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How do simple wave models perform compared with sophisticated models and measurements in the Gulf of Finland?

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ABSTRACT

Wave parameters form the base for the design of coastal structures. For this purpose, commonly modelled wave properties are employed. This approach is usually adequate in open ocean conditions where spatial variations in wave properties are normally quite limited. The situation is different in nearshore areas of complicated shapes, where wave properties can be highly variable. In such instances, long and sufficiently detailed wave measurements for model validation are usually unavailable. The use of default settings of wave models means that possible errors remain unknown, and employing data with substantial uncertainties could lead to overdimensioned structures or structural failures. We address the magnitude of possible errors in such conditions by comparing the output of simple wave models (such as the fetch-based SPM model or the SWAN model forced with one-point homogenous wind) and the sophisticated multi-nested SWAN wave model forced with ERA5 winds with recent wave measurements in various nearshore locations in the eastern Baltic Sea. We use records of different length spanning over more than ten years. While in some locations simple models or models forced with homogenous wind yield acceptable results, in most areas more sophisticated models are needed to adequately replicate wave properties. The outcomes of our analysis provide several site-specific hints for practical coastal engineering.

Introduction

Wave parameters set the base for the design of coastal management activities and coastal engineering structures. However, specification of the necessary parameters is a significant challenge in water bodies of complicated shapes. Even though wind wave fields are relatively homogeneous in offshore locations, local bathymetry and geometry often give rise to extensive variations in nearshore wave properties (Hanes and Erikson 2013; Björkqvist et al. 2017). Additionally, wave fields in many semi-sheltered regions, such as the Baltic Sea, have intermittent nature: long periods of almost calm time are interspersed with short but ferocious storms (Soomere and Eelsalu 2014).

The most reliable way for evaluating wave parameters near a particular location under such conditions is to measure wave properties at this location during a long time. However, this is usually not feasible because of time and financial constraints. Wave measurements are scarce in terms of spatial (and often temporal) coverage in the world ocean and also in the Baltic Sea region (Björkqvist et al. 2018). In many occasions, wave measurements have only covered short time periods. For example, technically, waves have been measured in numerous places in the Gulf of Finland (Fig. 1), but many measurements have been carried out with the same device and not simultaneously (Suursaar 2013, 2015). For this reason, the local wave climate is commonly estimated using wave modelling. When doing so, the wave model is usually calibrated and/or validated against in situ measurements in the neighbourhood of the location of interest. The output of a validated wave model can be considered as mostly adequate in open sea areas downwind from the measurement location and

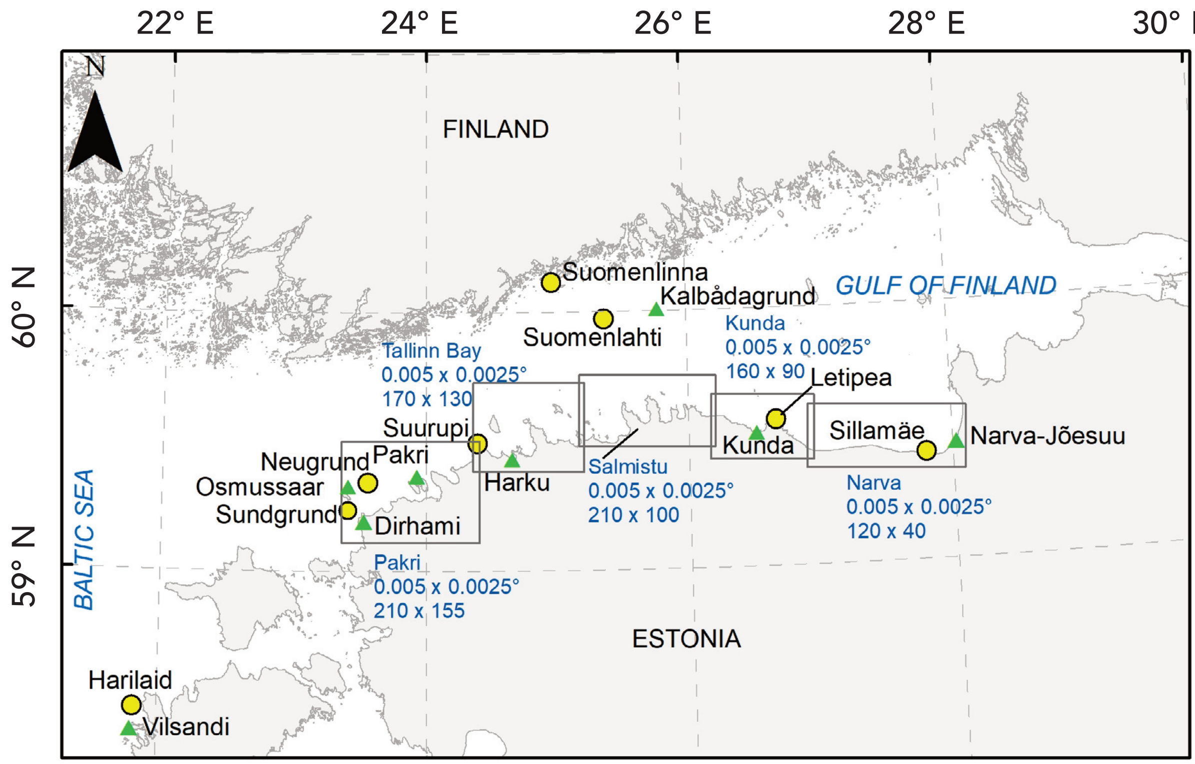

Fig. 1. Wave (yellow circles) and wind measurement locations (green triangles) in the Gulf of Finland and on Saaremaa Island. Five rectangles denote the third-level grids in the SWAN model. The resolution and number of grid cells are presented at each grid in blue font.

in the nearshore of relatively straight coastal segments, provided the wind information is acceptable.

This approach is not straightforward in the nearshore of semi-sheltered regions with rugged coastlines. The complex topography and bathymetry of the Baltic Sea is one of the reasons why the local wave climate is highly inhomogeneous (Soomere and Räämet 2011). Another reason is the specific bidirectional structure of moderate and strong winds (Soomere 2003). Even the use of most advanced contemporary wave models and state-of-the art wind data leads to differences in the properties of the local wave climate in areas sheltered from predominant wind directions (Giudici et al. 2023). Moreover, some of the strongest storms in this region seem to occur from directions where winds blow infrequently (Soomere 2001, 2003). While the most frequent wind direction is from the southwest, the most ferocious wave storm in the neighbourhood of the study area, in the Sea of Bothnia, was generated by northerly winds that reached 32.5 m/s (Björkqvist et al. 2020). The severest wave conditions ever recorded in the Gulf of Finland, with a significant wave height of 5.2 m, were documented in 2001 during a southwestern storm and recurred in 2012 during an eastern storm (Pettersson et al. 2013). These events are not necessarily represented in the measured or modelled wave climate.

In such situations, it is not always justified to fully rely on numerical wave models forced with simulated wind fields, even if carefully calibrated and validated. Moreover, in practice, it is sometimes required to produce an express estimate of the wave climate and its possible extremes at short notice. This leaves little time for detailed study of wave model sensitivity and its ability to replicate possible extreme situations. A solution in the past has been to use a simple or simplified (often parametric) model, such as the Sverdrup–Munk–Bretschneider type models (e.g. USACE 1984). They are based on robust physics and have been shown to work properly in many occasions all over the world. These models generally work well for smaller and relatively deep water bodies with short fetch (and thus limited time for building up energy transfer via nonlinear wave–wave interactions).

Given the high computational cost of contemporary spectral wave models and extensive problems with the resolution and accuracy of modelled wind speeds over the Baltic Sea (Lorenz and Gräwe 2023), simple techniques for rapid replication of wave properties presumably have a niche in wave science along with the WAM, SWAN and other rather demanding third-generation models. It is likely that these simpler techniques can be effectively used for express estimates of present and past wave climates at particular locations. Still, the question remains, how trustworthy are these models? Can they produce reasonable results, at least to a first approximation?

