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Interactive comment on "Better Baltic Sea wave forecasts: Improving resolution or introducing ensembles?" *by* Torben Schmith et al.

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Response to Anonymous Referee #1 with authors responses marked with *

1 General comments The paper addresses a topical issue in the operational oceanography in the marginal seas – whether to introduce ensemble forecasting. The Authors have run the wave model WAM for the Baltic Sea with different horizontal and spectral resolutions and different atmospheric forcing to study whether one should increase resolution or introduce ensembles to provide better forecast accuracy. The question is interesting, but one would expect a more thorough and systematic approach in building and introducing the model and forecast system configurations and in analysing the results. It has been long known, although not perhaps explicitly said, that the open

sea areas of the Baltic Sea, where the shallow water effects can be neglected, do not much benefit of reducing the grid size. That said, there are several areas, where the high resolution is important to solve the shallow water effects and address the effects of islands and irregular shoreline on the wave fields.

* It may be common knowledge that for most areas in the Baltic Sea wave forecasts will not benefit from (further) decrease of the grid size, '..although perhaps not explicitly said'. It is not clear to us, what the intention of this remark is; we find it a perfect motivation for our study.

Due to the small size of the Baltic Sea, the wave field is dominated by the wind waves and the accuracy of the wave forecast is largely dependent on the accuracy of the atmospheric forcing. Therefore comparing systems run with wind forcing from different NWP systems to address the question about choosing between ensembles and resolution is not entirely valid. Also the earlier studies the Authors refer to in the discussion most likely have different/older versions of the WAM model. Therefore the differences or non-differences cannot directly be connected to resolution or the atmospheric forcing. And also, if the time periods used in verification are relatively short (2-3 years) and different ones, the inter-annual variability in the wind conditions might also affect the accuracy. I'd expect more discussion about these subjects.

* We agree that wind waves dominate the Baltic Sea and therefore comparing wave forecasts driven by wind forcing from different NWP-systems will not be entirely valid. However, due to an unfortunate error in table 1, there is a misunderstanding about the wind forcings in our study. We will explain this below and will revise the manuscript and in particular table 1 accordingly. Discussion of length of verification period will be included in the revised manuscript. Btw., our three-years verification period is not short compared to other published work. For instance, (Bunney and Saulter 2015) use eight months, (Pezzutto et al. 2016) use seven months, and (Cao et al. 2009) use 12 months.

The only driving factor in reducing the grid size in the open sea wave modelling is not the accuracy of the wave forecast. There might also be other factors. For example coupling of wave and 3D ocean models might benefit of having high enough resolution. Same applies also for atmosphere – wave coupling. Furthermore, the benefits of higher resolution come also when using high-resolution wind fields nowadays available for the Baltic (e.g. HARMONIE with 2.5 km resolution), which are not possible to get full benefit from if wave model resolution is coarser. I'd also like to see more discussion related to these subjects.

* We will include a discussion of higher resolution required by two-way coupling to atmospheric model and ocean model.

* We agree that increasing the horizontal resolution of the NWP-system may lead to better wind forecasts, due to better descriptions of processes in cyclones, etc. This does not necessarily dictate that the wave model should be run at the same high resolution. We will include some discussion on this.

Also, I think that the title should include indication, that you are focusing on the open sea, deep water areas.

* We will change the title to emphasize the focus on the open sea.

Is same wind forcing used both for HIGH and LOW NSB grids? This is not explicitly said in the manuscript. And is the forcing used the deterministic ECMWF or the HIRLAM wind field? Table 1 mentions both HIRLAM and ECMWF and Table 2 only states that one ensemble member is used as forcing, but not indicated whether the 1 ensemble is the ECMWF or HIRLAM deterministic forecast or something else. If HIRLAM is used for the HIGH and LOW NSB grids, then you are comparing wave model results with different NWP forcings against each other. Is it then question about resolution or different wind forcings? I suggest that you run both HIGH and LOW NSB grids using the control forecast from the ECMWF ENS system and compare the difference between them and the LOWENS to find what type of effects the resolution and introducing en-

sembles causes to the system. Furthermore, it is of course interesting to see, if with higher resolution wind forcing (e.g. HIRLAM) the results would further improve. If and when you use the HIRLAM forcing for the wave models, please specify, how you process the wind fields with 3 km resolution to the wave model grid with 5 km (and/or 10 km) resolution.

