1 Supplemental material

This supplement describes the WWIII setup for the Baltic Sea applied in the presented study. Two different versions of WWIII were used: While v6.07 was applied for the figures in the article and the model validation shown here, the model calibration was performed by version 5.16 and the parameters were not readjusted after switching to the new version. We used the source term packages defined after the switch file Ifremer2, which is part of the model source code. This includes wind input and dissipation (ST4) after Ardhuin et al. (2010) and the SHOWEX bottom friction scheme (BT4) after Ardhuin et al. (2003). For the latter, a sediment map with a median grain size (D50) based on EMODnet data (Fig. 1) is applied to define a spatially dependent bottom friction. Wind data from the UERRA/Harmonie-v1 analysis/forecasts (Ridal et al., 2017) were used. Analyses are available every six hours (00,06,12,18UTC) and were combined with the forecasts for +1 to +5 hours to create a dataset of hourly data. Model calibration and validation is based on this dataset.

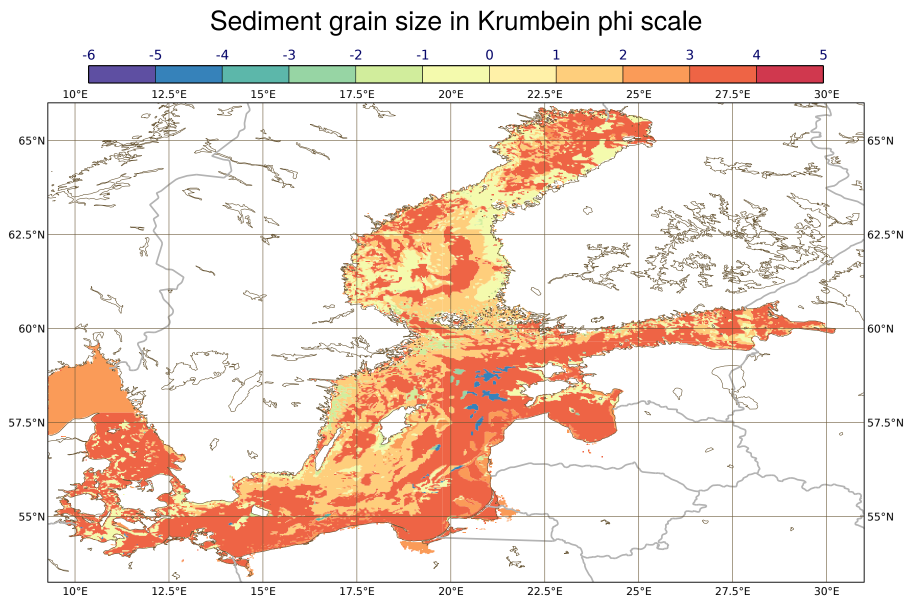

Figure 1. Grain size in Krumbein Phi scale used for the SHOWEX bottom friction scheme.

1.1 Calibration

Wind input and dissipation from the ST4 physics were tuned specifically to the Baltic Sea region. A sensitivity study of the impact of the wind input parameter betamax and the dissipation parameter SDSC2 has been conducted for this purpose, comparing to observed significant wave heights for January 2017, which were available from the CMEMS data base. The bias, rmse, correlation and the scatter index are used as objective scores for model validation acording to Zambresky (1989). The parameters were varied inside their valid range (Gorman and Oliver, 2018). The figures 3, 4 and 5 show the scores over the valid range of the betamax parameter. If increasing betamax, an improvement of the scores is visible, but for the eastern of the three stations betamax should be much higher than for the western stations. An overall good performance for the entire Baltic Sea is the aim of the calibration, what can not be achieved by only tuning betamax. The sensitivity study shows that a compromise between the wind input parameter and the dissipation parameter has to be found. Figure 6 shows the sensitivity in the scores for two different betamax values over a wide range of the dissipation parameter SDSC2. Additionally, sensitivity tests for the

