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An atmosphere-wave regional coupled model: improving predictions of wave heights and surface winds in the Southern North Sea

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Abstract

Reduction of wave forecasting errors is a challenge especially in dynamically complicated coastal ocean areas as the southern part of the North Sea area – the German Bight. Coupling of different models is a favoured approach to address this issue as it accounts for the complex interactions of waves, currents and the atmosphere. Here we study the effects of coupling between an atmospheric model and a wind wave model, which in the present study is enabled through an introduction of wave induced drag in the atmosphere model. This, on one side, leads to a reduction of the surface wind speeds, and on the other side, to a reduction of simulated wave heights. The sensitivity of atmospheric parameters such as wind speed, and atmospheric pressure to wave-induced drag, in particular under storm conditions, is studied. Additionally, the impact of the two-way coupling on wave model performance is investigated. The performance of the coupled model system has been demonstrated for extreme events and calm conditions. The results revealed that the effect of coupling results in significant changes in both wind and waves. The simulations are compared to data from *in-situ* and satellite observations. The results indicate that the two-way coupling improves the agreement between observations and simulation for both wind and wave parameters in comparison to the one-way coupled model. In addition, the errors of the high-resolution German Bight wave model compared to the observations have been significantly reduced in the coupled model. The improved skills resulting from the proposed method justifies its implementations for both operational and climate simulations.

1. Introduction

Wind forcing is considered as one of the largest error sources in wave modelling. In numerical atmospheric models wind stress is parameterized by the drag coefficient which is usually considered as spatially uniform over water. In reality, wind waves extract energy and momentum from the atmosphere while they are growing under the wind. This effect is the largest for young sea states and high wind speeds. One can thus consider the drag coefficient as sea-state dependent and non-uniform in time and space. This dependence needs to be accounted for in the coupled atmosphere-wave models. As stated by Lionello et al. (2003) the wave model receives wind data from the atmospheric model and sends back information on sea surface roughness to the atmospheric model. This feedback enables a non-linear interaction between the atmosphere and the waves. In particular under extreme conditions non-linearities increase and the intensity of the storms could be modified. This has to be accounted for by the coupling because strong winds cause an increase of the drag coefficient of the sea surface, which leads to a reduction of the wind speed and also to modification of the wind direction (Warner et al., 2010).

In the present study we present intercomparisons between coupled and standalone model and validation against observations with the aim to quantify the effects of atmosphere-wave model coupling.

The coupling between atmospheric and wind wave models was first introduced operationally in 1998 at the European Centre for Medium-Range Weather Forecasts (ECMWF). The method which uses the theoretical work of Janssen (1991) has contributed to an improvement of both atmospheric and surface wave forecasts on the global scale. Coupling of wave and atmospheric models is the first step towards developing of a fully coupled ocean-atmosphere modelling system enhancing the description of interactions and exchanges in the atmospheric boundary layer. Accurate modelling of the boundary layer is of upmost importance for long range predictions. At ECMWF oceanic and atmospheric model were first coupled in 1997 accounting for effects of wind, heat, precipitation and sea surface temperature in either model (Stockdale et al. 1998). Recently, Breivik et al. (2015) incorporated the effects of surface waves onto the ocean dynamics *via* surface stress, turbulent kinetic energy due to wave breaking, and the Stokes–Coriolis force into the ECMWF system.

At Meteo-France, a coupled system (CNRMCM5) is used for operational forecasts, composed of an atmospheric, an ocean circulation, a sea-ice and a river discharge model (Voldoire et al. 2012).

In the United States a coupled ocean–atmosphere–wave–sediment transport (COAWST) modelling system has been developed (Warner et al. 2010, Kumar et al. 2012) which uses a coupling toolkit to exchange data between the various models.

With increasing the model grid resolution, the impact of coupling on the model predictions becomes more important (Janssen et al. 2004) thus emphasizing the need for coupling also on regional scales. For the Baltic Sea, e.g., a regional coupled atmosphere-wave model is run operationally since 2001 by the Finnish Meteorological Institute (Järvenoja and Tuomi 2002). They emphasize on the necessity to use wind data with fine temporal discretization in the wave model to ensure that the latter reacts physically correct to rapidly changing winds. For the meteorological model they hardly found any differences caused by the coupling except for the surface wind speeds. For the Mediterranean Sea however, Cavaleri et al. (2012) found a compensation of the reduced wind velocities by a more limited deepening of pressure fields of atmospheric cyclones.