Wave time series hindcasts generated using different models, including very simple ones, usually show qualitative matches with recorded time series, especially over longer time periods. For instance, wave hindcasts produced at Harilaid, located in the northeastern part of Saaremaa Island, by completely different models with varying and independent wind forcing have yielded rather synchronous time series (Fig. 2). A locally calibrated point model (LCPM) was forced with single-point wind data from Vilsandi meteorological station (Fig. 1), while the SWAN model was forced with the ERA5 wind field. The difference in the magnitude of wave heights (Fig. 2) can be explained by the different position of the LCPM modelling location (1.5 km off the coast) and the

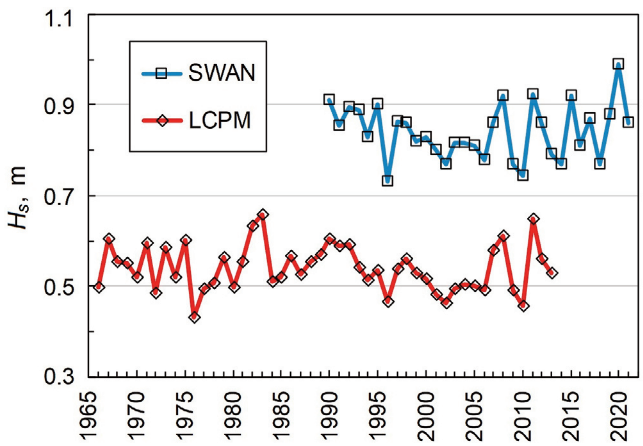

Fig. 2. Comparison of wave hindcasts obtained for the same location (near the Harilaid Peninsula, Saaremaa Island) using a simple, locally calibrated point model (LCPM) forced with single-point wind (1966–2011, redrawn from Suursaar 2013, updates from Suursaar et al. 2014) and the SWAN wave model forced with the ERA5 wind field (redrawn from Najafzadeh et al. 2024).

corresponding SWAN mesh cell on the near-coastal slope. Such a difference in location considerably affects the magnitude of significant wave height (Kudryavtseva et al. 2019; Najafzadeh et al. 2024) but generally preserves the temporal variations in wave height. Nevertheless, the suitability of different models to reproduce relatively short-term variability of wave properties in different scales should be studied in a greater detail. Comparisons of outputs of various wave models and wind sources (e.g. Suursaar et al. 2014; Giudici et al. 2023) have raised questions regarding the representativeness of wind input data and the role of calibration procedures in shaping the results.

We address these questions in the context of the Gulf of Finland in the eastern Baltic Sea (Fig. 1). This water body has a short fetch (around 100 km) for most predominant wind directions. The majority of beaches on its southern side are well sheltered from waves produced over longer fetches. We start with the description of wind data and different wave models used in the analysis. The state-of-the-art model used for benchmarking is the SWAN wave model with high resolution, forced with modelled wind data from the ERA5 reanalysis (Björkqvist et al. 2018; Giudici et al. 2023). The other two models used are SWAN within the Delft3D suite, valued for its user-friendly graphical interface, and a fetch-based semi-empirical wave model. The modelling results are compared with in situ measurements carried out at different locations. Given the importance for coastal designers and managers to know wave properties in extreme wind conditions, we also assess the models' performance in high wave cases. The last section provides a discussion about the comparisons made and offers recommendations.

Data and methods

Wind forcing

Our aim is to compare the outputs of different wave models that are forced with similar input data. To construct a 'virtual ground truth' for wave properties, we employ high-resolution wind data with maximally realistic spatial and temporal variations (the wind is blowing at different speeds and in different directions at every spot and time step), which force a model in SWAN. These results are used as a benchmark for the rest of the calculations. The wind data are extracted from the ERA5 database (Hersbach et al. 2020), the fifth-generation global atmospheric reanalysis produced by the European Centre for Medium-Range Weather Forecasts (ECMWF) from 1979 to the present, with trimestral updates. In this paper, we use the data aligned with the latest WMO (World Meteorological Organization) climatological standard normal, 1991–2021.

Compared to its predecessors, ERA5 incorporates a more recent version of the ECMWF Integrated Forecast System model (IFS 41r2, ECMWF 2006), with increased temporal output, horizontal and vertical resolutions (1 h, 0.25° and 137 vertical levels, respectively), and several improvements to parameterisations (e.g. convection and microphysics) and the data assimilation scheme. The hourly near-surface u and v components of wind velocity at a height of 10 m, obtained from Hersbach et al. (2018), are used to compute wind speed and direction for the model.

If the goal is to produce an express estimate of the local wave climate, the above-described wind data and wave model may be complicated to access and implement, and local wind measurements tend to be easier to use. In such cases, it is natural to force wave models with measured winds in certain locations. For this purpose, we used one-point wind data from selected Estonian coastal weather stations, operated by the Estonian Environment Agency (EEA 2023).

The problem is how to decide which weather stations (Fig. 1) represent well marine winds – those that can, at least from some directions, freely approach the nearshore across the sea. However, coastal wind measurements are always impeded to some extent (see e.g. Keevallik et al. 2007; Žukova 2009) and some are almost unusable (Keevallik 2003). The best stations in this respect are located either on small islands or peninsulas in western Estonia (e.g. Vilsandi, Sõrve, Kihnu). Vilsandi is known to adequately represent sea wind properties from most directions (Soomere 2001), serving as a reference for wind properties in the northeastern Baltic Proper.

Along the southern coast of the Gulf of Finland, there are no equally good measurement locations. They are plagued either by limited openness towards the sea, the influence of the Baltic Klint, changes in station locations, or gaps in time series (Keevallik 2003; Keevallik and Vint 2012; Suursaar 2023). Even though stations in Kunda and Narva-Jõesuu are somewhat problematic, they still adequately capture marine winds from the northwest and north (Žukova 2009; Suursaar 2010). The Kunda station, located just 10 km west of the Letipea measuring site (Fig. 1), is sheltered by land (especially by a cliff) from southerly winds but the measurements apparently represent the marine wind from northerly sectors (Soomere and Keevallik 2003). Narva-Jõesuu is the easternmost Estonian weather station near the mouth of the River Narva. Wind data from this location have not been used for the analysis of wind regime over the Gulf of Finland. The applicability of wind information from weather stations on

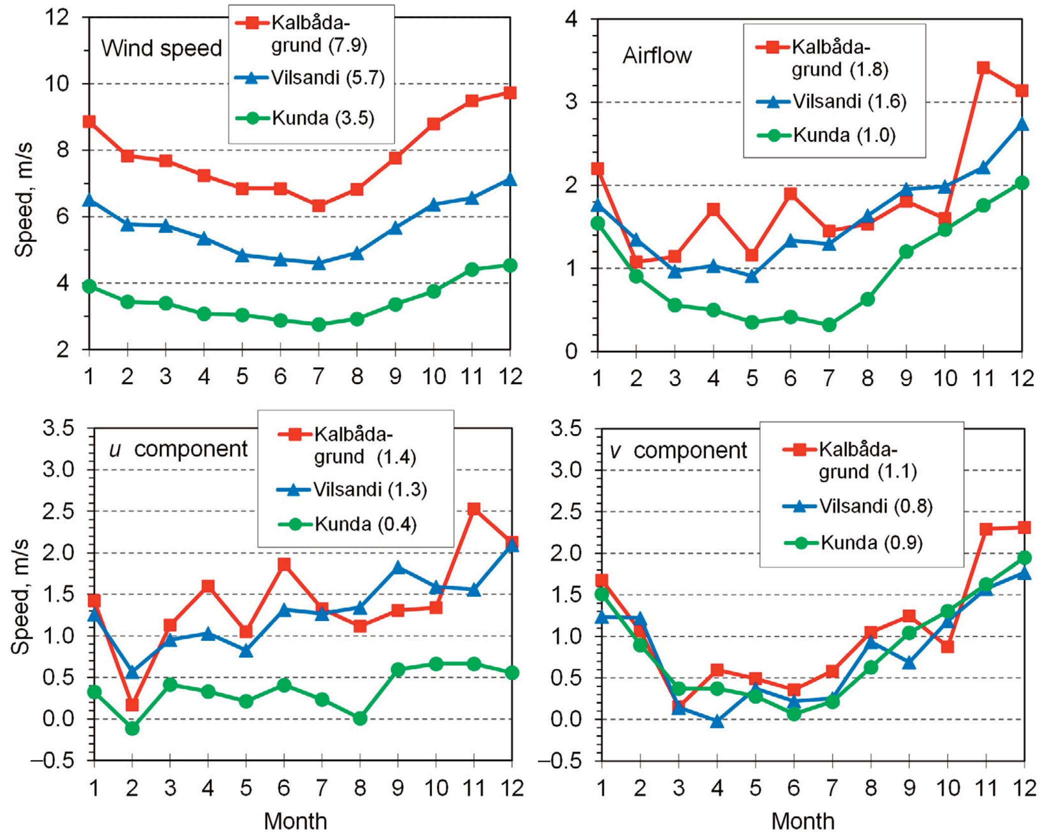

Fig. 3. Comparison of monthly average wind speeds, *u* and *v* components, and average airflow speeds (computed from *u* and *v*) at selected stations. The values in parentheses represent corresponding averages in 2004–2021 (for Kalbådagrund and Vilsandi) or in 2004–2013 (for Kunda; the station was slightly relocated in March 2014).

Osmussaar Island and in Harku, Pakri and Dirhami to replicate marine wind conditions is analysed in Soomere and Keevallik (2003). Since autumn 2003, MILOS-520 automatic devices have provided hourly data about wind speeds and directions with a resolution of 0.1 m/s and 1°, respectively, at weather stations operated by the EEA.