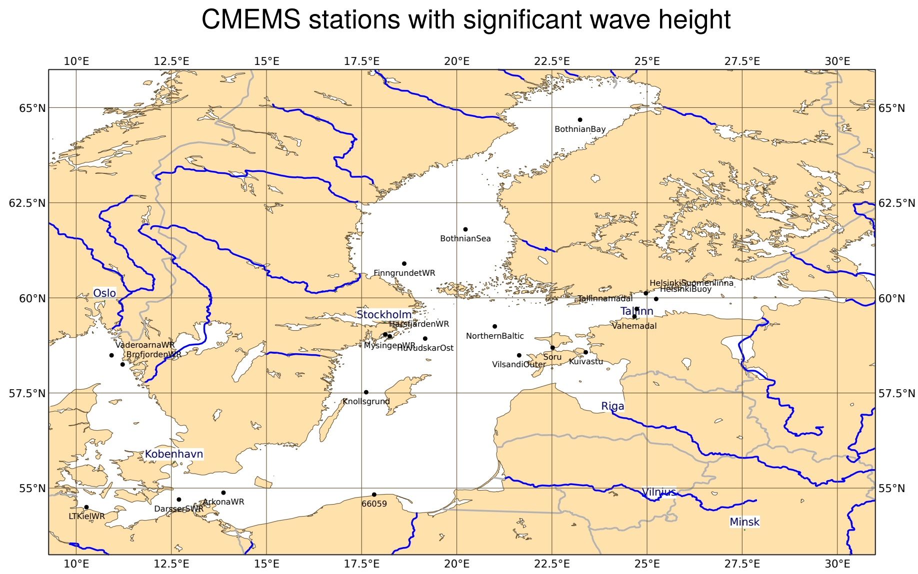

Figure 2. Station data available from CMEMS.

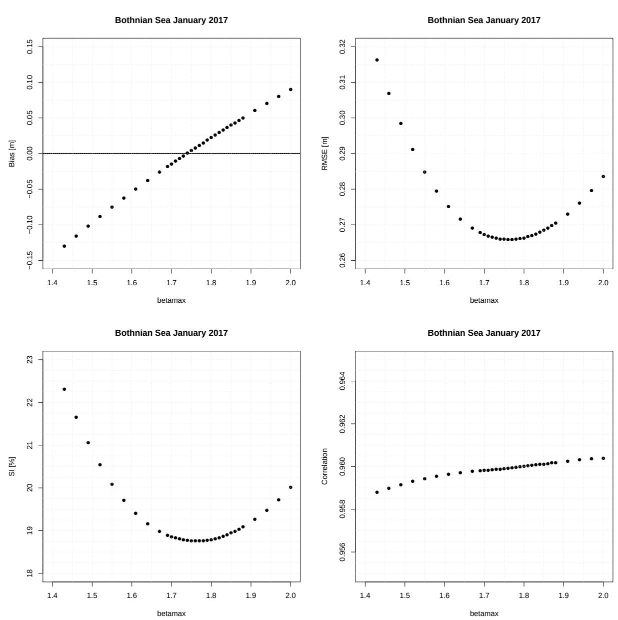

Figure 3. Verification scores for January 2017 for sensitivity study of wind input parameter betamax for station Bothnian Sea.

sheltering parameter taushelter and the tail factor (FXFM3) have been done. Based on tests with different parameter sets and a subjective interpretation, the four parameters were changed with regard to the default parameter set (Table 1).
As the calibration of the model is based on the previous model version 5.16, January 2017 has been recalculated with the actual version 6.07. The final choice of the parameter set is based on a subjective interpretation of the different test parameter sets.

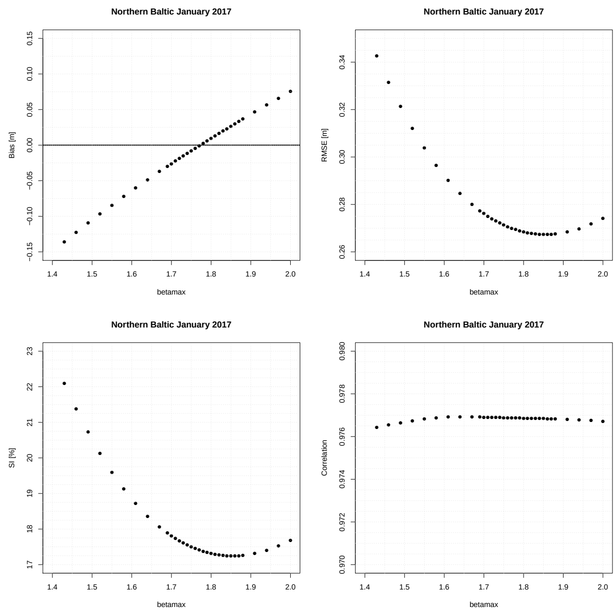

Figure 4. Verification scores for January 2017 for sensitivity study of wind input parameter betamax for station Northern Baltic.