Air-sea interaction is also of great importance in regional climate modelling. Rutgersson et al. (2010) introduced two different parameterisations in a European climate model. One of them was using the roughness length and including the effect of growing sea only as introduced by Janssen (1991), and another one using the wave age and introducing the reduction of roughness due to swell (see also Rutgersson et al. 2012). In both cases they found a significant impact of these parametrisations on long term averages of atmospheric parameters and also the impact of swell waves on the mixing in the boundary layer is not insignificant and needs to be considered when developing wave-atmosphere coupled regional climate models. Recently, high resolution regional full coupled models are also subject to further development. Katsafados et al. (2016) did set up such a system for the Mediterranean Sea and focused on air–sea momentum fluxes in conditions of extremely strong and time-varying winds. They demonstrated more realistic representation of the momentum exchanges in the wave-atmosphere coupled modelling system by including the sea-state dependent drag coefficient: the effects on wave spectrum and its feedback on the momentum flux lead to improvements of model predictions.

In our study we decided to start with using the formulation of Janssen (1991) and to perform a simple perturbation experiment. We coupled our wave and atmospheric model *via* a coupler. In the one-way coupled setup, the wind wave model only receives wind data from the atmospheric model. In the two-way coupled setup, the wind wave model sends back to the atmospheric model the computed sea-surface roughness. We can then statistically access the impact of the two-way coupling and validate the two setups against *in situ* and remote sensing data. By introducing the interaction of wind waves and atmosphere we aim at further reduction of modelling errors.

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Novel here is the simultaneous run using the coupler of a regional North Sea coupled wave-atmosphere model together with a nested-grid high resolution German Bight wave model (one atmospheric and two wind wave models). Using this setup allows us to study the individual and combined effects of coupling and grid resolution, especially in severe storm conditions, which is challenging for the wave modelling in the German Bight since it is a very shallow and dynamically complex coastal area. Previous validations of model results against observations indicated that wave heights are often over-predicted here (Staneva et al., 2016).

The paper is structured as follows: in Section 2 we describe the models used, as well as the technical coupling. It also contains the specification of different setups, period of model integration and available data for validation. Discussion on model results and sensitivity experiments is given in Section 3. The paper ends with a summary and an outlook to future works.

2. Model description and set-up

The atmospheric model COSMO is coupled to the wave model WAM *via* the coupler OASIS3-MCT. In the coupled model 10m wind field is transferred from COSMO to WAM and the wave dependent Charnock parameter is transferred from the North Sea WAM setup to COSMO for surface flux calculations.

2.1 The atmospheric model COSMO

The atmospheric model used in the study is the non-hydrostatic regional climate model COSMO-CLM (CCLM) version 4.8 (Rockel et al. 2008, Baldauf et al. 2011). The model is developed and applied by a number of national weather services affiliated in the COnsortium for SMall-scale MOdeling (COSMO). The climate mode COSMO-CLM (CCLM) is developed and applied by the Climate Limited-area Modelling Community. CCLM is based on the primitive thermo-hydrodynamical equations that describe compressible flow in a moist atmosphere. The model equations are formulated in rotated geographical coordinates and a generalized terrain following vertical coordinates. The model uses primitive equations for momentum. The continuity equation is replaced by a prognostic equation for the perturbation pressure (i.e. the deviation of pressure from a reference state representing a time-independent dry atmosphere at rest which is prescribed to be horizontally homogeneous, vertically stratified and in hydrostatic balance).
In our setup we use a spatial resolution of about 10km and 40 vertical coordinate levels to discretize the area around the North Sea and Baltic Sea (Fig.1a). Forcing and boundary condition data are taken from the coastDat-2 hindcast data base for the North Sea (Geyer 2014) covering the period 1948-2013 with

spatial resolution of about 24 km (0.22^o) and temporal resolution of one hour. These hindcast simulations are forced by 6-hourly data from the NCEP/NCAR weather reanalysis at model boundaries with a spatial resolution of about 210 km.

