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Evaluating accuracy of Baltic Sea wave forecasts

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Abstract

Accurate prediction of surface waves in the Baltic Sea is crucial for enhancing the safety and efficiency of maritime transport. Over the years, the accuracy of wave forecasts in this area has seen considerable improvement and has proven reliable for forecast windows of 2 to 3 days. However, the issuance of warnings for marine operations often requires longer forecast ranges. This study investigated the forecasting accuracy over a longer time frame of 4 to 6 days and assessed its effectiveness in issuing warnings for moderate and severe wave conditions. To achieve this, we have evaluated the high-resolution wave forecasts for the Baltic Sea available at the Copernicus Marine Services Monitoring Forecasting Centre (BAL MFC) against buoy and altimeter data. Our analysis demonstrates strong agreement between the model predictions and the observed data for shorter forecast ranges. Nevertheless, starting from the third day of the forecast, there is a growing bias in the values of significant wave height. The underestimation becomes more pronounced on the last day of the forecast, with significant wave heights underestimated by approximately 10% compared to buoy data and 20% compared to altimeter data. Part of this underestimation was addressed to the forecast system setup that used the combination of Harmonie and ECMWF winds. As the wind-wave coupling was tuned to Harmonie winds, which without tuning lead to overestimation of significant wave height, it affected negatively the longer forecasts using ECMWF wind forcing. To access the forecast ability to predict high-sea wave events, a 4-meter threshold was employed, aligning with Finnish Meteorological Institute wave warning. The results of two cases show that forecasts 84, 96, and 120 hours in advance provide valuable insights for effective warning issuance.

Keywords: Baltic Sea; sea surface waves; forecasting; warnings; BAL MFC; Copernicus Marine Service

1 Introduction

Wave forecasting in the Baltic Sea using third-generation wave models started in the late 1990s (e.g., *Tuomi et al.*, 1999; *Nielsen et al.*, 2002) and since then a lot of development has been done in terms of improving wave model physics, applying subgrid scale parameterisations and moving towards higher spatial and spectral resolution. Although the accuracy of the first operational Baltic Sea wave forecasting systems was relatively good in open sea areas, the resolutions used back then were not sufficient to resolve the coastal archipelago areas. Also, the first forecast system did not account for the seasonal ice conditions of the Baltic Sea.

The quality of the forecast improved significantly when resolution was increased and methods that account for unresolved islands and ice conditions were implemented (e.g., *Tuomi et al.*, 2014; *Björkqvist et al.*, 2017a; *Tuomi et al.*, 2019). Further advances were gained by coupling with a 3D ocean model, especially in the near-coastal areas (e.g., *Kanarik et al.*, 2021; *Tuomi et al.*, 2023). A summary of the Baltic Sea wave forecast and hindcast models and their development can be found in *Soomere* (2022).

Recently, there has been discussion about whether increasing spatial resolution or providing ensemble forecasts would be the best way to improve the capabilities of Baltic Sea wave forecast systems. Due to limitations in computational power, advancing simultaneously both of these options might not be feasible. According to *Schmith et al.* (2018) the choice depends on the focus of the forecast system. The open sea areas of the Baltic Sea were estimated to benefit more from providing ensemble forecasts, whereas improving the accuracy in coastal areas would require an increase in grid resolution.

The open sea areas of the Baltic Sea can experience a severe wave climate. According to *Björkqvist et al.* (2017b), from the time the wave buoy was first deployed in 1996 until 2017, the northern part of the Baltic Proper recorded a significant wave height of 8.2 metres, with heights exceeding 7 metres occurring four times. More recently, the Northern Baltic wave buoy recorded two additional instances of significant wave heights exceeding 7 metres on 10 February 2020, and 22 November 2023. Also, in the Bothnian Sea, the measured record value reaches 8 m (*Björkqvist et al.*, 2020). Having the ability to accurately forecast high wave events is important for the safety of maritime traffic and offshore activities. Several Meteorological Institutes issue warnings of high sea states as part of their weather warning services to alert of approaching dangerous weather events. The Finnish Meteorological Institute (FMI) issues warnings on dangerous or hazardous phenomena in Finland. For waves, there are two warning categories effective all year around: moderately high ($H_s > 4\,\mathrm{m}$) and high ($H_s > 7\,\mathrm{m}$) wave conditions. During the summer season, an additional category for leisure boating ($H_s > 2.5\,\mathrm{m}$) is issued. FMI's warnings are given 5 days ahead, since several marine operations require information about potentially harmful weather conditions well in advance. Typically, duty forecasters use several datasets, including observation and model data from both national and international sources, when issuing warnings.

Many of the earlier studies in the Baltic Sea have evaluated the quality of the first 6–12 hours of the forecast length, which is quite natural to studies intended to improve the capabilities of the modelling system. While these studies have greatly improved our wave forecasting capabilities in the Baltic, they do not provide information about the accuracy of the longer forecast lengths, which are typically more dependent on the accuracy of the forcing wind fields (e.g., *Signell et al.*, 2005; *Christakos et al.*, 2020). However, for issuing warnings and ensuring safety on the seas, the accuracy of longer forecast lengths is essential.

In this paper, we focus on the accuracy of the wave forecast up to 5–6 day forecast lengths and estimate their capability to provide sufficiently accurate information for issuing warnings. We focus on the exceedance values in the FMI warnings for moderate and severe wave conditions. As source data, we use the Copernicus Marine Service's Baltic Monitoring and Forecast Centre's (BAL MFC) wave forecasts with 6 day forecast length for the Baltic Sea. We estimate the overall accuracy of the forecasts and then focus on a few specific cases relevant to issuing wave warnings.