* All configurations in the NSB-domain are forced with wind from the DMI-HIRLAM NWP-system. For the HIGH and LOW configurations the horizontal resolution is 3 km, while for the LOWENS it is 5 km. The ECMWF-forced North Atlantic domain is deterministic in all cases, and serves only as boundary data.

* Unfortunately, there was an error in in table 1 in the submitted manuscript and this table will in the final manuscript be modified to: Table 1 Specifications of DMI-WAM nested setup. Domain North Atlantic North Sea/Baltic Sea Longitude 69W-30E 13W-30E Latitude 30N-78N 47N-66N Atmospheric forcing ECMWF GLM Hirlam S03/S05 Boundary condition JONSWAP Nested Bathymetry Rtopo Rtopo/IOW/GEO

* We will include a sentence on how the 3/5 km HIRLAM wind fields are transformed to 5 and 10 km WAM grids by bilinear interpolation

Also, you should separately check, what can be addressed to spectral resolution and what to grid resolution. And also please check other parameters than SWH, for example it would be interesting to see, if there are affects to wave periods or directions, when using higher spectral resolution. Checking the effect of changing spectral resolution and grid size separately. This could certainly be interesting, but would require a lot of additional work. The scope of this work is to intercompare the performance of different operational configurations, rather than idealised studies aiming at isolation effects.

* Verification analysis of wave period and wave direction, although not as extensive as for significant wave height, will be included in the revised manuscript. One example would be to show scatter diagrams as the one shown in Fig 1.

When looking through the supplement material, I was bit confused, why Arkona and Vahemadal were chosen to be the stations shown in the manuscript. E.g. looking Fig S2 Finngrundet, Nothern Baltic, Huvudskar show that HIGH gives lower rmse in many cases for the higher (of over 3 m) significant wave heights than LOW or LOWENS. If the lower rmse of LOWENS over longer forecast ranges come mainly from forecasting smaller than 3 m SWH it might not be that useful for duty forecasters. This type of conditions typically do not affect the marine traffic or the offshore structures, it is the extremes. Therefore it would be important to see how the different forecast systems behave in high wave conditions. The time period used in this study contains at least the January 2017 storm. It would be interesting to see a detailed comparison of the results during this storm and also in some other high wind events.

* Vahemadal was chosen because it stands out against all other stations in the analysis (HIGH forecasts performs better for this station), and Arkona because for this station, together with Darss Sill, the ENSMEAN performed significantly better than the other forecast classes. For the four last stations, the ENSMEAN perform best, but this result is not statistically significant. We will follow the referees' suggestion and show stations representing the three different situations. Remember, however, that for SWH above 3 m there are few observations/forecasts and the statistics becomes very uncertain, as shown by the large error bars on fig. S2, and also mentioned in the text.

* Introducing the 11 January 2017 'Toini' storm as a case is a good suggestion. We vill devote a section to this in the revised manuscript, including and discussing the plot shown in Fig 2 of SWH during January 2017, 48 hour forecast for Northern Baltic.

It is good that the Authors have shown that with ECMWF ENS forcing the accuracy of the wave forecasts is ok in the open sea areas of the Baltic Sea. I suggest that the authors do the more comprehensive model runs suggested above and also more detailed analysis of the results and also discuss the advantages and disadvantages of each system more thoroughly. Furthermore, it would be interesting to see how much skill the ensemble forecasts have for longer forecast period. To my experience, there is

not much spread in the ensembles for the first two or three days and the true benefits of the ensemble system and probabilistic forecast usually comes with longer forecast ranges. It would be interesting to see up to which forecast lengths the ensemble system shows skill in forecasting the Baltic Sea wave conditions both in average and extreme conditions.

* As explained above, our runs are all forced with DMI-HIRLAM ensembles, and therefore they only reach 48 hour forecast time.