2.2 The wave model WAM

WAM Cycle 4.5.4 is an update of the third generation WAM Cycle4 wave model (Komen et al. 1994). The basic physics and numeric are kept in the new release. The source function integration scheme of Hersbach and Janssen (1999) and the reformulated wave model dissipation source function (Bidlot et al., 2005), later reviewed by Bidlot et al. (2007) and Janssen (2008), are incorporated. Depth induced wave breaking (Battjes & Janssen, 1978) has been included as an additional source function. Depth and/or current fields can be non-stationary.
The nested-grid setup includes a regional model for the North Sea with a spatial resolution of about 5 km and a finer wave model for the German Bight with a resolution of about 900 m. These models are described by Staneva et al. (2016). Both models use a directional resolution of 15^0 and 30 frequencies, with equidistant relative resolution between 0.04 and 0.66. The boundary values for the North Sea model are taken from the regional model of the German Weather Service (DWD) EWAM (European WAM). The forcing wind data are provided by the atmospheric model (see section 2.1). The German Bight wave model uses boundary values of the outer North sea model and accounts additionally for depth induced wave breaking and depth refraction The WAM model code already contains the calculation of sea state dependent roughness length according to Janssen (1991), thus the model only had to be adapted for usage with the OASIS3-MCT coupler (see section 2.3).

2.3 Coupling of Models

WAM and CCLM are coupled via the coupler OASIS3-MCT version 2.0 (Valcke et al. 2013). The name OASIS3-MCT is a combination of OASIS3 (the Ocean, Atmosphere, Sea, Ice, and Soil model coupler version 3) at the European Centre for Research and Advanced Training in Scientific Computation (CERFACS) and MCT (the Model Coupling Toolkit) which was developed by Argonne National Laboratory in the USA. Details of properties and usage of the coupler OASIS3 can be found in Valcke (2013).
To couple WAM and COSMO using the coupling library of this coupler, modifications in source code of WAM and COSMO have to be done. The source code of CCLM was modified for the coupled system WAM/COSMO-CLM in a similar way used for the atmosphere-ocean-sea ice coupled system model

COSTRICE (Ho-Hagemann et al. 2013). Exchanging fields between atmospheric and wave models in this study are only wind and sea surface roughness length.

For our perturbation experiment we perform one-way and two-way coupled simulation. In the one-way coupled mode only the atmospheric model sends wind data to the North Sea wave model. This is thus equivalent to the familiar forcing of a wave model by 10m wind fields. We will refer to the results of this simulation as COSMO-1wc and WAM-NS-1wc, respectively, where '1wc' and 'NS' stay for 'one-way coupled' and 'North Sea'. In the two-way coupled mode the North Sea wave model sends back sea surface roughness lengths obtained from the atmospheric model wind forcing which in return might reduce wind speeds, *i.e.* the two-way coupling results in a non-linear interaction between the two models. We will refer to the results of this simulation as COSMO-2wc and WAM-NS-2wc, respectively. The coupling time step in either simulation is 3 minutes. This small coupling time step is a big advantage for modelling fast moving storms compared to an uncoupled run, where wind fields are usually available at the most hourly.

The German Bight wave model is forced in the two simulations by the respective wind and boundary data. Although the German Bight model does not send roughness information to the atmosphere we will refer to the two differently forced setups as WAM-GB-1wc and WAM-GB-2wc, because in the second experiment roughness information is sent to the atmospheric model by WAM-NS-2wc.

2.4. Integration Period and Data Availability

The described models were used to simulate the three months period from October to December 2013. This period was chosen since it includes on December 6th the storm 'Xaver' one of the most severe storms of the last decade. 'Xaver' originated south of Greenland and rapidly deepened as it moved eastwards from Iceland over the Norwegian Sea to South-Sweden and further to the Baltic Sea and Russia. Exceptional was also the long duration of the storm event of nearly two days. The German Bight coast was affected by three surges due to the storm coming almost constant from Northwest.