2 *Materials and Methods*

2.1 *Wave model*

We used a forecast from the Copernicus Marine Service's Baltic Sea wave analysis and the forecast product `BALTICSEA_ANALYSISFORECAST_WAV_003_010` (*EU Copernicus Marine Service Product*, 2023a) available twice a day (00 and 12 UTC). The longer forecast lengths are not stored in the Copernicus Marine Service database, but for the purposes of this study, we stored them for Baltic Sea wave buoy locations for the period of 26 January 2021 – 22 September 2022. In addition, the whole wave field was stored once a day from 00 UTC forecasts for the time period of 21 April – 11 October 2022.

The wave forecast system was based on WAM cycle 4.6.2 (*WAMDIG*, 1988; *Komen*, 1994). The wave spectra comprised 36 directions and 35 frequencies between 0.041 77 Hz and 1.067 19 Hz. The source terms used for wind input are from P. A. E. M. *Janssen* (1989, 1991), white capping dissipation from *Bidlot et al.* (2005, 2007), weak nonlinear wave-wave interactions from *Hasselmann et al.* (1985), and depth-induced wave-breaking dissipation from *Battjes and* J. P. F. M. *Janssen* (1978)[1]. Small islands, unresolved by the size of the model grid, are taken into account using the obstruction grids described in *Tolman* (2003) and *Tuomi et al.* (2014).

The wind forcing for the forecasts is compiled from two different sources, namely: MetCoOp-HARMONIE Numerical Weather Prediction (NWP) system with a horizontal resolution of 2.5 km (first 66 hours) and ECMWF deterministic forecast with a horizontal resolution of 9 km (from hour 67 onwards up to 6 days). The reason behind this type of setup was to use the higher resolution and accuracy product at the beginning of the forecast. A more detailed system description is given in the Product User Manual (*Tuomi*, 2020).

Copernicus Marine Service also provides information on the accuracy of the product through the Product Quality Dashboard (`https://pqd.mercator-ocean.fr`) and the Quality Information document (*Vähä-Piikkiö et al.*, 2020; *Kanarik and Tuomi*, 2023). The quality information document is provided as part of each major update to the model system and describes the quality of the best estimate time series since the pre-operational runs are done in hindcast mode. Product Quality Dashboard, on the other hand, continuously follows the quality of forecast production at different forecast lengths during production. Generally, the accuracy of the first 6 hours of the forecast is good. According to *Vähä-Piikkiö et al.* (2020), the bias against the observations of the Baltic Sea wave buoys was -0.02 m, RMSE 0.20 m, and SI 0.22. However, in comparison with altimeter

[1] Since October 2022, the forecast product provided by Copernicus Marine Services has been updated to new version. For updates, see Chapter II: Product system description in *Kanarik and Tuomi*, 2023.

measurements, it was shown that the model setup had some challenges in the shallower, near-coastal areas, where the significant wave height was overestimated, contrary to the validation against wave buoys, which are located in the central areas (Fig. 2.1).

2.2 *In-situ measurements*

For validation of the wave forecasts, we used data from the Baltic Sea wave buoys including five FMI wave buoys: Bothnian Bay (BB), Bothnian Sea (BS), Gulf of Finland (GoF), Nothern Baltic Proper (NBP), and one Swedish Meteorological and Hydrological Institute (SMHI) wave buoy: Finngrundet (FG). The buoy locations are shown in Fig. 2.1. All of these buoys are Datawell Directional Waveriders and provide significant wave height, peak period, and mean direction at the spectra peak. Data were acquired from the Copernicus Marine Environment Monitoring Service (CMEMS) portal (`https://marine.copernicus.eu/`, *EU Copernicus Marine Service Product*, 2023b). But they are also available from national open data services (`https://en.ilmatieteenlaitos.fi/open-data`, see also the web interface for data download [in Finnish]: `https://www.ilmatieteenlaitos.fi/havaintojen-lataus`).

The measurement period in the northern Baltic Sea is limited due to seasonal ice cover. The buoys need to be recovered well before the ice season, to reduce the risk of icing and contact with the ice floes. During the period in question, measurements were not available from the GoF wave buoy between 18 January – 1 April 2021, and in the next winter between 29 January – 4 March 2022. From BB there were no buoy measurements from 9 January – 6 June 2021, and again between 25 November 2021 – 5 June 2022. Due to mild ice winters, BS and NBP have recorded data throughout the year. Finngrundet buoy records were unavailable from 2 February 2021 – 28 April 2021, but the buoy measured throughout the winter 2021/2022.

2.2.1 *Altimeter data*

To get a better overview of the spatial accuracy of the forecasts we used satellite altimetry data obtained from CMEMS portal (`WAVE_GLO_WAV_L3_SWH_NRT_OBSERVATIONS_014_001`, *EU Copernicus Marine Service Product*, 2023c), for the period March – October 2022. During that time, data from six satellites are available: Jason-3 (J3), Sentinel-3A (S3A), Sentinel-3B (S3B), Saral-AltiKa (AL), CFOSAT (CFO), Cryosat-2 (C2), and Hai Yang-2B (H2B). This dataset is produced and quality checked by the Copernicus Marine Service's WAVE Thematic Assembly Centre (WAVE-TAC, *Taburet et al.*, 2023). WAVE-TAC has masked the data for land and ice contamination. As these datasets cover the entire world, we performed additional checks for the Baltic Sea tracks by checking the data for sudden jumps along the altimeter track near the coast and even checking the events with a large difference to modelled fields. No data rejection was needed for any of the datasets used.

