Good comparison results (like these presented in Fig. 3) can rarely be seen in wave modelling. Regarding limitations, this is a simple, first-generation model, which cannot take into account the gradual wave growth and decay or swell formation. The model is therefore applicable in small and medium-sized water bodies. Its results represent the wave climate at the location or neighbourhood with a similar exposition and fetch conditions. However, when a larger number of such hindcasts are obtained and site-dependent change patterns revealed, the whole coastal sea can be covered.

The hindcast results showed some quasi-periodic cycles with high stages in 1980–1995, and probably also from about 2007, the prevailing overall decrease in mean wave properties, an increase in high wave events in selected locations, and their relations with wind regimes. The climate-induced changes in wave conditions, like in sea level, are not necessarily similar within the whole of the Baltic Sea. The spatially contrasting results for westerly and northerly–easterly exposed coastal sections are probably related to the changes in atmospheric pressure patterns above North Europe and a poleward shift of cyclones trajectories. Although ultimately (but still selectively) governed by atmospheric conditions, the developments found in wave hindcasts can help us to pinpoint important shifts also in atmospheric climate. However, the wave modelling results always depend on the quality or specific properties of the routinely measured (or modelled) wind data (e.g. instrument changes, long-term gradual changes in land use), which may lead to inhomogeneities and uncertainties also in long-term wave hindcasts.

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REFERENCES

Bishop, C. T., Donelan, M. A. & Kahma, K. K. 1992. Shore protection manual's wave prediction reviewed. *Coastal Engineering*, **17**, 25–48.

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**(S), 165–184.

Gidrometeoizdat 1990. *Nauchno-prikladnoj spravochnik po klimatu SSSR* [*Scientific-Practical Handbook of the Climate of the USSR*], Series 3, Parts 1–6, 4th ed., Gidrometeoizdat, Leningrad, 208 pp. [in Russian].

Huttula, T. 1994. Suspended sediment transport in Lake Säkylän Pyhäjärvi. *Aqua Fennica*, **24**, 171–185.

Jaagus, J. & Kull, A. 2011. Changes in surface wind directions in Estonia during 1966–2008 and their relationships with large-scale atmospheric circulation. *Estonian Journal of Earth Sciences*, **60**, 220–231.

Jaagus, J., Post, P. & Tomingas, O. 2008. Changes in storminess on the western coast of Estonia in relation to large-scale atmospheric circulation. *Climate Research*, **36**, 29–40.

Jönsson, A., Broman, B. & Rahm, L. 2002. Variations in the Baltic Sea wave fields. *Ocean Engineering*, **30**, 107–126.

Keevallik, S. 2011. Shifts in meteorological regime of late winter and early spring in Estonia during recent decades. *Theoretical and Applied Climatology*, **105**, 209–215.

Keevallik, S. & Soomere, T. 2009. Seasonal and diurnal variations of wind parameters at Pakri. *Estonian Journal of Engineering*, **15**, 227–239.

Keevallik, S., Soomere, T., Pärg, R. & Žukova, V. 2007. Outlook for wind measurement at Estonian automatic weather stations. *Proceedings of the Estonian Academy of Sciences, Engineering*, **13**, 234–251.

Keevallik, S., Männik, A. & Hinnov, J. 2010. Comparison of HIRLAM wind data with measurements at Estonian coastal meteorological stations. *Estonian Journal of Earth Sciences*, **59**, 90–99.

Komen, G. J., Cavaleri, L., Donelan, M., Hasselmann, K., Hasselmann, S. & Janssen, P. A. E. M. 1994. *Dynamics and Modelling of Ocean Waves*. Cambridge University Press, 532 pp.

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

Lehmann, A., Getzlaff, K. & Harlass, J. 2011. Detailed assessment of climate variability in the Baltic Sea area for the period 1958 to 2009. *Climate Research*, **46**, 185–196.

Leppäranta, M. & Myrberg, K. 2009. *Physical Oceanography of the Baltic Sea*. Springer Praxis, Berlin, Heidelberg, New York, 378 pp.

Luhamaa, A., Kimmel, K., Männik, A. & Rõõm, R. 2011. High resolution re-analysis for the Baltic Sea region during 1965–2005 period. *Climate Dynamics*, **36**, 727–738.

Massel, S. R. 1996. *Ocean Surface Waves: Their Physics and Prediction*. World Scientific, Singapore, 491 pp.

Pinto, J. G., Ulbrich, U., Leckenbusch, G. C, Spangehl, T., Reyers, M. & Zacharias, S. 2007. Changes in storm track and cyclone activity in three SRES ensemble experiments with the ECHAM5/MPI-OM1 GCM. *Climate Dynamics*, **29**, 195–210.

Räämet, A. & Soomere, T. 2010. The wave climate and its seasonal variability in the northeastern Baltic Sea. *Estonian Journal of Earth Sciences*, **59**, 100–113.

Räämet, A., Suursaar, Ü., Kullas, T. & Soomere, T. 2009. Reconsidering uncertainties of wave conditions in the coastal areas of the northern Baltic Sea. *Journal of Coastal Research, Special Issue*, **56**, 257–261.

Samad, M. A. & Yanful, E. K. 2005. A design approach for selecting the optimum water cover depth for subaqueous disposal of sulfide mine tailings. *Canadian Geotechnological Journal*, **42**, 207–228.

Seymour, R. J. 1977. Estimating wave generation in restricted fetches. *Journal of the Waterway, Port, Coastal and Ocean Division, Proceedings of ASCE*, **103**, 251–263.

Soomere, T. 2001. Wave regimes and anomalies off northwestern Saaremaa Island. *Proceedings of the Estonian Academy of Sciences, Engineering*, **7**, 157–173.