In our study we perform a statistical analysis for the whole period of integration and investigate the stormy period in more detail. Figure 2 shows the distribution over the selected period of wind speeds and directions at the *in-situ* platform FINO-1 data station (see Figure 1c for its location). North-westerly winds are generally dominant, but during 'Xaver' strong winds are also coming from west and south-west as the storm moved eastwards. For the validation of our experiment we used wind speed and significant wave height measured by altimeter satellites SARAL/AltiKa, Jason-2 and CryoSat-2 over the North Sea. The first two carry on-board a classical pulse-limited altimeter which operates in low resolution mode (LRM), while the CryoSat-2 instrument operates in LRM or in Delay Doppler (DD) mode. The CryoSat-2 data used here have been extracted from the RADS database (Scharroo et al. 2013), where CryoSat-2 data acquired in DD mode in our region has been processed to generate pseudo-LRM data (PLRM). Accuracy and precision of PLRM data are slightly lower than LRM and SAR data (Smith and Scharroo, 2015). The altimeter satellites measure along their ground-track offshore up to few kilometres from the coast (see Figure 1b). Their ground track pattern and the repeat period are different for each mission, for the three missions above the same location is revisited every 27, 10, 350 days respectively (Chelton et al., 2001). The data from SARAL/AltiKa data is here of special interest since this satellite passed over the German Bight during the storm 'Xaver' when the surge was at his maximum (Fenoglio-Marc et al. 2015). Additionally, we used wave data from four directional Datawell wave riders in the German Bight operated by the Federal Maritime and Hydrographic Agency (BSH) (see Figure 1b for satellite tracks). At station FINO-1 there were also wind speed measurements at 50 and 100 m available for the selected period.

3. Results

3.1 Validation of models

To quantify the performance of one-way *versus* two-way coupling we compared the atmospheric and wave model output against *in situ* and remotely sensed data. Table 1 gives for both wave height and wind speed the statistics of the difference between model and the altimeter-derived values over the selected three-month period, which is bias and standard deviations of differences. For all the three satellites the standard deviation in the two-way coupled setup is smaller than in the one-way setup. Similarly, for Jason-2 and SARAL/Altika the bias in the two-way coupled setup is smaller than in the one-way setup and measured values are below modelled ones. In the one-way coupled setup biases are about 30 cm and 0.7 m/s for wave height and wind speed, respectively while in the two-way coupled setup these values are nearly halved due to the reasons explained above, thus giving a first indication of improved model skills in this case. For Cryosat-2 instead the opposite is true and measured values are above modelled ones in mean for both wave height and wind speed. CryoSat-2 biases in the one-way setup (18 cm and 0.4 m/s for wave height and wind speeds respectively) have similar magnitude than biases in the two-way coupled setup of the other two satellite (e.g. -0.12 and -0.33 for SARAL/Altika). Fenoglio-Marc et al. (2015) also found that CryoSat-2 derived wave height data overestimate the LSM wave model data from the DWD. For the wind speed they however found the opposite, which is that CryoSat-2 derived wind speed underestimates the COSMO wind model data from the DWD. This using both RADS PRM data and from SAR. On the other hand the coastDat2 data used to force our COSMO model with used NCEP/NCAR data as driving fields which might explain this disagreement. Moreover, it is well know that the determination from satellite altimetry wave height is particularly challenging for waves smaller than one meter (Passaro et al., 2014) and that an additional correction in form of a Look Up Table to be applied to the altimeter-derived wave height is needed. This has been successfully applied in LRM and still under investigation in DD altimetry.

To perform qualitative comparison between the model simulations and the satellite data we analysed individual tracks over the North Sea, two of which are shown in Figure 3. The selected SARAL/AltiKa passages are very diverse: one was taken under calm conditions and the other during the storm ‘Xaver’, thus providing the possibility to compare measured and modelled wave heights and wind speeds along the satellite tracks under different atmospheric and wave conditions. In both cases measured and modelled wave heights are in good agreement. Under calm conditions differences between the results of the one- and two-way coupling are very small. Both models (WAM-NS-1wc/2wc) overestimate the measured wave height over a large part of the track (Figure 3a), however the reduced wave height simulated from the two-way coupled model is closer to the measurements. During storm ‘Xaver’ the difference of the wave height between the WAM-NS-1wc and WAM-NS-2wc simulations increases up to 1m in the southern North Sea. The altimeter-derived quantities in this situation get very fluctuating but still, the two-way coupled model results are closer to the measurements. It is noteworthy here, that the measured peak of the storm, is underestimated by both runs and is also shifted northwards by approximately 2 degrees (Figure 3b).