In addition, data from Kalbådagrund (Fig. 1) were downloaded from the website of the Finnish Meteorological Institute (FMI 2023). Located on a caisson lighthouse ca 37 km off the Estonian coast, the station is open to marine winds from all directions (Launiainen and Laurila 1984). Data from this station have been frequently used by oceanographers and wave modellers (Myrberg 1997; Soomere et al. 2008), usually with some height corrections because the wind is measured 32 m above mean sea level. Indeed, comparisons of wind speeds (Suursaar 2023) have shown that the average wind speed at Kalbådagrund tends to be nearly twice as high as at Kunda and ca 1.4 times higher than at Vilsandi (Fig. 3), which is one of the windiest stations in Estonia. At Kunda, only northerlies are not shielded by land. Differences in airflow components are much smaller, though the *u* component at Kunda is notably smaller than at the other two locations (Fig. 3). As immediate wind stress on the sea surface is crucial for wave excitation, differences in wind speed usually translate into even larger variations in the outputs of wave models. Following an overview of relevant aspects and recommendations from Soomere (2005), we apply a factor of 0.85 to compute the wind speed at 10 m height at Kalbådagrund.

SWAN forced with modelled high-resolution wind

We relied on wave time series (significant wave height, period, direction, etc.) in the Gulf of Finland calculated using the SWAN wave model, cycle III, version 41.31A, in the setup described by Giudici et al. (2023). The SWAN model (Booij et al. 1999) is a third-generation phase-averaged spectral wave model developed at the Delft University of Technology, the Netherlands. Giudici et al. (2023) implemented a three-level nested scheme of rectangular model grids. The main (first-level) grid covered the entire Baltic Sea (approximately 5500 m), with a resolution of 3 nautical miles (nmi). The results were used as boundary conditions for finer second-level grids, with a resolution of 1 nmi (about 1850 m), which covered the Gulf of Finland and the Gulf of Riga. The third level (Fig. 1) focused on coastal areas in both gulfs, with resolutions varying from 260 to 560 m, depending on the shoreline geometry (Giudici et al. 2023).

The wave simulations were performed for idealised ice-free sea surface. For this reason, we only compared wave properties during ice-free periods. However, actual ice conditions were considered in the production of the modelled wind properties (Giudici et al. 2023). The bathymetry for this and other models was obtained from the databases of the Estonian Transport Administration (personal communication with Peeter Väling in February 2020) and the Latvian Institute of Aquatic Ecology (personal communication with Maris Skudra in February 2020), and the Baltic Sea Bathymetry Database by the Baltic Sea Hydrographic Commission. Hereafter, we refer to this model as the ‘ERA5 suite’.

Delft3D with non-stationary unidirectional wind

Next, we employed the SWAN model, version 40.11, in the Delft3D (WAVE 2013) suite to replicate waves under a variety of non-stationary unidirectional homogeneous (one-point) wind conditions. We intentionally used the default settings of the model, as the aim was to analyse the performance of simple wave models. The same set of computational grids was selected as for the model forced with ERA5 winds. The forcing (one-point) wind was chosen based on measured wind data from nearby meteorological stations. Below, we describe only a selection of results, using the most suitable wind data. These modelled results are referred to as 'D3D'.

Fetch-based SPM model

Prior to the advancement of spectral wave models, several simple semi-empirical wave models and wave prediction nomograms were used in coastal engineering already in the 1950–1960s. A popular example, known as the significant wave method or the SPM method (after a series of Shore Protection Manuals, e.g. USACE 1984), followed the original fetch-limited equations by Sverdrup, Munk and Bretschneider (see e.g. Massel 2013). For this reason, similar models are often referred to as SMB-type models (Barua 2005). In practical applications, the main challenge for such models, given the irregular coastline and bathymetry of a water body, was the accurate description of effective fetch length for each wind direction. Additionally, the choice of depth parameters (in shallow water cases) and the influence of wind measurement properties (e.g. wind instrument altitude) needed to be considered. Traditionally, fetches were described as the headwind distances from the nearest shores for different wind directions. Sometimes, an algorithm was applied to take into account basin properties in a wider wind sector (Tolvanen and Suominen 2005; Massel 2014). Nevertheless, these relatively simple models were able to deliver reasonably good and quick results, specifically in semi-enclosed medium-sized water bodies and big lakes (Seymour 1977; Huttula 1994), where the memory time of the wave fields was relatively short.

These models have also been successful in Estonian waters. Suursaar and Kullas (2009) and Suursaar et al. (2010, 2013) proposed an SPM model calibration scheme for the Estonian coastal sea, enabling the model to act as a 'virtual' extension of fixed-point measurements in hindcasts. Wind forcing was taken from the nearest weather station (see overviews by Suursaar 2013, 2015). For point model calibration, the angular distribution of fetches was first measured with a step of 20° from nautical charts for the exact wave measurement location. As it was difficult to assess the exact influences of islands, shoals, and the coastline on waves, the initial comparison of the measured and modelled hourly time series was not satisfactory.

By trying to keep the maximum and average wave heights equal in both modelled and reference series, and minimizing the root mean square deviation (D_{rms}), the iterative calibration procedure eventually yielded the best set of fetches and, in a way, compensated for local wind impediments around the specific weather station. As discussed above, wind (forcing) data derived from coastal measurements are usually far from ideal, i.e. full openness to every direction. The described procedure also appeared to modify the fetches from directions where measured wind speed was restricted or distorted compared to undisturbed wind properties at the wave measuring and modelling site. Finally, by maintaining specific calibration settings for each wind input source and location, it was possible to 'extrapolate' wave conditions beyond the actual measurement time, as long as wind data from the same station were available.

To mimic a simple and fast approach to wave hindcast, we followed the procedure given in Kamphuis (2010), which is based on the Shore Protection Manual (USACE 1984). Below, we refer to this model as 'SPM'. Wave parameters for a particular wind speed and direction were evaluated, using wind data from a neighbouring station. We calculated wave parameters (H_S and T_p) with a one-hour time step. Fetches were measured from nautical maps and considered in ±11° sectors. No model calibration or wind speed tuning was used, as the wave model comparison was meant for arbitrary locations and non-predefined tasks. Presumably, the simple models without any tuning or calibration would deliver results that are much inferior to purposely-calibrated simulations described by Suursaar (2010, 2013, 2015).

Measurements

The longest available recorded datasets of wave properties near Estonian waters are those of Pohjois-Itämeri (northern Baltic Proper, NBP in the research literature, from 1996), Suomenlahti (from 2000), and Suomenlinna (from 2016) in the Gulf of Finland. These data from the FMI webpage (FMI 2023) are used to compare the wave models.

We employed episodically measured wave conditions in the coastal sea of Estonia for model comparisons, which were mostly performed close to coastal geomorphic case study locations (e.g. Suursaar et al. 2008, 2014), using a Recording Doppler Current Profiler (RDCP-600). Altogether, 1624 days' worth of measurements (typically hourly) were obtained in 2003–2014 at ten locations (Suursaar 2013, 2015). In this study, we used the measurements made in the Gulf of Finland (Fig. 1; Table 1). The RDCP-600 applies the Doppler effect to measure flow velocity and is equipped with sensors for temperature, conductivity, oxygen, turbidity, and pressure. The high-accuracy quartz-based pressure sensor (resolution 0.001% of full scale) enables the measurement of wave parameters (Suursaar and Kullas 2009). The self-contained upward-looking instrument was deployed at the seabed by divers, mostly 1–2 km off the nearest shore. The mooring depth varied between 10 and 20 m. Although shorter recording intervals of 10 or 20 min were used in earlier measurements, the interval was usually set to 1 h. One hour is conveniently also the interval for the routinely measured meteorological data used in wave model calibrations and hindcasts. In the RDCP, H_S is calculated based on the energy spectrum. It is the most commonly used wave parameter, coinciding almost exactly with the average height of the 1/3 highest waves for Rayleigh-distributed wave fields (Massel 2013) and matching well with the visually observed average

Table 1. Details about wave measurements. The recordings at Suomenlinna and Suomenlahti were retrieved from the database of the Finnish Meteorological Institute. Other measurements were performed using the RDCP-600

No.	Location	N coordinate	E coordinate	Start	End	Data points	Depth, m
1	Suomenlinna	60.123°	24.973°	04.05.2016	31.12.2020	25970	12
2	Suomenlahti	59.965°	25.235°	26.12.2004	31.12.2020	71666	48
3	Neugrund	59.333°	23.500°	20.11.2009	24.04.2010	3069	14.5
4	Sundgrund	59.250°	23.400°	18.09.2011	10.11.2011	1275	10
5	Suurupi	59.483°	26.667°	10.12.2013	29.04.2014	3351	20
6	Letipea	59.567°	26.667°	10.08.2006	29.09.2014	10875	11.5
7	Sillamäe	59.417°	27.800°	29.07.2009	10.09.2009	1033	12
8	Harilaid	58.467°	21.850°	20.12.2006	23.05.2007	6012	14

wave height (Massel 1989). The instrument also produces several estimations for wave periods.

Results

The model runs were validated by comparing the significant wave height (H_S) and peak period (T_p), calculated using the ERA5, D3D, and SPM suites at different locations in the Gulf of Finland (Fig. 1) with the results of in situ measurements. While the output of ERA5 was meant to adequately represent the wave properties excited by realistic winds, D3D and SPM were forced with non-stationary unidirectional (one-point) wind from different stations. We start by comparing the whole time series of measurements and then focus on waves where H_S as a threshold was ≥0.8 m. Finally, we also select and study single high wave events, because decisions are usually based on extreme events. We focus mainly on H_S, but also briefly comment on T_p.