* The experience that the benefits of an ensemble system shows up after three days only is contrary to our results (Fig S1), where the effect of ensembles for some stations shows up from about 36 hours.

Please also see my specific comments given below.

2 Specific comments 2.1 Introduction Lines 29-35: I'd expect that the concept of deep and shallow water waves is introduced here, since this is one of the key issues in the discussion of the results.

* Agree, we will do that in the revised manuscript.

Line 33: Bathymetry is important only if waves interact with bottom.

* Agree, we will make a more precise formulation

Lines 29-25: How about weak non-linear wave-wave interactions?

* Agree, (Non-linear) wave-wave interaction should be mentioned here

Lines 41-42: Seasonal ice conditions vary quite a lot in the Baltic. Perhaps this description refers to an average ice winter?

* Yes, this is included to remind the reader that sea ice is an issue in the Baltic Sea.

Line 51-52: Is Baltic Sea shallow considering the average wave conditions? If then the use of higher resolution should make a difference, which is not in agreement with the conclusion drawn by the Authors later on. Baltic Sea is shallow compared to the Oceans, but when considering the typical wave periods/lengths in the Baltic, in most cases waves in the open sea areas are deep water waves, expect for high and extreme wave conditions.

* We agree that we use ‘shallow sea’ in two different meanings throughout the manuscript 1) as opposed to the deep world ocean, and 2) the small water depth allows the wind waves to sense the bottom. This is confusing and we will clarify this in the revised manuscript

2.2 Model and setup This section needs restructuring. All information needed is basically given, but the order of things and the fact that some information is only given in Tables and the table is not referred in the corresponding place in text makes it difficult to follow.

* We will restructure our section 2.2 to make it more understandable.

Also please define explicitly, which wind forcing is used for LOW and HIGH configurations. Table 3 indicates that deterministic ECMWF forcing is used for the coarse, larger domain and HIRLAM (and possibly also ECMWF?) for the smaller high resolution domain.It is not clear to me if this Table refers to DMI operational setup or for the setup used in this paper.

* We will clarify the wind forcing in the different configurations, as explained above (table 1).

Lines 73-77: Please specify the source terms and formulations used in the model runs.

* Source terms are described on page 93-99. We will consider extending the description a bit.

Lines 78-82: Specify the horizontal resolution of the areas already here or cite a Table where they are given. I also suggest adding the resolution info to Table 1.

* Horizontal resolutions are given in Table 2, which we will refer to.

Line 88: Specify the various sources used to compile the bathymetry

* We will specify these extra various sources.

Line 121-122: You use only 11 members of the total 50 available from ECMWF. How do you select, which members you use?

* As explained above, we use DMI-HIRLAM atmospheric ensemble forcing, of which 11 ensemble members are run at routine basis at DMI. The ensembles are generated by perturbing a number of processes, e.g. cloud physics, which do not have a direct impact on the wind field. A subset of 11 ensembles was recommended by the DMI-HIRLAM ensemble developers to cover the spread in surface wind.

Table 2: It is unclear to me what the column ‘Ensemble members’ mean for LOW ad HIGH.

* ‘1’ means deterministic forecast. We will replace by ‘-‘.

2.3 Observations Why not use Helsinki wave buoy data from Gulf of Finland? This should be available through CMEMS. Helsinki site mostly represent deep water conditions and it would be interesting to see, how the setups behave there compared to Vahemadal.

* Helsinki wave buoy does not have many valid data in our verification period, compared to the stations used, see plot in Fig 3. Therefore it is not included.

Table 3 gives only model depth at the buoy locations. It would be important to know also the actual depth at the buoy locations to evaluate, whether the model is adequately able to account for the deep and shallow water features in the wave field.

* We will list the actual water depths in table 3.

It is bit unclear to me, what is the function of Figure 3. The details are lost here, since the images are so small. If they area meant to represent the overall description of the wave conditions at each site, please also (or maybe instead) give some description in the text. And if it is to show the gaps in the measured data, that could be put in a table.