The modelled wind speed fits well the altimeter-derived wind speed in the calm situation for both setups (COSMO-1wc/2wc, Fig. 3a). For wind speeds of above 10m/s the lowered wind speeds from two-way coupled setup s northwards of 55 degrees approach the values from measurements (Figure 3a). On the contrary, during the storm ‘Xaver’ the measured wind data are fluctuating around 18 m/s whereas the modelled data show higher values with mean of 20 m/s and a more plausible behaviour (Figure 3b). This might indicate that the algorithm for retrieving wind speeds is saturated under these extreme conditions. Fenoglio-Marc et al. (2015), who had compared the same altimeter data to ERA-Interim, NOAA/GFC and COSMO/EU winds, have suggested that low altimeter-derived wind speed are caused by an overestimation of the atmospheric attenuation of the radar power in Ka-band. Indeed, a larger attenuation correction would result in a too large backscatter coefficient and hence in a reduced wind speed. The correction in the SARAL/AltiKa products is larger than the correction based on surface pressure, near-surface temperature, and water vapour content (Lillibridge et al., 2014).

Below we will analyse the temporal variability of the significant wave heights in the German Bight under stormy conditions. This allows us to investigate not only the impact of two-way coupling but also of model resolution on the model performance. Figure 4 shows a comparison between data from two wave rider buoy (the location of the buoys is shown in Fig. 1) during the storm ‘Xaver’ and model output from the coarse North Sea wave model setups (WAM-NS-1wc/2wc) and the fine German Bight ones (WAM-GB-1wc/2wc). Throughout the period WAM-NS-1wc shows the highest values of significant wave height. The lowest simulated values originate from the WAM-GB-2wc output. At the beginning of December all model results are very close but when the storm starts the differences in the wave growth between the different model simulations become significant. The peak of the storm from the WAM-NS-1wc simulation overshoots the measured wave heights by about 3 m at Helgoland station (water depth 30m, Figure 4c) and even by 4 m at the shallow water Westerland station (water depth 13m, Figure 4d) whereas the wave heights predicted by the WAM-GB-2wc are in a better agreement with the observations.

The influence of spatial resolution on the simulated characteristics can be clearly seen in the time series at the deep water buoy at Helgoland. This buoy is located in an area of large gradients in water depth; here differences of wave height during ‘Xaver’ reach about 1 to 1.5m in the corresponding North Sea and German Bight simulations. This makes clear the influence of different resolutions, *i.e.* different water depths in the region.

At the shallow water buoy at Westerland station the differences are additionally enhanced by depth induced wave breaking which is present only in the German Bight model. This can also be seen in the snapshots of wave height in the North Sea and German Bight at the peak of the storm (Figure 4a,b): shoreward of the 15m isobaths the wave heights drop from 6 to 4m in the German Bight model, whereas in the North Sea model the 6m high waves reach the Southeastern coast. WAM-GB-1wc performs worse than WAM-NS-2wc at Westerland, showing convincingly the importance of two-way coupling for the coastal German Bight areas, where the model wind speeds are even higher (by about 2m/s) than at Helgoland. The wind fields in both locations are very similar in the COSMO-1wc/2wc model runs, only the peak of the storm is reduced from 26 to 22 m/s.

Measured wind speeds close to the shore of the island of Sylt, nearby the buoy Westerland location, and on the island of Helgoland were provided by the DWD. At the beginning of the storm the modelled wind speeds grow too early and too high at either location (see again Figure 4c,d). The storm characteristics are matched well at Helgoland but are slightly underestimated by the model at Westerland. Still, the overall model performance at Westerland is satisfying considering how strongly fluctuating the wind measurements there are.

Additionally, wind speeds were validated against measured data from FINO-1 in 50 and 100m height over the whole modelling period (Table 2). Even though differences between COSMO-1w/2wc decrease with increasing height of the atmosphere, we still found a better agreement in the two-way coupled run. The bias in wind speed is negative for the one-way coupled setup, thus modelled wind speeds overestimate the measured ones. Bias is significantly reduced due to the lower wind speeds in the two-way coupled model. The rmse is about 3m/s in either case but slightly improved for the full coupled setup.

For a more quantitative validation of the WAM-GB-1wc/2wc results we used four buoys (see Figure 1c for their locations) in water depths from 13 to 30 m. Table 3 gives statistics for significant wave height (Hs) over the three months period. In either water depth and regardless of the way of coupling the bias for Hs is slightly negative, i.e. the modelled data over-predict the measured values. For WAM-GB1wc the bias is about 15 cm except for buoy Elbe where it is 7 cm. Modelled wave heights are smaller in WAM-GB-2wc, and thus bias is reduced from 15 cm by about 10 cm and from 7 to 1 cm at buoy Elbe. The rmse of about 50 cm is unaffected by the two-way coupling except for the buoy FINO-1 where it is reduced by about 5%. In any case the error distribution (not shown here) becomes more symmetrical in the two-way coupled cases.