Soomere, T. 2003. Anisotropy of wind and wave regimes in the Baltic proper. *Journal of Sea Research*, **49**, 305–316.

Soomere, T. & Räämet, A. 2011. Long-term spatial variations in the Baltic Sea wave fields. *Ocean Science*, **7**, 141–150.

Soomere, T. & Zaitseva, I. 2007. Estimates of wave climate in the northern Baltic Proper derived from visual wave observations at Vilsandi. *Proceedings of the Estonian Academy of Sciences, Engineering*, **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. *Natural Hazards and Earth System Sciences*, **8**, 37–46.

Suursaar, Ü. 2009. Interpretation of Doppler effect-based vertical velocity measurements in the coastal waters of Estonia, Baltic Sea: possible influence of upwelling, Langmuir circulation and turbidity. In *Fluid Structure Interaction. WIT Transactions on the Built Environment, Vol. 105* (Brebbia, C. A., ed.), pp. 193–203. WIT Press, Southampton, Boston.

Suursaar, Ü. 2010. Waves, currents and sea level variations along the Letipea–Sillamäe coastal section of the southern Gulf of Finland. *Oceanologia*, **52**, 391–416.

Suursaar, Ü. & Aps, R. 2007. Spatio-temporal variations in hydro-physical and -chemical parameters during a major upwelling event off the southern coast of the Gulf of Finland in summer 2006. *Oceanologia*, **49**, 209–228.

Suursaar, Ü. & Kullas, T. 2009. Decadal variations in wave heights off Kelba, Saaremaa Island, and their relationships with changes in wind climate. *Oceanologia*, **51**, 39–61.

Suursaar, Ü. & Sooäär, J. 2007. Decadal variations in mean and extreme sea level values along the Estonian coast of the Baltic Sea. *Tellus A*, **59**, 249–260.

Suursaar, Ü., Jaagus, J., Kont, A., Rivis, R. & Tõnisson, H. 2008. Field observations on hydrodynamic and coastal geomorphic processes off Harilaid Peninsula (Baltic Sea) in winter and spring 2006–2007. *Estuarine Coastal and Shelf Science*, **80**, 31–41.

Suursaar, Ü., Szava-Kovats, R. & Tõnisson, H. 2011. Wave climate and coastal processes in the Osmussaar–Neugrund region, Baltic Sea. In *Coastal Processes II, WIT Transactions on Ecology and Environment, Vol. 149* (Benassai, G., Brebbia, C. A. & Rodriguez, G. R., eds), pp. 99–110. WIT Press, Southampton, Boston.

Zaitseva-Pärnaste, I., Suursaar, Ü., Kullas, T., Lapimaa, S. & Soomere, T. 2009. Seasonal and long-term variations of wave conditions in the northern Baltic Sea. *Journal of Coastal Research, Special Issue*, **56**, 277–281.

Zaitseva-Pärnaste, I., Soomere, T. & Tribštok, O. 2011. Spatial variations in the wave climate change in the eastern part of the Baltic Sea. *Journal of Coastal Research*, *Special Issue*, **64**, 195–199.

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

USACE 1984. *U.S. Army Coastal Engineering Research Center, Shore Protection Manual*, Vol. 1, Third Ed., U.S. Govt. Printing Office, Washington D.C., 719 pp.

USACE 2002. *Coastal Engineering Manual*. Department of the Army. U.S. Army Corps of Engineers. Manual. No. 1110-2-1100, 2002, CD.

Weisse, R. & Günther, R. 2007. Wave climate and long-term changes for the Southern North Sea obtained from a high-resolution hindcast 1958–2002. *Ocean Dynamics*, **57**, 161–172.

Eesti rannikumere lainetingimuste lokaalselt kalibreeritud modelleerimistulemused aastail 1966–2011

Ülo Suursaar

On esitatud lainetingimuste pikaajaline arvutus neljas erisuunalise avatusega Eesti rannikumere kohas: Harilaiu poolsaare juures (lääs-loe), Letipeal (põhi-kirre), Matsi lähedal (edel) ja Kõiguste lahe juures (kagu). Olulise lainekõrguse mudel on neis kohtades kalibreeritud merepõhja asetatud mõõtekompleksiga Recording Doppler Current Profiler aastail 2006–2011 saadud andmete põhjal ja lainearvutus aastate 1966–2011 kohta on tehtud Eesti Meteoroloogia ja Hüdroloogia Instituudi ilmajaamade digiteeritud tuuleandmete alusel. Modelleeritud aegread näitasid kvaasiperioodilisi muutusi, sealhulgas kõrget faasi aastate 1980–1995 paiku ja arvatavasti ka alates 2007. aastast, valitsevat langustrendi lainete keskmistes parameetrites ning tormilainetuse kasvu läände avatud randades, kuid langust põhja ja kagusse eksponeeritud rannalõikudel. Need ruumiliselt kontrasteeruvad tulemused on tihedalt seotud analoogiliste muutustega mõõdetud rannikujaamade tuuletingimustes, mis omakorda on ilmselt põhjustatud muutustest suuremastaabilistes atmosfääriprotsessides Põhja-Euroopa kohal ja tsüklonite valdavate trajektooride mõningasest põhjasuunas nihkumisest. Kuigi mudeli kalibratsioonitulemused on suurepärased, sõltuvad pikaajalised lainearvutused kasutatud sisendandmete kvaliteedist ja omapärast. Vanemate andmete puhul on võimalik, et tuuleandmete mittehomogeensus mõõteaparatuuri muutuste ja ilmajaama ümbruse avatuse muutuste tõttu lisab ebatäpsust ka pikaajalistesse lainearvutustesse.