For validation, we only considered altimeter measurements east from 13° E, thus excluding the Skagerrak and Kattegat regions from the analysis. Each altimeter measure-

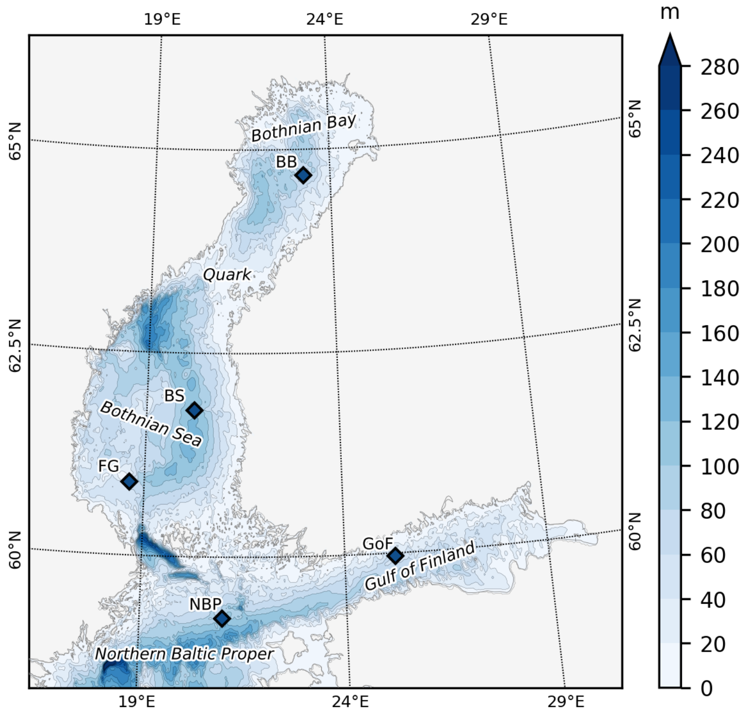

Fig. 2.1: Northern Baltic Sea bathymetry and basins with five wave buoys (marked with blue diamonds) located in the study area.

ment was compared to the closest model grid point with a maximum time difference of 30 minutes.

2.3 Model Validation and Error metrics

To quantify the forecast errors the following four metrics were used: bias value (Bias), root mean square (RMSE), Correlation Coefficient (R) and scatter index (SI)

$$\text{Bias} = \frac{1}{N}\sum_{\mathrm{i}=1}^{N}(m_{\mathrm{i}} - r_{\mathrm{i}}) \;, \tag{2.1}$$

$$\text{RMSE} = \sqrt{\frac{1}{N}\sum_{\mathrm{i}=1}^{N}(m_{\mathrm{i}} - r_{\mathrm{i}})^2} \;, \tag{2.2}$$

$$R = \frac{\text{cov}(m,r)}{\sqrt{\text{var}(m)\,\text{var}(r)}} \;, \text{and} \tag{2.3}$$

$$\text{SI} = \frac{\text{RMSE}}{\bar{r}} \;, \tag{2.4}$$

where m and r are the model and records (buoy or altimeter) value respectively, and N is the total number of records. The overbar refers to the mean value, and cov denotes covariance and var variance. The metrics for the Baltic Sea are calculated using individual buoy locations and satellites.

3 Results

3.1 Validation of wave forecasts

Validation of the wave forecast against wave buoy data indicated a positive bias ranging from 0.02 m to 0.03 m during the first 60 hours of the forecast, which then shifted to a negative bias (see Table 3.1 and Fig. 3.1). The bias increased towards the end of the forecast, reaching −0.14 m for the 133–144 hour forecast lengths. The change of sign in the bias occurs close to the 66 h forecast length, at which point the wind forcing changes from MetCoOP Harmonie to ECMWF forcing. Throughout the forecast period, both the root mean square error and the scatter index showed a steady increase, while correlation displayed a declining trend.

As the wave buoys are located primarily in the central parts of the basins, we validated the forecast against altimeter data, which offers broader spatial coverage, including nearshore areas. In contrast to buoy validation, the bias was negative for the entire forecast, from around −0.1 m during the first 48 hours and increasing to −0.2 m by the 144 h forecast length. Furthermore, Fig. 3.1 shows a larger variation in the bias between altimeters compared to the buoys. Although the accuracy of the altimeters has been demonstrated to be reliable in the Baltic Sea (e.g., *Kudryavtseva and Soomere*, 2016), there exist differences between the two types of observations. Most altimeters in the CMEMS product show a slight overestimation of H_s compared to in situ measurements (*Taburet et al.*, 2023), reflecting the bias compared to validation against buoys. Also, it can be seen in Fig. 3.1 that one of the altimeters (S3A) showed different performance compared to the others with lower correlation. As Sentinel 3 missions are rather new, further calibration and validation activities might still be necessary to achieve better accuracy in the Baltic Sea area. Both Sentinel 3 missions (S3A and S3B) also show the largest bias and RMSE compared to the other altimeters during the study period. The altimeters also provide data closer to the coastal areas, and part of the differences may also be related to differences in the wave model performance between the coastal and open-water areas. As wave buoys are retrieved from the sea during the ice-covered period, they do not represent the quality of the model during winter. Satellites can also have measurements of the wave field from the ice edge. If the satellite has many measurements of events when the wave model had ice at the nonoptimal location, it can be revealed as lower quality metrics.