3.2. Impact of two-way coupling on modelling results

In the following the impact of coupling will be analysed for the North Sea focusing on the spatial patterns under different physical conditions. Three months averaged significant wave height and wind speed is reduced significantly (Figure 5) due to the two-way coupling which results in an extraction of energy and momentum by waves from the atmosphere. The bias in wave height gives values of about 20 cm which is a reduction of about 8% of the three month mean value (~2.3 m). The root mean squared difference (rms) between two simulations is about 40cm in the central North Sea. For the wind speeds the bias is about 30 cm/s when averaged over the model area, corresponding to a reduction in wind speed of about 3% of the three month mean value (~10m/s) with an rmse of about 80cm/s.

The spatial patterns in the bias in Figure 5 can be explained by the dominating westerly winds. As the wind coming from land (Great Britain) hits the North Sea, the differences in the wind speed between the two models are larger closer to the coast because of differences in the of sea surface roughness. Moving further to the east, the atmospheric boundary layer adapts in either case to the winds over sea and the differences between one- and two-way coupled setups become smaller. This theory is supported when looking on the effect of coupling for the wind stress (Figure 6). One can clearly see how rapidly the stress decreases in the two-way coupled setup east off the British coast and then, after adaptation to the new wind, the differences in wind stress between one- and two-way coupled setup stay nearly constant at a low value. For the wave height, differences in bias close to the western coasts and in the English Channel are smallest since it needs some fetch for the waves to evolve and this fetch is too short here.

The differences in the mean sea-level pressure between COSMO-1wc/2wc for the storm ‘Xaver’ period is analysed in the following addressing the hypotheses that the higher friction should in case of a low pressure system result in an air flow which tends to fill the low, *i.e.* increased pressure in the pressure low minimum is expected (Janssen and Viterbo, 1996). The mean sea level pressure at the peak of the storm (Figure 7a) shows values of about 900 hPa over Norway and of about 1000 hPa over the North Sea. Compared to the one-way coupled setup the pressure increased by about 50-100Pa in the South East (Figure 7b). The slightly decreased pressure in the remaining part of the model area indicates a shift of the pressure low minimum, confirming results of Cavaleri et al. (2012) who found similar patterns in the Mediterranean under developing cyclones. As was pointed out by Janssen and Viterbo (1996) the timescale of impact of waves on the atmospheric circulation is of the order of five days. However our model area might be still be too small for such effects to play a major role. More plausible is our results might instead have been caused by the wave-mean flow interactions in the atmosphere. This will be analysed more deeply in future experiments.

Another illustration of the influence of the coupling is given by the two time series at FINO-1 station each of about two weeks and taken under very different conditions: one period is in November which was rather calm and thus contains much young and developing wind seas (Figure 8a) another one in December with several storms coming from the North Sea (including ‘Xaver’) and thus with higher wave ages (Figure 8b). The differences in significant wave height and wind speed between the one- and two-way coupled models are mostly positive, i.e. both parameters are reduced in the two-way coupled model run. Largest differences can be observed when wave age (the ratio of phase velocity at the peak of the wave spectrum with friction velocity) is well below 20 and occurs for the waves before the maximum wave height is reached (this can be well seen for ‘Xaver’, Figure 8b) thus the waves grow slower in the two-way coupled model. Negative differences occur seldom and only when wave age rapidly increases (we do not consider situations where wave age exceeds 50 since there the wind speeds go to zero and thus wave age to infinity).