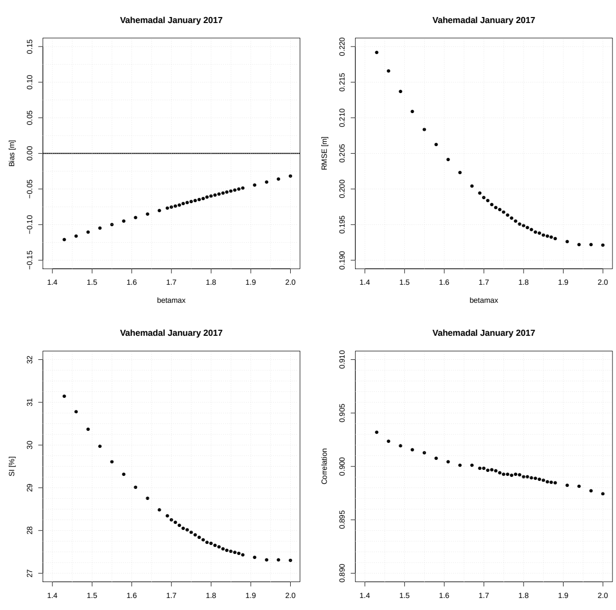

Figure 5. Verification scores for January 2017 for sensitivity study of wind input parameter betamax for station Vahemadal.

An objective calibration procedure like the one demonstrated by Gorman and Oliver (2018) was out of the scope of this study. For our purposes, the wave model shows a satisfactory model performance based on the demonstrated calibration procedure. To test if the calibration of the WWIII model based on the UERRA/Harmonie-v1 wind data is also appropriate for the wind fields hindcasted with the WRF-ARW model, one month of data were produced. For this purpose, every six hours, an eighteen

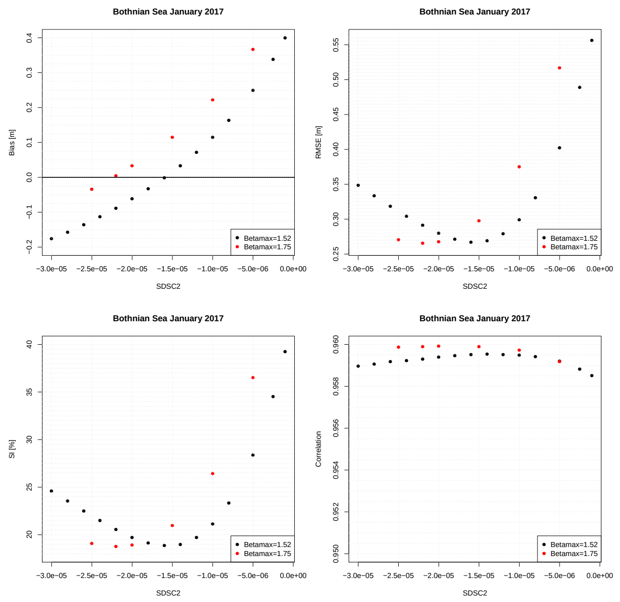

Figure 6. Verification scores for January 2017 for sensitivity study of dissipation parameter SDSC2 for station Bothnian Sea.

Table 1. Adapted parameter sets of the WAVEWATCH III® setup with Ifremer2 source term packages for the Baltic Sea based on the sensitivity study.

Parameter	betamax	SDSC2	taushelter	FXFM3
Default value	1.43	2.2E-5	0.3	2.5
Adjusted value	1.60	1.8E-5	0.2	5

hour hindcast was produced for January 2019. From these 18h hindcasts, the first 12h were considered as a model spinup and the last six hours were taken and combined to an hourly dataset.

The performance of WWIII with the WRF-ARW wind is also satisfactory based on the UERRA/Harmonie-v1 calibration. Over land areas, the wind is stronger in the WRF-ARW setup as in UERRA/Harmonie-v1. A comparison with the Corine land cover dataset showed that the roughness length for different land usages are lower in the WRF-ARW setup, which can explain the higher wind speeds over land. A test with modified roughness lengths showed only a small impact in the western part of the Baltic Sea, as this region is an enclosed coastal-ocean area with close proximity of the sea grid cells to land. The roughness of the sea surface is assumed to be constant in the applied WRF-ARW setup. Under strong storm conditions, the roughness of the sea surface should increase, which has an effect on the wind speed. This could be one reason for the outlying members in the demonstrated example of the significant wave height in the 2002 storm surge event. Nevertheless, the wave height in WWIII with UERRA/Harmonie-v1 is very close to the one with the WRF-ARW setup for the presented 2002 event. A coupled WWIII/WRF-ARW model would include the effect of the sea surface on its roughness length.