Although the comparison shows a deterioration in forecast quality with increasing forecast length, the bias is not large even for the longer forecast lengths. However, the increase in RMSE and SI indicates a large scatter in the results, which can also be seen in the scatter plots presented in Fig. 3.2. The comparison against buoy data showed that there is a certain small percentage of good matches even for longer forecast lengths. But many cases show large under- or overestimation, of several metres, of H_s. A similar change in accuracy in terms of forecast length was also seen when comparing the altimeter data (Fig. 3.3).

Table 3.1: Comparisons of significant wave height skill metrics between the Baltic Sea forecast against buoy data for the period corresponding to January 2021 – September 2022 (00 and 12 UTC forecasts), and against Altimeter data for the period between April 2022 and October 2022 (00 UTC forecasts).

Parameter	Forecast range	N	Bias (m)	RMSE (m)	R	SI
H_s (Buoy)	1 – 12 h	45 306	0.02	0.19	0.97	0.19
	13 – 24 h	45 342	0.02	0.21	0.96	0.22
	25 – 36 h	45 346	0.02	0.24	0.95	0.25
	37 – 48 h	45 390	0.03	0.28	0.93	0.29
	49 – 60 h	45 414	0.02	0.32	0.91	0.32
	61 – 72 h	45 433	−0.02	0.34	0.88	0.37
	73 – 84 h	45 462	−0.10	0.41	0.84	0.47
	85 – 96 h	45 489	−0.11	0.45	0.80	0.53
	97 – 108 h	45 513	−0.10	0.45	0.75	0.58
	109 – 120 h	45 540	−0.12	0.54	0.71	0.64
	121 – 132 h	45 556	−0.13	0.59	0.64	0.71
	133 – 144 h	45 463	−0.14	0.63	0.59	0.77
H_s (Altimeter)	1 – 24 h	65 594	−0.10	0.23	0.91	0.29
	25 – 48 h	65 595	−0.10	0.27	0.88	0.34
	49 – 72 h	65 279	−0.11	0.30	0.84	0.39
	73 – 96 h	65 078	−0.16	0.37	0.77	0.50
	97 – 120 h	64 846	−0.16	0.43	0.69	0.60
	121 – 144 h	64 533	−0.20	0.52	0.53	0.77