* We will put Figure 3 in the supplementary information; we think the reader should have the opportunity to see which data series were actually used. In the main text we will replace figure 3 by a table showing fraction of swh-height intervals in m to give the reader a feeling of the data: 0-1 1-2 2-3 3-4 4-5 ArkonaWR 0.47 0.39 0.12 0.01 0.00 BothnianSea 0.46 0.38 0.12 0.02 0.01 DarsserSWR 0.67 0.31 0.02 0.00 0.00 FinngrundetWR 0.69 0.27 0.04 0.01 0.00 Knollsgrund 0.62 0.31 0.06 0.01 0.00 NorthernBaltic 0.39 0.37 0.18 0.05 0.01 Vahemadal 0.78 0.20 0.02 0.00 0.00

2.4 Verification Give some explanation, why you have selected Bothnian Sea, Arkona and Vahemadal stations for more detailed analysis

* As explained above, we will explain why we choose these stations.

I also suggest doing some verification of the forcing wind fields.

* We will find and properly cite exsisting verification of HIRLAM. We think that doing extra verification of HIRLAM is a paper in itself and beyond the scope of this work.

In addition to verifying the general accuracy, I'd expect to see some verification of high wind/wave events. They are the most important ones to forecast accurately considering the marine traffic and offshore structures.

* Sections 5.1.1 (RMSE and BIAS as function of SWH) and 5.3 (Brier score verification) are already verifications of high wave events. In addition we will include a qualitative intercomparison of the Jan 2017 storm, as stated above.

I would also expect more discussion of the importance of wind field accuracy on the accuracy of the wave forecast. The accuracy of wave forecast in the open sea areas might not benefit from higher resolution in the wave model grid, but what about when the wind forcing has high resolution, such as the HARMONIE forecasts run for the

Baltic with 2.5 km resolution in several of the MET services. In order to account for the benefits of this, higher resolution in wave model grid might become important.

* We agree that increasing the horizontal resolution of the NWP-system may lead to better wind forecasts, due to better descriptions of processes in cyclones, etc. We will include discussion on this in the revised manuscript.

2.5 Discussion You should very carefully analyse and explain, what you are actually comparing in Table 2. To my understanding you are comparing wave forecast system, which have different resolutions, wind forcing and also most likely different wave model versions. So the differences in accuracy cannot solely be attributed to resolution.

* We do not understand this remark on table 2.

Table 4 – Why have you not calculated rms errors for the Helsinki wave buoy for LOW, HIGH and HIGHENS?

* Due to lack of observations, see above.

I'm not sure why the ice coverage is discussed here. You are comparing the forecasts against buoy measurements and the buoys are recovered well before there is a risk of ice in the area. Therefore handling of ice should not cause any problems in your verification results. That said, you of course have this element during the season and in the areas where you are unable to do the verification. You could also give a short description of the ice conditions in 2015-2017 so that readers would be able to evaluate, how big effect this might be.

* The effect of ice cover is described because it is a potential systematic error source of the wave forecasts, i.e. a potential for future improvement of wave forecast in the Baltic Sea.

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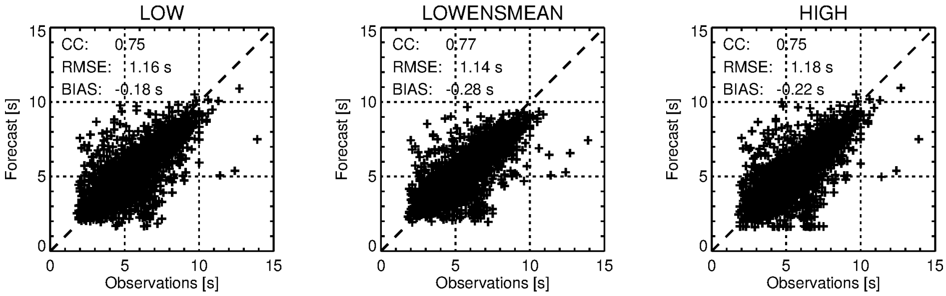