Significant wave height

When considering the whole modelling period for **Suomenlinna** (2016–2020), it can be seen that the ERA5 suite gives quite good results (H_S bias = 0.30 m, D_{rms} = 0.37 m, R = 0.90). Surprisingly, the SPM model forced with Kalbådagrund wind data yields a better match with the recorded wave properties (H_S bias = 0.11 m, D_{rms} = 0.39 m, R = 0.62) than D3D (H_S bias = 0.50 m, D_{rms} = 0.71 m, R = 0.45). For moderate and high wave conditions (H_S ≥0.8 m), ERA5 (H_S bias = 0.51 m, D_{rms} = 0.58 m, R = 0.61) performs better than the other two models, for which D_{rms} > 0.64 m and R < 0.20.

For the whole modelling period for **Suomenlahti** (2004–2020), the ERA5 suite gives the best results: H_S bias = 0.11 m, D_{rms} = 0.21 m, and R = 0.95. Here, the D3D version forced with Kalbådagrund wind data (H_S bias = –0.03 m, D_{rms} = 0.60 m, R = 0.80) outperforms the SPM model forced with the same wind (H_S bias = –0.27 m, D_{rms} = 0.51 m, R = 0.67). The performance of the D3D and SPM models is slightly worse for higher wave conditions (H_S ≥ 0.8 m). The H_S bias is almost the same for D3D and increases to –0.48 m for SPM, but D_{rms} = 0.24 m for ERA5 vs 0.71 m for both D3D and SPM.

We start the analysis of locally recorded wave conditions from the western Gulf of Finland. Neugrund (155 days of wave recordings) and Sundgrund (48 days) are situated only around 10 km apart from each other. However, the comparison results differ significantly for these two locations.

At **Neugrund**, D3D forced with Kalbådagrund wind data seems to be the best option (H_S bias = 0.06 m, D_{rms} = 0.26 m, R = 0.71), while with ERA5, H_S bias = 0.51 m, D_{rms} = 0.58 m, and R = 0.76. The D3D and SPM simulations forced with wind data from Vilsandi and Pakri (both are located closer to Neugrund than Kalbådagrund) yield slightly worse results than those obtained using Kalbådagrund wind data, but still better than those of ERA5. For higher waves (H_S ≥ 0.8 m) at Neugrund, the D3D suite forced with Kalbådagrund wind data still leads to the best match (H_S bias = –0.23 m, D_{rms} = 0.35 m, R = 0.71), while the match with ERA5 simulations is slightly worse. The D3D suite forced with wind information from Vilsandi and Pakri yields the worst match.

Interestingly, at **Sundgrund**, the ERA5 suite provides a much better match (H_S bias = 0.35 m, D_{rms} = 0.41 m, R = 0.93) than at Neugrund. The use of the D3D suite with Kalbådagrund wind data leads to the following outcome: H_S bias = –0.24 m, D_{rms} = 0.41 m, and R = 0.78. Similar to previously described results, ERA5 tends to overestimate wave heights, while the D3D and SPM models tend to underestimate them. The match of ERA5 output for wave fields with H_S ≥0.8 m is about the same as for all wave heights, while other models lead to worse matches than for all wave conditions.

The ERA5 suite clearly overestimates wave heights at **Suurupi** (H_S bias = 0.35 m, D_{rms} = 0.41 m, R = 0.91). Note that Giudici et al. (2023) present erroneous estimates for this location. The magnitude of the H_S bias is much smaller for the D3D and SPM models forced with Kalbådagrund (0.06 m for both models) and Osmussaar (–0.05) wind data. The D_{rms} of wave heights simulated by the D3D model is 0.33 m and 0.35 m for Kalbådagrund and Osmussaar, respectively, while the SPM model leads to D_{rms} > 0.41 m, which is higher. The attempts of using wind information from other possible locations (Pakri, Dirhami, Harku) yield clearly worse matches with recorded wave data (H_S bias below –0.21 m and D_{rms} > 0.45 m). For higher wave fields (H_S ≥ 0.8 m), the match is about the same for the output of the ERA5 suite. However, the match with the outputs of other models and forced winds is clearly worse. For example, the D3D model forced with Kalbådagrund wind shows that H_S bias = –0.39 m, D_{rms} = 0.52 m, and R = 0.79.

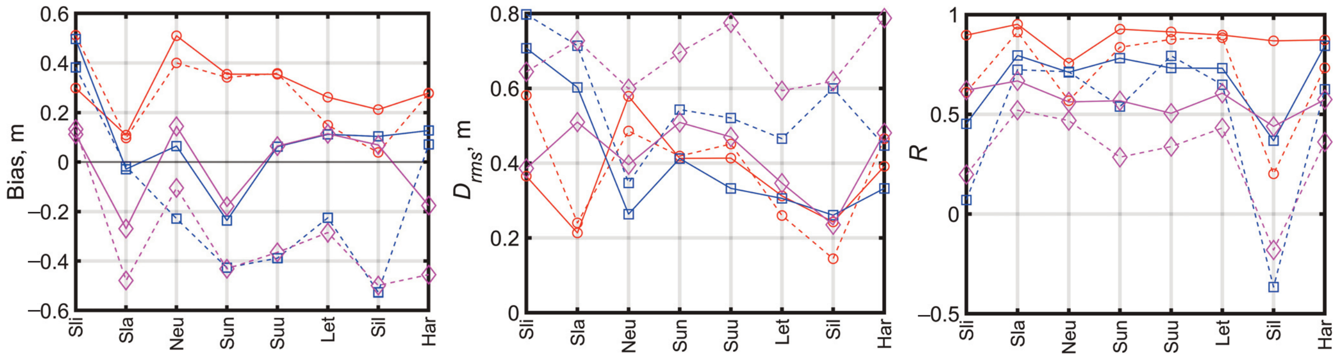

Fig. 4. Bias, root mean square difference (D_{rms}), and correlation coefficient (R) of the recorded and modelled H_S. Continuous line corresponds to all wave conditions, dashed line indicates measured $H_S \geq 0.8$ m, red line with circles denotes modelled results using ERA5, blue line with squares and magenta line with diamonds represent the outputs of SWAN in Delft3D (D3D) and the fetch-based SPM model, respectively, both forced with non-stationary homogenous wind from Kalbådagrund. Abbreviations: Sli – Suomenlinna, Sla – Suomenlahti, Neu – Neugrund, Sun – Sundgrund, Suu – Suurupi, Let – Letipea, Sil – Sillamäe, Har – Harilaid.

For all available recorded wave data at **Letipea** (several sessions in 2006–2014), the ERA5 suite again gives the best match, although overestimating wave heights to some extent (H_S bias = 0.26 m, D_{rms} = 0.31 m, R = 0.90). As this location is relatively close to Kalbådagrund, it is not surprising that the D3D model forced with Kalbådagrund wind data (H_S bias = 0.11 m, D_{rms} = 0.31 m, R = 0.73) outperforms the same model forced with wind data from Kunda (H_S bias = –0.27 m, D_{rms} = 0.44 m, R = 0.62), Narva-Jõesuu (H_S bias = –0.30 m, D_{rms} = 0.45 m, R = 0.71), as well as the SPM model forced with wind data from Kalbådagrund (H_S bias = 0.11 m, D_{rms} = 0.35 m, R = 0.61), Kunda, and Narva-Jõesuu (the latter two not shown here). For stronger wave conditions ($H_S \geq 0.8$ m), the output of the ERA5 suite shows that H_S bias = 0.15 m, D_{rms} = 0.26 m, and R = 0.88. Therefore, the ERA5 suite better represents waves of appreciable height but tends to overestimate the heights of low waves. In contrary, the D3D model forced with Kalbådagrund wind data shows a worse match for such waves: H_S bias = –0.23 m, D_{rms} = 0.47 m, and R = 0.65.

The shortest measurement campaign (43 days) was carried out at the easternmost location, **Sillamäe**. Similar to several occasions above, the recorded waves best matched with the output of the ERA5 suite (H_S bias = 0.21 m, D_{rms} = 0.24 m, R = 0.87), although this model version clearly overestimated wave heights. In contrast, the D3D and SPM models forced with local wind data from Narva-Jõesuu (D3D: H_S bias = –0.14 m, D_{rms} = 0.23 m, R = 0.63; SPM: H_S bias = –0.11 m, D_{rms} = 0.22 m, R = 0.60) yielded better results compared to the runs with wind data from Kalbådagrund (D3D: H_S bias = 0.10 m, D_{rms} = 0.26 m, R = 0.37; SPM: H_S bias = 0.07 m, D_{rms} = 0.24 m, R = 0.44) and Kunda (D3D: H_S bias = –0.12 m, D_{rms} = 0.25 m, R = 0.24; SPM: H_S bias = –0.10 m, D_{rms} = 0.23 m, R = 0.34). As this measurement location is characterised by an almost straight coastline and is completely open to the north, it is expected that the D3D and SPM models produce similar results. For situations where $H_S \geq 0.8$ m, the output of the ERA5 suite shows that H_S bias = 0.04 m, D_{rms} = 0.14 m, and R = 0.20. The match of the outputs of the D3D and SPM models forced with the closest (Narva-Jõesuu) wind data is clearly worse: both models show that H_S bias = –0.71 m, D_{rms} = 0.72 m, and R = 0.53 for D3D and 0.33 for SPM.