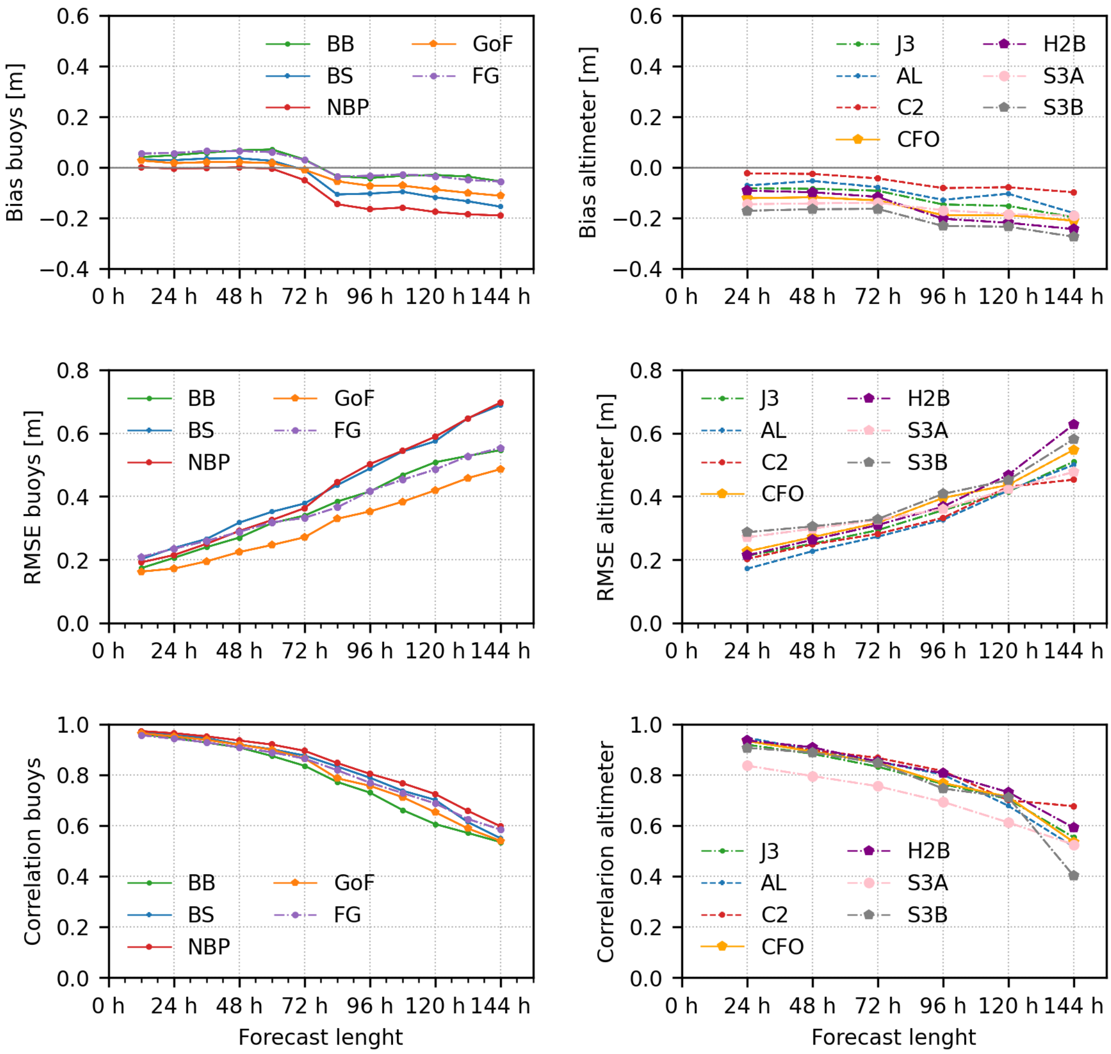

Fig. 3.1: Error metrics as a function of forecast time. Results are shown for all satellite and buoy records available for the Baltic Sea.

3.2 *High wave events*

The accuracy of the forecasts is important, especially for high-wave events that can play an important role in the safety and efficiency of maritime traffic and other offshore activities. Therefore, we took a closer look at the H_s values exceeding 4 m at each buoy location (Fig. 3.4). For shorter forecast lengths, the H_s is slightly overestimated with, e.g., bias of 0.21 m for the 1–12 hour forecast lengths. This is significantly larger than the bias over the entire H_s range, 0.02 m. The largest individual absolute differences between the buoys and the forecast were slightly less than 1.7 m for the 1–12 hour forecasts, increasing to -4.2 m for the longest forecast range 131–144 h (Fig. 3.4). Overall, the skill of the forecast for issuing warnings is on the same level up to 2 days and gradually starts to decrease after that.

High-wave events are relatively rare in the Baltic Sea. For example, according to (*Björkqvist et al.*, 2024), there are less than 10 events a year in the northern Baltic Proper,

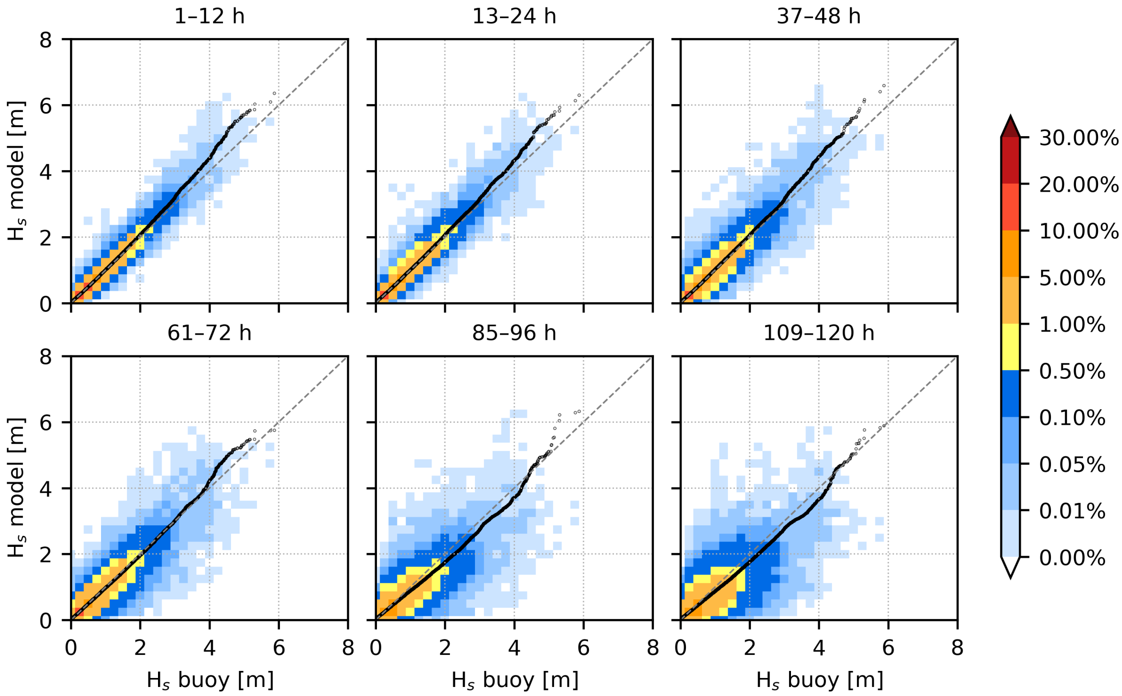

Fig. 3.2: Scatter plots comparing modelled and measured wave height (H_s) at Baltic Sea for period of 26 January 2021 – 22 September 2022.