Fig. 1. Scatter diagram of 48 hour forecast of peak period for Northern Baltic

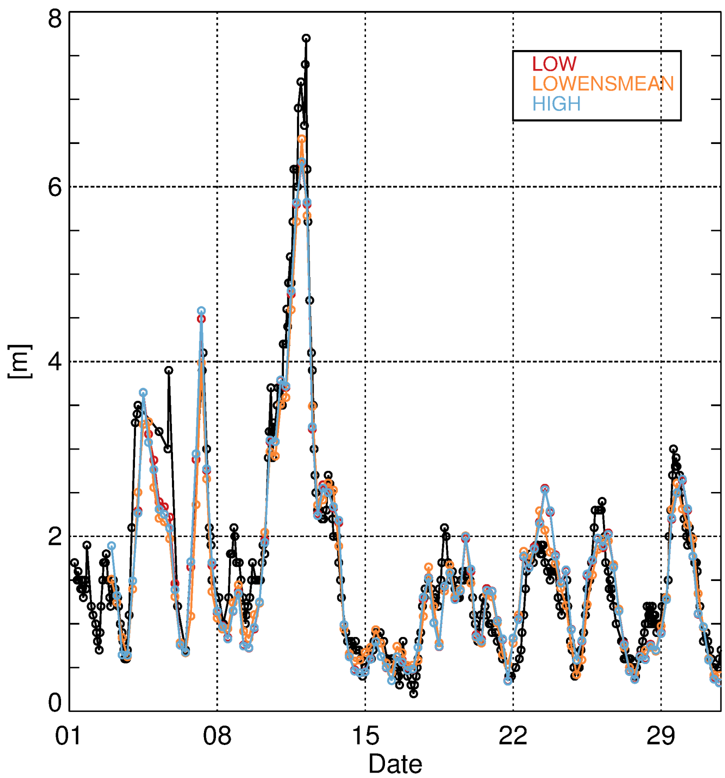

Fig. 2. Observed and forecasted (48 hour) SWH for Northern Baltic during storm Toni

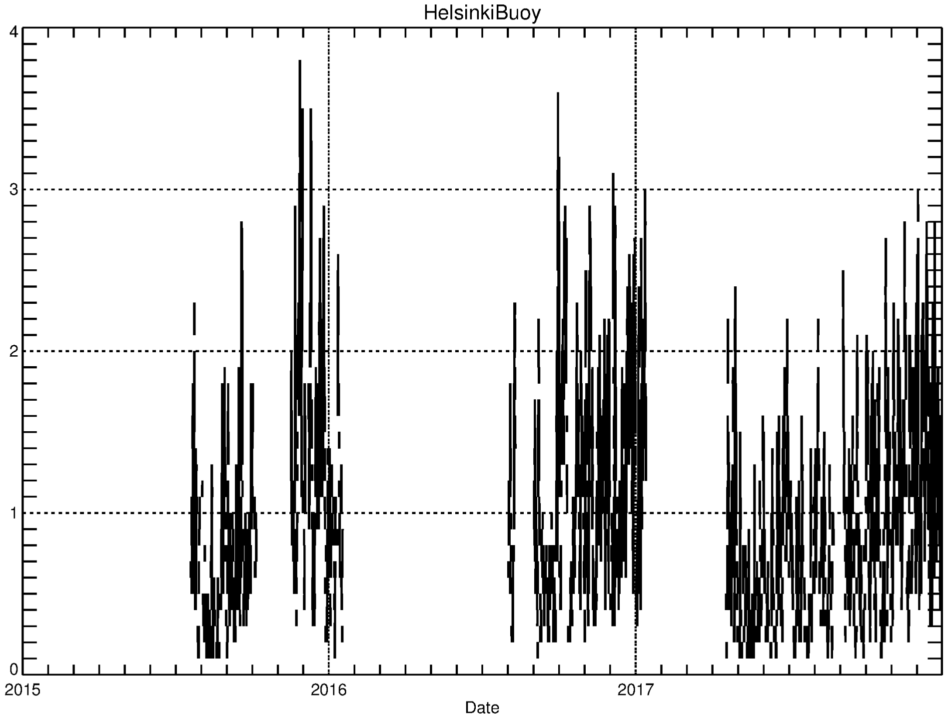

Fig. 3. Observations from Helsinki Buoy