To offer insight into neighbouring sea areas, we provide similar estimates for the match of recorded and modelled wave heights at **Harilaid** (several sessions in 2007–2013) in the nearshore of the West Estonian Archipelago in a location that is completely open to the west. In contrast to previous cases, the D3D model forced with nearby Vilsandi wind data gives the best results (H_S bias = 0.13 m, D_{rms} = 0.33 m, R = 0.84). However, the ERA5 suite (H_S bias = 0.28 m, D_{rms} = 0.39 m, R = 0.87) still outperforms the SPM model (H_S bias = –0.18 m, D_{rms} = 0.48 m, R = 0.57). Interestingly, the match for parameters of stronger wave systems ($H_S \geq$ 0.8 m) is worse for all models at this location.

The analysis presented signals that the ERA5 suite tends to systematically overestimate wave heights at all measurement locations, as the H_S bias is consistently over 0 m (Fig. 4). Part of this feature is apparently connected with the tendency to overestimate the heights of low waves. This conjecture is supported by the observation that both the H_S bias and D_{rms} are smaller when only wave heights with $H_S \geq 0.8$ m are considered from wave recordings performed in Estonian coastal waters. However, this is not the case with Suomenlinna, which is apparently site-specific, since it is located near the northern shore of the Gulf of Finland. If, in relatively calm conditions, wave heights in ERA5 are overestimated, this feature eventually translates into the overall wave climate estimates.

It is also notable that the magnitude of the H_S bias and the D_{rms} of wave fields reconstructed using the D3D and SPM models increase when only wave fields with $H_S \geq 0.8$ m are considered. This means that these models mimic milder wave conditions somewhat better than high wave events. This feature may reflect a relatively small impact of bathymetry-driven refraction for low and short waves. Furthermore, as relatively mild conditions are frequent in the Baltic Sea (Soomere and Eelsalu 2014), the inadequacy of replication of severe waves may remain unnoticed.

Interestingly, the D3D model forced with Kalbådagrund wind data gives better results than the ERA5 suite at Neugrund. The H_S bias and D_{rms} are smaller, and the correlation coef-

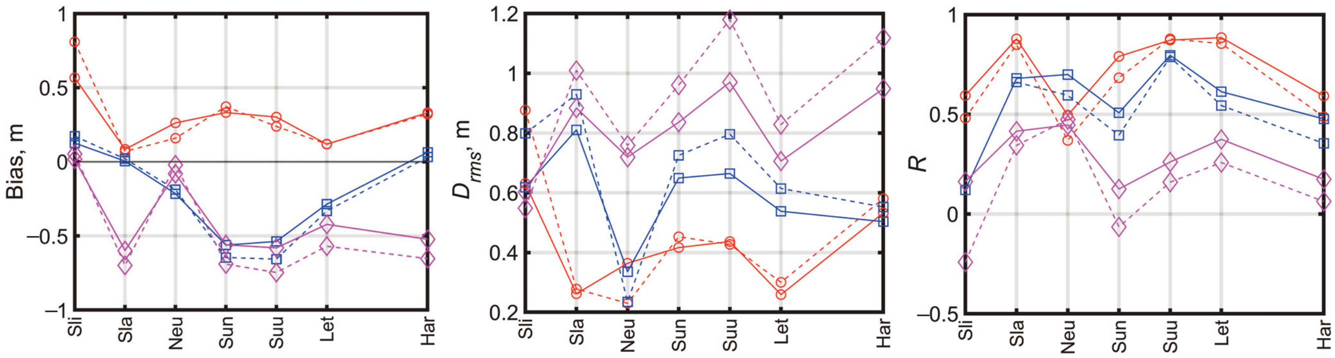

Fig. 5. Bias, root mean square difference (D_{rms}), and correlation coefficient (R) of the recorded and modelled H_S for stronger wave conditions. Continuous line corresponds to recorded $H_S \geq 1.2$ m, dashed line indicates measured $H_S \geq 1.5$ m, red line with circles denotes modelled results using ERA5, blue line with squares and magenta line with diamonds represent the outputs of SWAN in Delft3D (D3D) and the fetch-based SPM model, respectively, both forced with non-stationary homogenous wind from Kalbådagrund. As measurements recorded at Sillamäe contain very few wave conditions with $H_S \geq 1.2$ m, this set is excluded. For abbreviations, see Fig. 4.

ficient is approximately the same. The replications of wave properties by simpler models have a similar quality as provided by the ERA5 suite also in the eastern part of the Gulf of Finland (Sundgrund, Suurupi), although the correlation is weaker and D_{rms} higher than with ERA5. The very weak correlation between recorded higher waves' ($H_S \geq 0.8$ m) properties and those replicated using simpler models at Sillamäe is apparently caused by short time series with waves of mostly modest heights (maximum $H_S = 1.3$ m).

Changes in the adequacy of wave height replication can be, to a first approximation, estimated by gradually excluding lower waves from the analysis. This exercise (excluding first situations where $H_S < 1.2$ m and then $H_S < 1.5$ m; Fig. 5) reiterates the above conjecture that the ERA5 suite performs better than the D3D and SPM models. The only exception is Neugrund, where the D3D model with suitable one-point wind data provides a better match of simulated wave heights than the ERA5 suite.

Wave period

The ERA5 suite replicates the measured peak periods T_p better than other models at almost all locations (Fig. 6) in terms of bias, D_{rms}, and correlation coefficient. The correlation coefficients between the recorded and simulated T_p are much smaller than those for H_S. The match is better for stronger wave conditions with $H_S \geq 0.8$ m. This conjecture matches a similar observation by Giudici et al. (2023) for wave fields with $H_S \geq 0.5$ m. The use of even higher thresholds, such as $H_S \geq 1.2$ m or $H_S \geq 1.5$ m, basically reiterates this conjecture (Fig. 7). Interestingly, the match of recorded wave periods with those replicated using the D3D and SPM models does not improve when only stronger wave conditions are taken into account. The relevant statistical parameters of the match remain almost unchanged (Fig. 6). The only exception is at Neugrund, where the magnitude of the T_p bias and D_{rms} slightly decrease when calmer conditions are excluded.

While comparing the results with those presented in Giudici et al. (2023), it must be noted that they averaged all hourly values of H_S and T_p, whereas in our study, only recorded values matching the timing of simulated values are taken into account, with no averaging over time. This methodological difference does not affect the results for H_S. However, since T_p values are more volatile, the difference in relevant procedures leads to certain discrepancies in the outcomes. For this reason, we only comment on the results for Suomenlinna, where the bias difference is more pronounced.

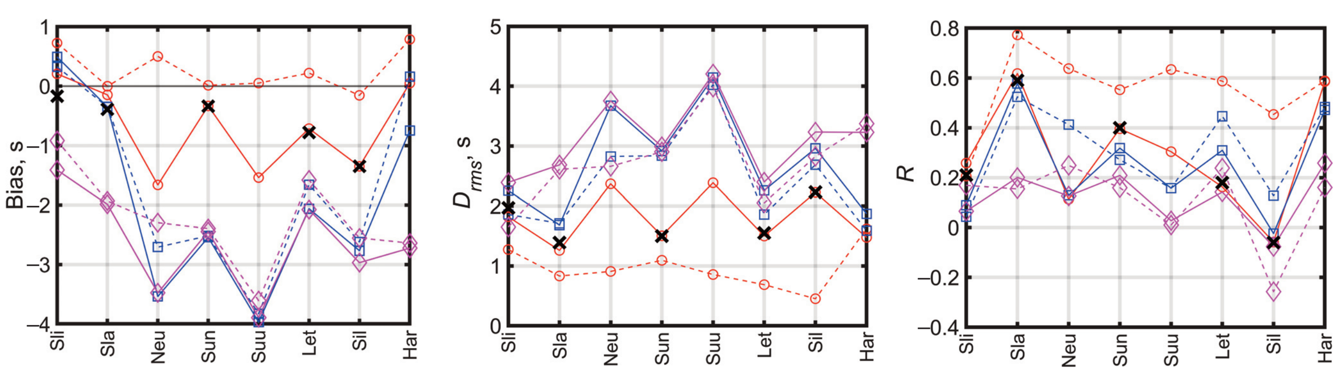

Fig. 6. Bias, root mean square difference (D_{rms}), and correlation coefficient (R) of the recorded and modelled T_p. Continuous line corresponds to all wave conditions, dashed line indicates measured $H_S \geq 0.8$ m, red line with circles denotes modelled results using ERA5, blue line with squares and magenta line with diamonds represent the outputs of SWAN in Delft3D (D3D) and the fetch-based SPM model, respectively, both forced with non-stationary homogenous wind from Kalbådagrund. Black crosses show the results from Giudici et al. (2023). The numbers accompanying the abbreviations of measurement locations indicate the year of the measurement session. For abbreviations, see Fig. 4.