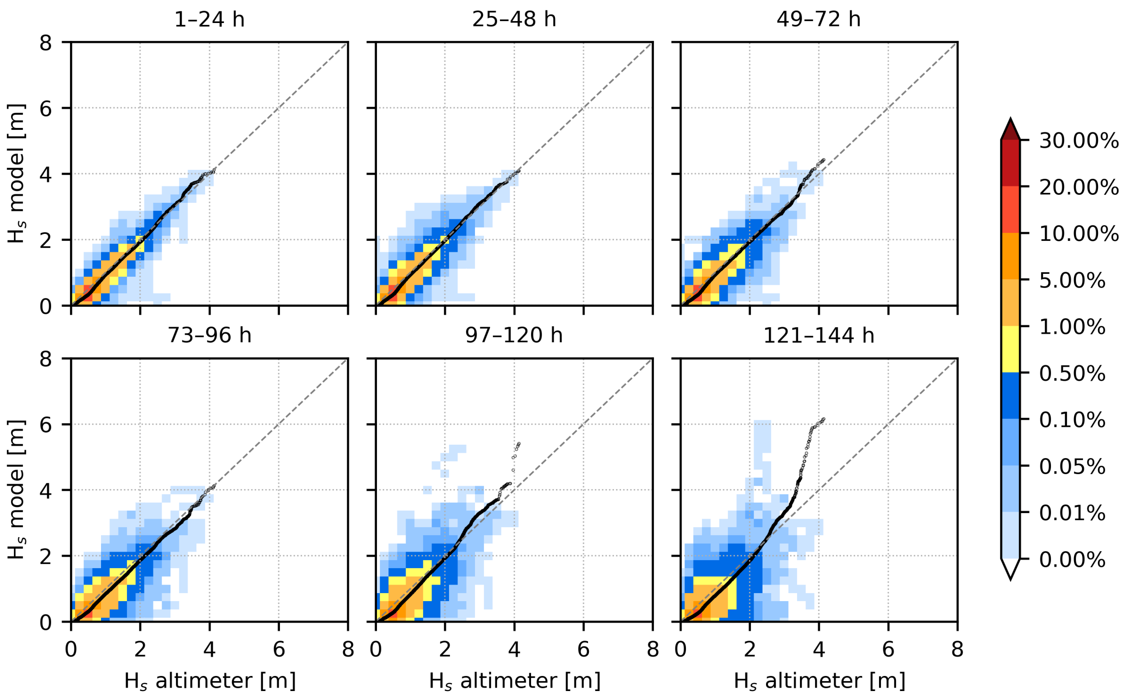

Fig. 3.3: Scatter plots comparing modelled and altimeter wave height (H_s) at Baltic Sea for the period of 21 April – 11 October 2022.

where H_s exceeds 4 m and their median duration was around 8 hours. As described by *Tuomi et al.*, 2011, the most severe wave conditions are typically in late autumn and early

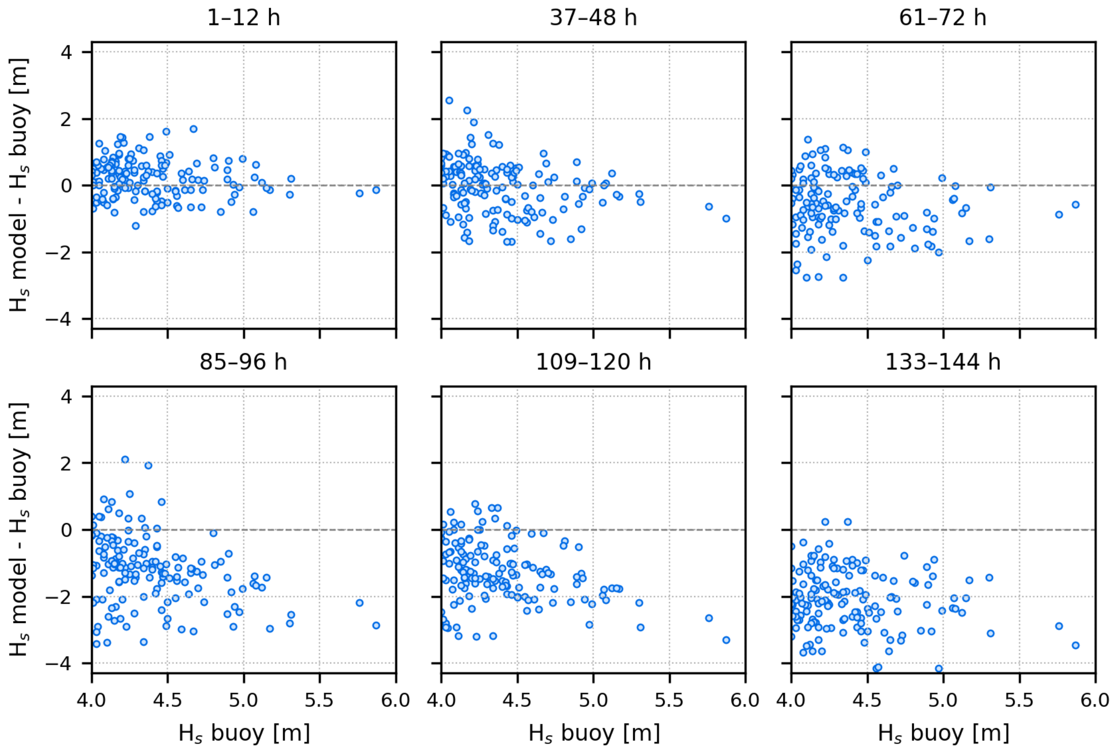

Fig. 3.4: Bias between model and measurements of cases where buoy has measured over 4 m significant wave height

winter. Of the northern Baltic Sea areas, where FMI issues warnings, these conditions are most often exceeded in the northern Baltic Proper and Bothnian Sea (see Fig. 2.1 for the locations of the Baltic Sea sub-basins). In the following, we focus on a few specific cases in these areas. Table 3.2 shows the events in which 4 m was exceeded at each of these buoys during the period in question. In addition, the maximum value of H_s during events and the exceedance time for the significant wave height greater than 3 m are presented in the table. From these events, we chose two for a more detailed inspection, namely 20 January 2022 for the Bothnian Sea area and 29 January 2022 for the northern Baltic proper.