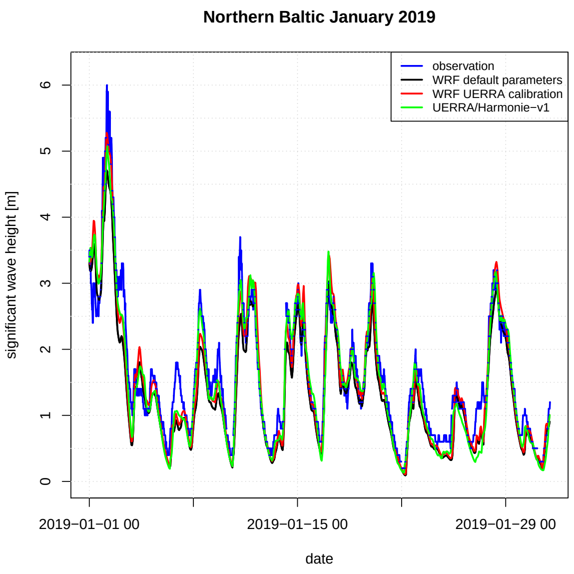

Figure 7. Observation, WWIII with default parameters driven with WRF-ARW (0.063°) wind, WWIII calibration for UERRA/Harmonie-v1 with WRF-ARW wind and UERRA/Harmonie-v1 wind for January 2019 at station Northern Baltic.

1.2 Hindcasts of Storms Rafael and Toini

For the 2002 storm surge event we presented, observations for wave parameters are not available. As proposed by the reviewers, two additional events were hindcasted. Ensemble generation procedure number five presented in the article was repeated here for hindcasting the storms Rafael and Toini, which provoked the highest observed significant wave heights in the Baltic proper. Detailed information about these two storm events can be found in Björkqvist et al. (2017). The newest WRF version v4.1.1 was used with 7km resolution. An obstruction grid based on the GSHHS shoreline dataset and generated with the gridgen[1] software is applied to take unresolved orography into account in the WWIII wave model. The WRF-ARW model runs were started for the Rafael storm on 21 December 2004 00UTC and finished on 24 December 2004 00UTC. SST is updated over the integration time, whereas in the article, the SST was kept constant after initialisation. Ten members from the ERA5 Ensemble of Data Assimilation were used as initial conditions for the perturbed runs together with stochastic perturbations. In addition, the entire January 2004 was hindcasted without the ensemble approach, using the UERRA/Harmonie-v1 wind data. Initial conditions in the wave model for the Rafael storm hindcast were taken from this previous model run on 21 December 2004 12UTC. Runs with WRF-ARW unperturbed and perturbed 5-minutes wind forcings were done for the period 21 December 2004 12UTC until 24 December 2004 00UTC. Sea ice data were taken from the ERA5 reanalysis. The same model setup was applied for the Toini storm. WRF-ARW runs started on 10 January 2017 00UTC and ended on 13 January 2017 00UTC. WWIII was driven with these data for the period 10 January 2017 12UTC until 13 January 2017 and initial conditions for WWIII were taken from a previous run for the entire January 2017 driven by UERRA/Harmonie-v1 winds. The hindcast of the storm Rafael shows an overall good performance with an underestimation of the peak wave height with UERRA/Harmonie-v1 by about 90 cm and by WRF-ARW of about 80 cm. One ensemble member matches the observed maximum. A finer discretization of the energy spectrum as proposed by Soomere (2005) increases the maximum wave height with the UERRA/Harmonie-v1 forcing by about 10 cm. The computation with this finer discretization took nearly four times as long as with the ERA5-equivalent discretization. For both wind data sets, the same parameter set is used. The strongest member slightly exceeds the observed significant wave height. Much higher waves in single ensemble members, as they occurred for the 2002 event, are not