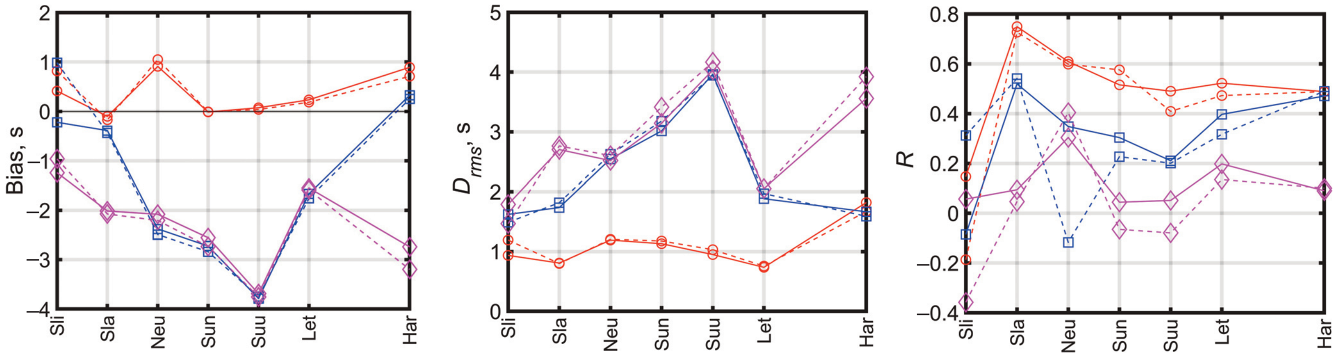

Fig. 7. Bias, root mean square difference (D_{rms}), and correlation coefficient (R) of the recorded and modelled T_p. Continuous line corresponds to measured $H_S \geq 1.2$ m, dashed line indicates measured $H_S \geq 1.5$ m, red line with circles denotes modelled results using ERA5, blue line with squares and magenta line with diamonds represent the outputs of SWAN in Delft3D (D3D) and the fetch-based SPM model, respectively, both forced with non-stationary homogenous wind from Kalbådagrund. As measurements recorded at Sillamäe contain very few wave conditions with $H_S \geq 1.2$ m, this set is excluded. For abbreviations, see Fig. 4.

The ERA5 suite performs better than other models at **Suomenlinna** (2016–2020), where the T_p bias = 0.20 s, D_{rms} = 1.82 s, and R = 0.26. For the D3D model forced with Kalbådagrund wind data, the corresponding values are as follows: T_p bias = 0.49 s, D_{rms} = 2.25 s, and R = 0.09. Giudici et al. (2023) found slightly different values for the years 2016–2021: T_p bias = –0.17 s, D_{rms} = 1.79 s, and R = 0.21. Omitting lower waves ($H_S < 0.8$ m) leads to a decrease in the T_p bias and D_{rms} (to 0.72 and 1.27 s, respectively), but also weakens the correlation to R = 0.21 (Fig. 6). As expected, the match between the recorded T_p and the modelled values is worse for the SPM model than for the D3D model.

Replication of severe wave conditions

The maximum H_S recorded during sessions reflected in Table 1 was around 3.4 m at Suomenlahti in November 2012 (Fig. 8). The output of the ERA5 suite accurately reflects the temporal course of H_S during this wave storm: H_S bias = 0.08 m, D_{rms} = 0.22 m, and R = 0.95. The peak period is also well represented: T_p bias = –0.1 s, D_{rms} = 0.9 s, and R = 0.86.

The match of the recorded H_S values with those simulated using the D3D model forced with Kalbådagrund wind data is less exact but still satisfactory: H_S bias = 0.23 m, D_{rms} = 0.40 m, and R = 0.91. In particular, wave heights at the storm peaks are overestimated by about 0.5 m. The performance of the ERA5 suite is comparable in terms of T_p bias = 0.1 s, D_{rms} = 1.1 s, and R = 0.74. The SPM model forced with the same (Kalbådagrund) wind source performs less satisfactorily. The likely reason is extensive hourly variation in the output time series of H_S and T_p. To a large extent, this variation is caused by the nature of the model, which has no 'memory' of the output wave fields and reacts immediately to any variations in wind properties. In particular, most changes in the forcing wind direction in a sea area of complicated shape may cause an immediate change in the effective fetch length and, therefore, the values of H_S and T_p. In such conditions, a sensible trade-off is provided by the envelope line of short-term maxima of H_S and T_p. These values perform somewhat more reasonably in terms of replicating the peak H_S. The values of T_p are still clearly underestimated, most likely because of the inability to replicate remotely (e.g. in the northern Baltic Proper) generated wave components.

In October 2011, H_S values up to 2.3 m were recorded at Sundgrund (Fig. 9). Although the peak H_S was overestimated

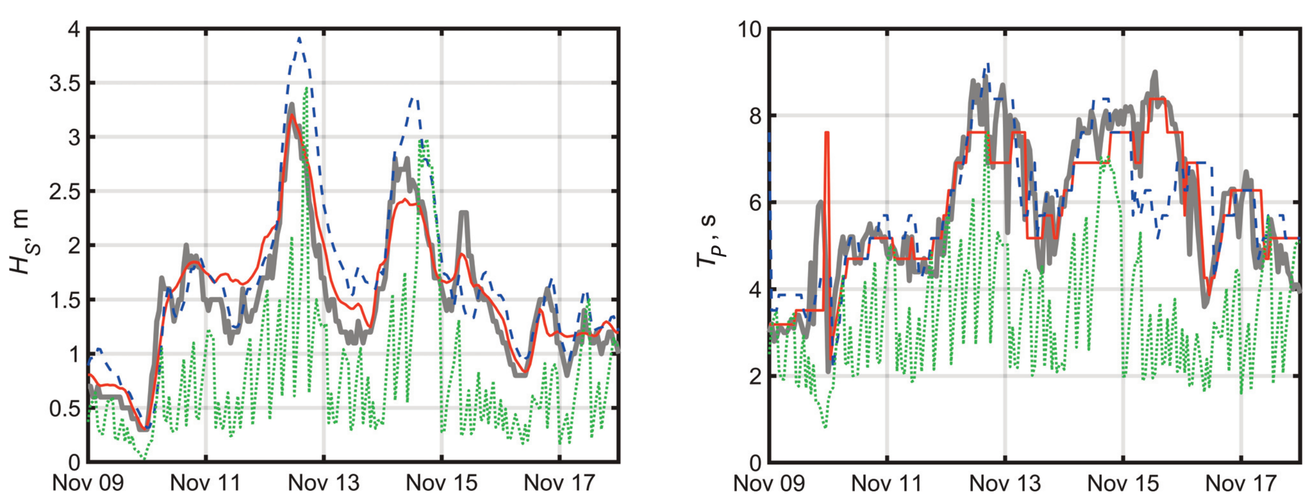

Fig. 8. Significant wave height (left) and peak period (right) at Suomenlahti in November 2012. Grey bold line corresponds to wave measurements, red line indicates modelled results using ERA5, blue dashed and green dotted lines denote the outputs of SWAN in Delft3D (D3D) and the fetch-based SPM model, respectively, both forced with non-stationary homogenous wind data from Kalbådagrund.

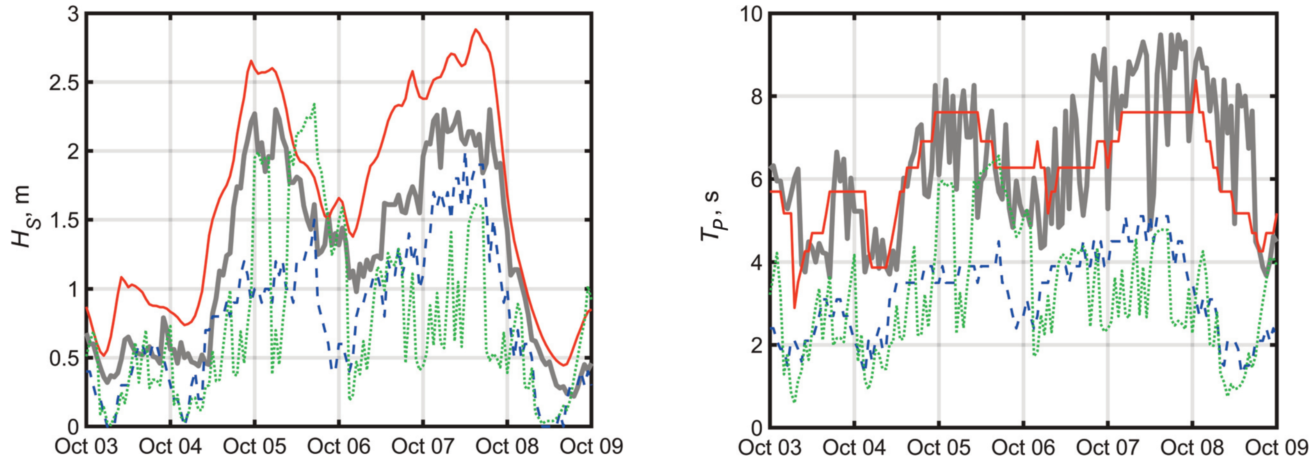

Fig. 9. Significant wave height (left) and peak period (right) at Sundgrund in October 2011. Grey bold line corresponds to wave measurements, red line indicates modelled results using ERA5, blue dashed and green dotted lines denote the outputs of SWAN in Delft3D (D3D) and the fetch-based SPM model, respectively, both forced with non-stationary homogenous wind data from Kalbådagrund.

by the ERA5 suite (H_S bias = 0.41 m), the output of this model has the highest correlation (R = 0.96 for H_S and 0.67 for T_p) and the smallest D_{rms} (0.46 m for H_S and 1.25 s for T_p) among all the models and forcings used. While the D3D and SPM models forced with Kalbådagrund wind data replicate part of the extremes reasonably well, they generally hindcast lower-than-measured values, fail to replicate the timing of H_S peaks, and severely underestimate T_p in this storm.