3.3 High waves on 20 January 2022

On 20 January, at 10 UTC, the wave buoy located in the Bothnian Sea recorded a H_s value of 4.9 m. The forecast lengths of 1–12 hours, given for this event, were able to accurately predict the duration of the storm, but H_s was overestimated by them. The maximum value of the 12 hour forecast was 0.7 m higher than the measured one. The 24 and 48 hour forecasts showed quite a good match with the observations, although they slightly underestimated the peak of the event (Fig. 3.5 and Table 3.2).

The longer forecasts were not as skilled in the timing of the peak of the event as the shorter-range forecast. Although all of them eventually exceeded 4 m H_s during the event, the timing of the peak was delayed by several hours. Considering the effectiveness of these forecasts for issuing warnings, the longer-range forecasts (72 hours and beyond) were able to predict that H_s would exceed the 4 m threshold, with a delay between 2–4 hours. However, the short-range (12 h and 24 h) forecast predicted the higher waves with precision on time, except for the 48 h forecast that estimated the threshold would be reached an hour earlier than it occurred, and the 60 h forecasts that predicted the highest wave one hour after the measurement record.

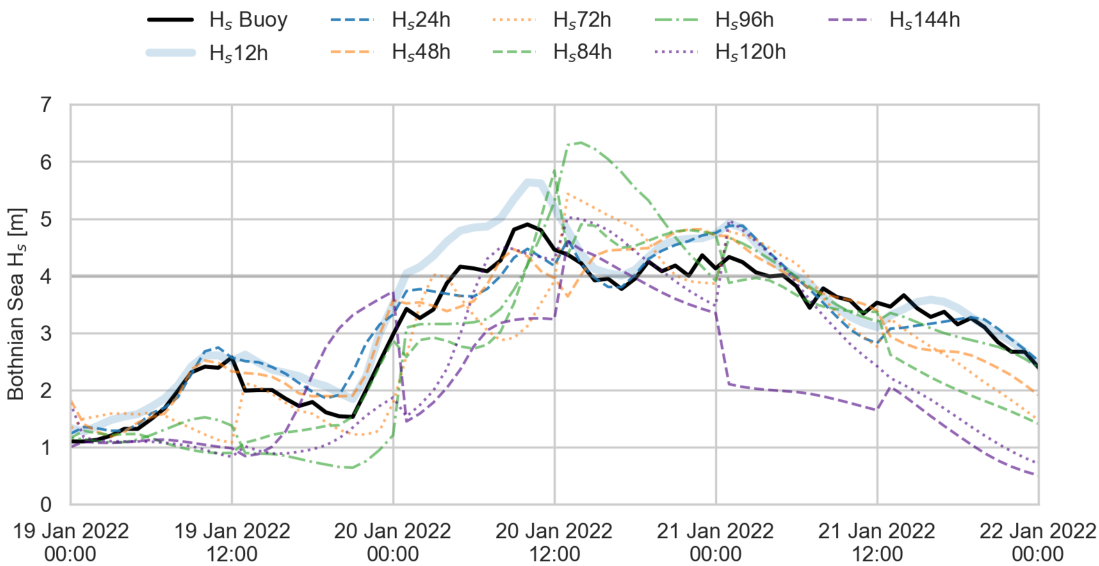

Fig. 3.5: Forecasts for the significant wave height (H_s) in BS wave buoy (shown in Fig. 2.1).

3.4 High wave event on 29 January 2022

On 29 January, in the Northern Baltic Sea, according to buoy records for that area, H_s reached 4.4 m at about 15 UTC and H_s fluctuation between 3 m to 4 m persisted for 32 hours (Fig. 3.6 and Table 3.2).

The increase in H_s, the highest peak and the duration of the event were accurately predicted by the shorter forecast lengths of 12 and 24 hours. However, they overestimated the H_s at the later stage of the event, by 1 m.

Considering the use of these forecasts to issue warnings, the forecast duration of up to 120 hours provided a good overview of the sea state conditions in this event. Although these forecasts were less precise in terms of significant wave height and storm duration than the shorter-range forecasts, they would have led to an accurate indication of the occurrence of the event. Only the longest forecast length, 144 h, failed to forecast the conditions.

4 Discussion and summary

Evaluating whether the accuracy of the forecast is sufficient to issue warnings is not necessarily an easy task. Duty forecasters base their decisions on several different sources