[1]https://github.com/NOAA-EMC/gridgen

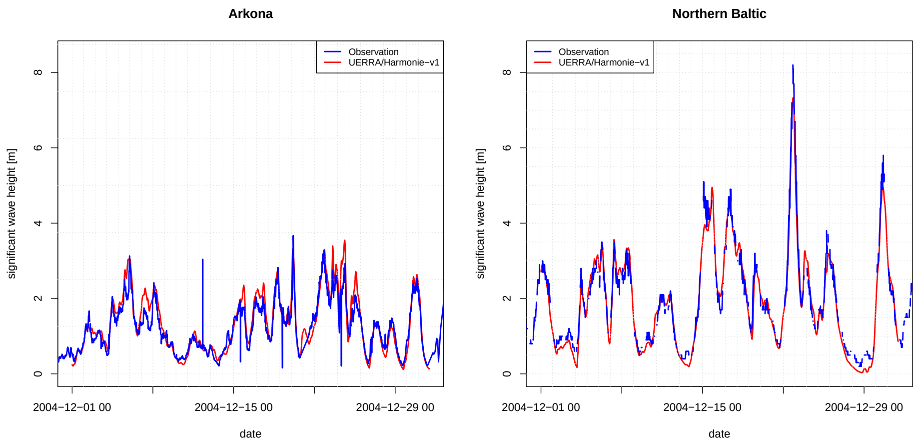

Figure 8. Significant wave height [m] at Arkona and Northern Baltic stations for December 2004.

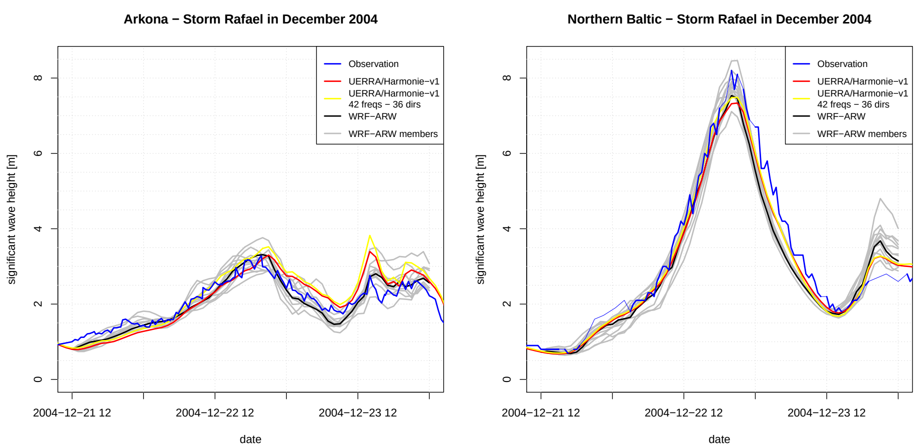

Figure 9. Significant wave height [m] at Arkona and Northern Baltic stations for Storm Rafael driven with UERRA/Harmonie-v1 wind and WRF-ARW ensemble hindcasts with eleven perturbed and one unperturbed runs.

generated in this ensemble hindcast. As the ensemble size is very small, it cannot be excluded that realisations with larger wave heights are possible. For the Toini storm, the unperturbed run generates too small wave heights. Nearly all perturbed members produce larger wave heights. The observed wave height is well covered by the ensemble. When we hindcasted the 2002 event with this 7 km setup with 11 perturbed members, one realisation showed a maximum of 9.5 m. This suggests that the 2002 event reacts more sensitive to the perturbations than the two other storm events.

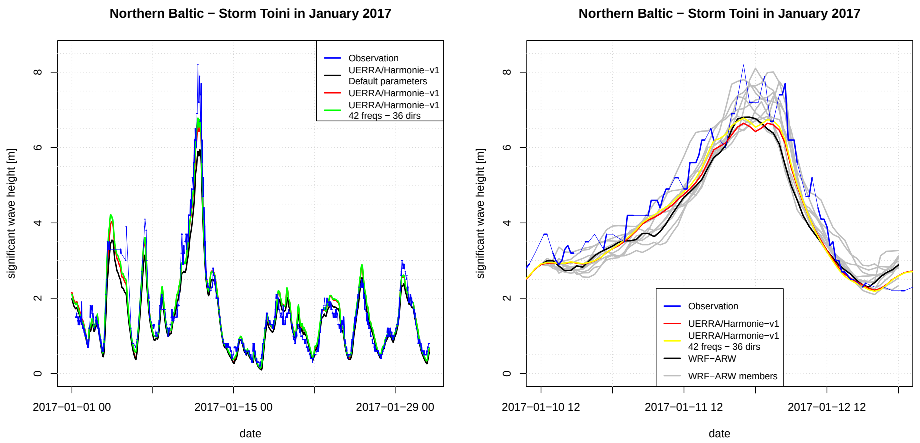

Figure 10. Significant wave height [m] at the Northern Baltic for Storm January 2017 and for storm Tioni driven with UERRA/Harmonie-v1 wind and WRF-ARW ensemble hindcasts with eleven perturbed runs and one unperturbed one.

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