There were two events with high waves in November 2006 and 2008 recorded in the eastern segment of the Estonian coastline of the Gulf of Finland at Letipea (Fig. 10). In both cases, the maximum H_S values (2.8 and 3.7 m, respectively) were very well replicated by the ERA5 suite. The relevant H_S biases during the time period presented in Fig. 11 were 0.29 and 0.25 m, respectively, with D_{rms} values of 0.41 and 0.32 m, respectively, and $R > 0.93$ for both cases. It seems that the ERA5 suite overestimates wave heights in relatively calm conditions. The output of the D3D model forced with Kalbådagrund wind data had even smaller H_S biases (about 0.07 m in 2006 and 2008) but larger D_{rms} values (0.66 and 0.38 m, respectively) and weaker correlation (R = 0.61 and 0.93, respectively). These values are basically on the same level or even better (bias) than those for the ERA5 suite. However, the D3D model fails to represent the peaks, falling short by at least 0.5 m, whereas in 2006, the timing of the H_S peak is incorrect. The match of the SPM model output with the recorded data is clearly worse (Fig. 11), even though this is not clearly visible in the statistical parameters (H_S bias = –0.02 m in 2006 and –0.12 m in 2008, D_{rms} = 0.63 and 0.53 m, respectively, and R = 0.62 and –0.86, respectively). Peak periods (not shown here) are reasonably well reflected by the ERA5 suite (T_p bias = 0.06 s in 2006 and –0.86 s in 2008, D_{rms} = 1.15 and 1.23 s, respectively, and R = 0.61 and 0.88, respectively). The quality of the replication of peak periods is clearly worse in the D3D and SPM models, whereas local maxima are not represented at all.

The maximum recorded H_S at Sillamäe in October 2009 was well below 1.5 m (Fig. 11). While the ERA5 suite reasonably replicated wave properties during these events, the use of wind data from Narva-Jõesuu to force the D3D and SPM models showed a generally better match with the recorded wave properties than the use of Kalbådagrund wind data. Only during a high wave event did the models forced with Kalbådagrund wind data show a better match. The peaks of

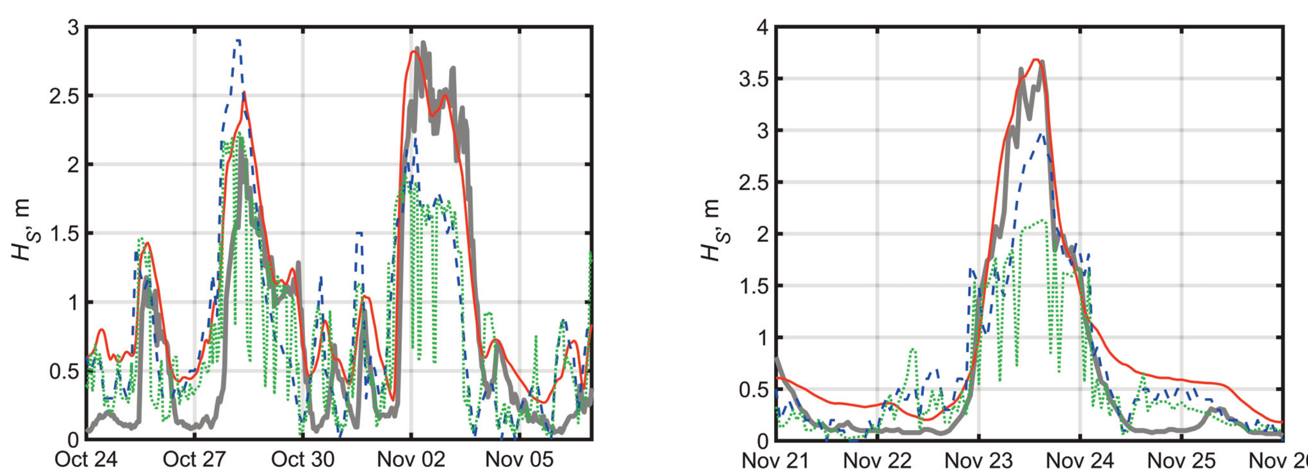

Fig. 10. Significant wave height at Letipea in autumn 2006 (left) and November 2008 (right). Grey bold line corresponds to wave measurements, red line indicates modelled results using ERA5, blue dashed and green dotted lines denote the outputs of SWAN in Delft3D (D3D) and the fetch-based SPM model, respectively, both forced with non-stationary homogenous wind from Kalbådagrund.

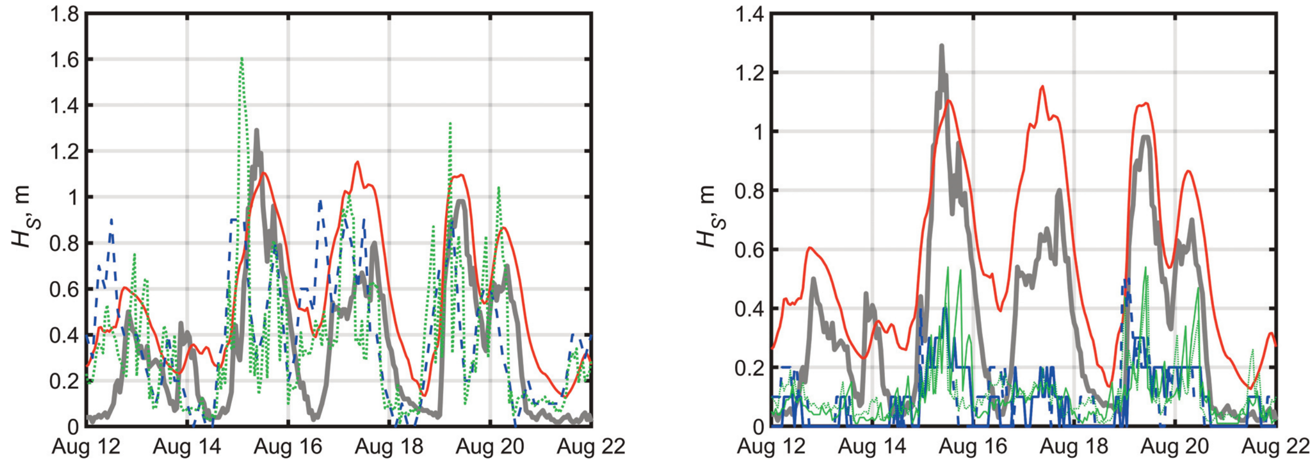

Fig. 11. Measured significant wave heights at Sillamäe in August 2009 (grey bold line) and modelled results using ERA5 (red line). Left graph: modelled results using SWAN in Delft3D (blue dashed line) and fetch-based SPM model (green dotted line) forced with Kalbådagrund wind. Right graph: modelled results using SWAN in Delft3D (blue continuous and dashed line) and fetch-based SPM model (green continuous and dotted line) forced with Narva-Jõesuu and Kunda winds, respectively. Even though the difference between the dashed and continuous blue and green lines is hard to distinguish, it shows that results forced with Narva-Jõesuu and Kunda winds are considerably smaller.

H_S are, to some extent, overestimated by the ERA5 suite and other models forced with Kalbådagrund wind data, but the use of winds from Narva-Jõesuu and Kunda fails to reach the peaks at all (Fig. 11). The wave periods are consistently underestimated (T_p bias about –2 s) by the D3D and SPM models.

To complete the analysis, we note that the ERA5 suite also overestimates H_S at Harilaid during the strongest wave event recorded in this location (H_S bias = 0.41 m, D_{rms} = 0.63 m, R = 0.73). However, the highest H_S peak is represented quite well (Fig. 12). Interestingly, the match of the H_S values modelled using the D3D model forced with local (Vilsandi) wind data with the recorded wave heights is of the same or even better quality (H_S bias = 0.17 m, D_{rms} = 0.54 m, R = 0.70). This suggests that this model could work well in the nearshore of an open coast if forced with high-quality wind data from the neighbourhood. In contrast, the SPM model leads to a clearly worse match (H_S bias = –0.56 m, D_{rms} = 0.92 m, R = 0.36), even though some maxima are mimicked well. As observed in several occasions above, the match of simulated T_p with recorded values is considerably worse.