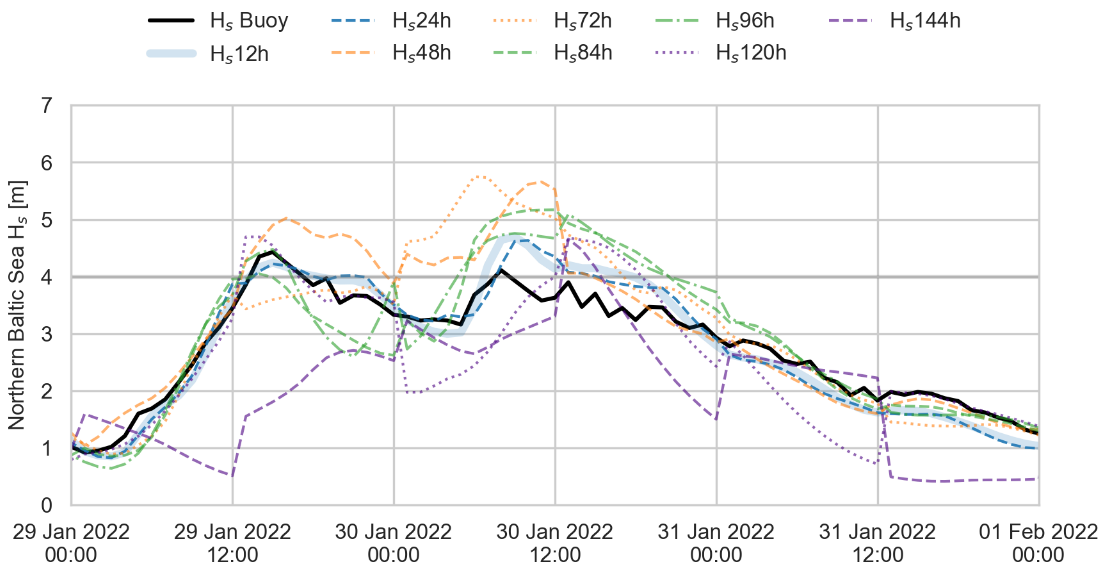

Fig. 3.6: Forecasts for the significant wave height (H_s) in NBP wave buoy (shown in Fig. 2.1).

and their expert knowledge. They often have first-hand experience with the performance of the different wind and wave forecasts and can account for known biases and specific known performance on certain types of high wind or storm situations. However, it is useful to assess the accuracy of longer wave forecasts in the Baltic to better understand their ability to be used to increase maritime safety.

The validation of the forecasts against wave buoys showed that the quality of the short-range forecast was good up to 2 days, the bias being almost the same, and with slightly increasing root mean square error (RMSE) and scatter index (SI), and lowering correlation. The longer forecast ranges showed a large bias and greater scatter, with similar results seen with comparison against altimeter data.

There was a clear shift in accuracy at about 3 days forecast length. This was attributed to the shift in the wind forcing from MetCoOp Harmonie to ECMWF at the 66th hour of the forecast. Although the combination of Harmonie and ECMWF forecasts can be justified by providing higher accuracy for the beginning of the forecasts, it might not be the optimal choice for the quality of the longer forecasts. Wave forecast models are typically tuned to account for the known biases in wind forcing (e.g., *Rascle and Ardhuin*, 2013; *Akpinar and Ponce de León*, 2016). Throughout the forecast, the tuning is typically kept the same. As using Harmonie winds leads to an overestimation of the H_s values, the wave forecast system was set up to compensate for this, leading to better accuracy for short forecast ranges. However, this tuning leads to an underestimation of H_s, when using ECMWF winds. This suggests that when wind forcing from different sources is combined, a more careful tuning should be made to consider both forcing datasets. Also, in case longer forecasts (over 2.5 days) are the main interest, it might be better to use data solely from one system to reduce the effects of unoptimal tuning. The analysis made in this paper are based on a model system that was operational from November 2020 to the end of November 2022. Since then, several improvements have been made to the BAL

Table 3.2: High wave events ($H_s \geq 4$ m) during January 2022

Station	Data	Date	Time	max H_s	$H_s \geq 3$ m
Finngrundet	Buoy	20 January 2022	12:00	4.5 m	22 h
	Forecast 12h	20 January 2022	10:00	4.9 m	26 h
	Buoy	30 January 2022	09:00	4.4 m	17 h
	Forecast 12h	30 January 2022	10:00	6.0 m	16 h
Bothnian Sea	Buoy	14 January 2022	09:00	5.1 m	24 h
	Forecast 12h	14 January 2022	10:00	5.5 m	24 h
	Buoy	17 January 2022	05:00	4.1 m	7 h
	Forecast 12h	17 January 2022	05:00	4.0 m	8 h
	Buoy	20 January 2022	10:00	4.9 m	35 h
	Forecast 12h	20 January 2022	10:00	5.6 m	35 h
	Buoy	30 January 2022	09:00	4.7 m	11 h
	Forecast 12h	30 January 2022	12:00	4.9 m	8 h
Northern Baltic Proper	Buoy	14 January 2022	11:00	4.5 m	18 h
	Forecast 12h	14 January 2022	16:00	5.8 m	17 h
	Buoy	29 January 2022	15:00	4.4 m	32 h
	Forecast 12h	29 January 2022	15:00	4.2 m	31 h

MFC wave forecast system, including upgrades of the model version and the physics package (see the system description of the updated product in *Kanarik and Tuomi*, 2023) that enhance the accuracy of the system compared to what has been presented here. Also, Numerical Weather Predictions systems are constantly improving, affecting the accuracy of wave forecasts. Although the results presented in this paper do not present the capabilities of the current operational BAL MFC wave system, they describe the overall behaviour of the accuracy as a function of forecast length.

The period we used for evaluation is not long enough to get a comprehensive view of the capabilities of the forecast system, especially concerning the high wave events, which are relatively rare. However, it serves as a good example of the capabilities of longer deterministic forecasts for the Baltic Sea. The high-wave events studied in this paper demonstrated that longer forecast ranges exhibit reasonable skill for issuing wave warnings. Although the timing of the peak of the event and the value of H_s at the peak of the event were not as accurate as those for short-range events and all high-wave events were not captured by the longer forecasts, in many cases they provide reasonably accurate data to improve the safety of maritime traffic and offshore activities in the Baltic Sea.

Author contributions

The study was initiated by LT. Data analysis and figures were done by DA under the guidance of HK. AJ contributed to the analysis of severe weather events and issuing wave warnings and provided information on the analysis as a duty forecaster. The manuscript was prepared by DA, LT, and HK with contributions from all coauthors.

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