Discussion and conclusion

The performed analysis primarily confirms, as expected, that contemporary third-generation wave models implemented at a high resolution and forced with state-of-the art modelled wind data, such as ERA5, generally replicate basic wave properties quite well, even in nearshore areas with complex bathymetry and geometry, such as the Gulf of Finland or the northeastern Baltic Proper. In most cases, they perform clearly better than less advanced models in terms of basic statistical parameters (bias, root mean square deviation, and correlation coefficient) when matching recorded and hindcast significant wave heights and peak periods. Although these models tend to overestimate wave heights at all measurement locations, they should be the baseline choice for wave modellers and (coastal) engineers for the detailed evaluation of local wave climate and for the specification of design parameters for coastal and offshore structures.

However, as relevant computations are highly demanding in terms of implementing these models, including feeding them with wind data and performing calculations, it is natural

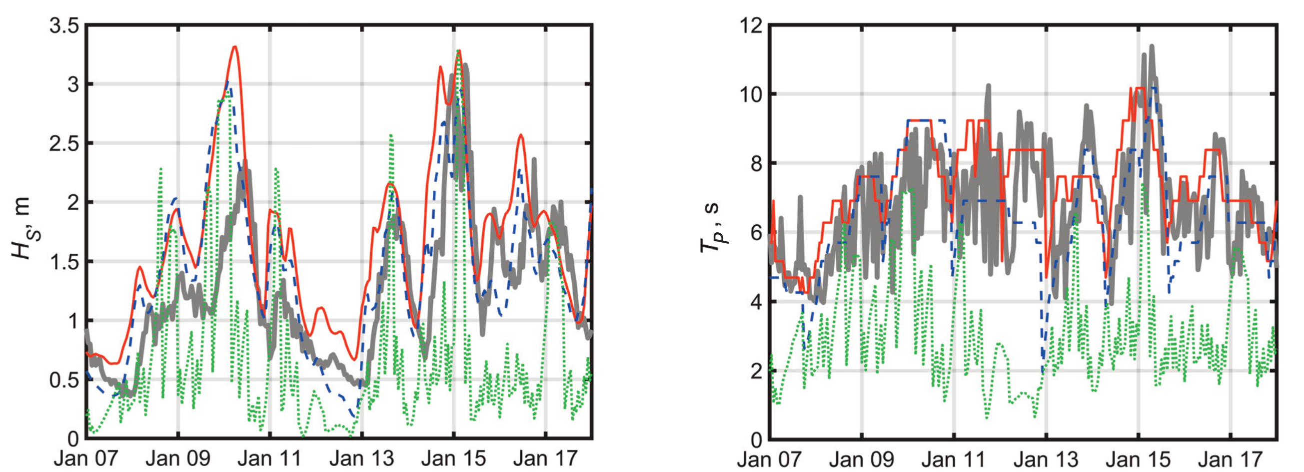

Fig. 12. Significant wave height (left) and peak period (right) at Harilaid in January 2007. Grey bold line corresponds to wave measurements, red line indicates modelled results using ERA5, blue dashed and green dotted lines denote the outputs of SWAN in Delft3D (D3D) and the fetch-based SPM model, respectively, both forced with non-stationary homogenous wind from Vilsandi.

to consider the output of third-generation models as a reference (or a kind of substitute or 'ground truth') for the calibration and validation of simpler models when wave measurements are unavailable. This strategy is particularly feasible in sea areas with complex shapes, where the numerical replication of wind conditions remains a challenge, and the use of local (measured) wind data may be preferable for achieving more reliable results.

Similar models, forced with high-quality one-point winds from the vicinity of the location of interest, are integral components of various commercial software packages and thus less demanding in terms of implementation. These models provide faster options for calculations and can be tuned to represent local, possibly specific wind conditions. Intriguingly, the performance of these models is basically the same or even better for significant wave heights at several locations along the southern nearshore of the Gulf of Finland and the northeastern Baltic Proper. The core component of their good performance is the availability of high-quality in situ offshore wind data at a reasonable distance (up to about 100 km) from the location of interest. Thus, models forced with Kalbådagrund wind data may be preferred at several locations (Harilaid, Neugrund, Sundgrund, Suurupi) west of Tallinn, Estonia, compared to the implementation of the above-described state-of-the-art model systems and their forcings. However, a clear disadvantage of these models is their lower accuracy in replicating wave periods compared to full models forced with ERA5 wind data.

Among various simplified models, systems that adequately evaluate time evolution of spatial wave parameter distributions, even when forced with one-point winds homogeneous across the entire computation area, have a clear preference over classic (now almost obsolete) parametric wave models, such as the Sverdrup–Munk–Bretschneider type (fetch-based) models and their derivatives (such as the SPM model discussed in this paper) that do not contain any memory of wave fields. An obvious limitation of such models is that modelled local wave properties immediately react to changes in wind speed and direction. Thus, replicated wave properties may contain extensive spurious zig-zag fluctuations even if the model adequately follows average wave conditions. This feature is particularly problematic in elongated, relatively narrow basins, such as the Baltic Sea or the Red Sea, where even small shifts in wind direction may translate into major changes in fetch length and therefore also in hindcast wave properties. This challenge can be suppressed to some extent (though not entirely removed) by using a smoothed (weighted) directional resolution to specify effective fetch lengths. Another option is to calibrate the simple model for a specific location using wave measurements, and the results would improve markedly (e.g. Suursaar et al. 2014).

Another shortage of the D3D and SPM models (with default settings) is their inability to replicate peak periods across virtually all wave conditions in the study area. The bias between modelled and recorded peak periods is usually about 2 s. This feature may stem from the frequent presence of longer waves generated in the Baltic Proper. Furthermore, these models often fail to ensure proper timing of wave storm maxima, even when they reasonably replicate the peaks themselves.

Having said that, it is noteworthy that hindcasts for the easternmost Gulf of Finland at Sillamäe using simpler models often well represent time series of wave properties. However, the analysis presented here signals that achieving good accuracy in the whole time series does not necessarily guarantee the right choice of wind source. The shortages of wave models become most evident during storms.

For practical purposes, it seems to be safe to use simple one-point wind to force the D3D or SPM models for rough estimates of design parameters of smaller projects. The threshold for a 'small' project depends on local conditions. In the study area, projects with a total cost of less than one million euros between Harilaid and Suurupi could be considered as small. However, the outcome should be interpreted in the light of established deficiencies in estimating wave periods accurately. For more expensive projects, wave measurements during the windy season and comparison with more sophisticated models are necessary. For projects with investments exceeding 2 million euros, at least two years of measurements should be carried out. The general recommendation is that for all locations, the results of simple models should be compared with the outputs of sophisticated models when measurements are unavailable.

Acknowledgements

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Kas lihtsate lainemudelitega saadud tulemused Soome lahes on kasutatavad ja võrreldavad keerukamatega?

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Rannikul ja meres paiknevate rajatiste projekteerimise üheks võtmetähtsusega aluseks on rajatise piirkonnas esineva tavalise ja ekstreemse lainetuse parameetrid. Nende mõõtmine ja analüüs on kallis ja pikaajaline protsess. Praktikas on tihti tarvis otsustamiseks nende kiiret ja samal ajal adekvaatset hinnangut. Selleks on eri aegadel tarvitatud väga erinevaid mudeleid, alates nn parameetrilistest (mereala suuruse ehk tuule jooksumaa ja kohaliku tuule omaduste alusel lainetuse omadusi hindavatest) mudelitest kuni kaasaegsete kõrglahutusega tuuleinfot rakendavate täisspektraalsete lainemudeliteni, nagu WAM või SWAN. Võrdleme kolme eri laadi tuuleinfot rakendava, erinevat tüüpi mudeli pakutavat laineinfot Soome lahe kaheksas kohas mõõdetud lainetuse omadustega. Küsime, kas lihtsa, tuule jooksumaa pikkusele ja ühes kohas mõõdetud tuule omadustele tugineva mudeli pakutud tulemused on võrreldavad kaasaegse lainemudeli SWAN abil rekonstrueeritud lainetuse omadustega ning millist lisaväärtust pakub see, kui SWAN kasutab kvaliteetset ERA5 tuuleinfot. Võrdlus selgitab, millise kvaliteediga olid varasematel aegadel lihtsate mudelitega tehtud lainekliima omaduste ja muutuste hinnangud ning millistel tingimustel ja kus võiks rahulduda lihtsate mudelitega. Näitame, et Soome lahes annavad lihtsad mudelid hea ettekujutuse lainekõrgusest, kuid hindavad lainete perioodi *ca* 2 s võrra lühemaks. Mõnes kohas annab kvaliteetse kohaliku tuuleinfo kasutamine paremaid tulemusi kui isegi väga hea modelleeritud tuuleinfo. Keskne järeldus kordab klassikalist sõnumit: lainetuse omaduste rekonstruktsiooni headuse määrab eelkõike kasutatud tuuleinfo kvaliteet.