4. Summary and Outlook

We have setup a two-way coupled wave-atmosphere model for the North Sea which includes the possibility of nesting a local wave model simultaneously. This was done by using the coupling software OASIS3-MCT which allowed the parallel run of several models on different model grids. Model intercomparisons gave encouraging results: the two-way coupled model were in a better agreement with the in-situ and remotely sensed data of significant wave height and wind speed compared to the one-way coupled model (COSMO forces WAM). We observe a general good agreement between model results and satellite-derived parameters except for a known degradation of wind speed in storm conditions, which is under investigation. Two-way coupling also improved the modelled significant wave heights in the German Bight which was demonstrated by the validation against observations from four different buoys. For the storm event 'Xaver' the impact of the two-way coupling was of highest significance: wave heights decreased from about 8 m to 5 m due to the coupling, matching buoy measurements very well. Nevertheless, model resolution was critical where the depth gradients were large. The corresponding wind speeds were lowered from 23 to 20 m/s. Besides this extreme event such large differences between one- and two-way coupled model results were only observed for young seas (wave age well below 20). We also found a slight spatial shift in the minimum of the cyclone mean sea level pressure together with a small increase of the pressure field. However, these results may also have been caused by the wave-mean flow interactions in the atmosphere. This will be subject of subsequent work where we will study in more depth the consequences of the coupling on other atmospheric parameters, not only at sea level but also the vertical structure of the planetary boundary layer.

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References

Baldauf, M., Seifert, A., Förstner, J., Majewski, D., Raschendorfer,M., and Reinhardt, T. (2011). Operational Convective-Scale Numerical Weather Prediction with the COSMO Model: Description and Sensitivities, Mon. Weather Rev., 139, 3887–3905.

Battjes, J., Janssen, J. (1978). Energy loss and set-up due to breaking of random waves. Coastal Engineering Proceedings 1 (16).

Bidlot, J., Janssen, P., Abdalla, S. (2007). A revised formulation of ocean wave dissipation and its model impact. Tech. Rep. Memorandum 509, ECMWF, Reading, UK.

Breivik, Ø., Mogensen, K., Bidlot, J. R., Balmaseda, M. A., & Janssen, P. A. (2015). Surface wave effects in the NEMO ocean model: Forced and coupled experiments. Journal of Geophysical Research: Oceans, 120(4), 2973-2992.

Cavaleri, L., Roland, A., Dutour Sikiric, M., Bertotti, L., Torrisi, L. (2012). On the coupling of COSMO to WAM. In Proceedings of the ECMWF Workshop on Ocean-Waves.

Chelton D., Ries J., Haines B., Fu L, Callahan P. (2002). Satellite Altimetry in Satellite Altimetry and Earth Sciences,- A Handbook of Thechniques and Applications, Academic Press

Fenoglio-Marc, L., Dinardo, S., Scharroo, R., Roland, A., Sikiric, M. D., Lucas, B., ... Weiss, R. (2015). The German Bight: A validation of CryoSat-2 altimeter data in SAR mode. Advances in Space Research, 55(11), 2641-2656.

Geyer, B. (2014). High-resolution atmospheric reconstruction for Europe 1948–2012: coastDat2. Earth Syst. Sci. Data, 6(1), 147-164.

Hersbach, H. and Janssen, P.A.E.M. (1999). Improvements of the short fetch behaviour in the WAM model. J. Atmos. Oceanic Techn., 16, 884-892.

Ho-Hagemann HTM, Rockel B, Kapitza H, Geyer B, Meyer E (2013). COSTRICE - an atmosphere - ocean - sea ice model coupled system using OASIS3. HZG Report 2013-5, 26pp.

Janssen, P.A.E.M. (1991). Quasi-linear theory of wind-wave generation applied to wave forecasting. Journal of Physical Oceanography, 21(11), 1631-1642.

Janssen, P.A.E.M. and Viterbo, P. (1996). Ocean waves and the atmospheric climate. Journal of climate, 9(6), 1269-1287.

Janssen, P. A., Saetra, O., Wettre, C., Hersbach, H., and Bidlot, J. (2004). Impact of the sea state on the atmosphere and ocean. In Annales hydrographiques (Vol. 3, No. 772, pp. 3-1). Service hydrographique et océanographique de la marine.

Janssen, P.A.E.M., (2007). Progress in ocean wave forecasting, J. Comput. Phys. 227, pp. 3572–3594.

Järvenoja, T., and Tuomi, L. (2002). Coupled atmosphere-wave model for FMI and FIMR. Hirlam Newsletter, 40, 9-22.

Katsafados P, Papadopoulos A, Korres G, and Varlas G, A fully coupled atmosphere–ocean wave modeling system for the Mediterranean Sea: interactions and sensitivity to the resolved scales and mechanisms, Geosci. Model Dev., 9, 161–173www.geosci-model-dev.net/9/161/2016/doi:10.5194/gmd-9-161, 2016.

Komen, G.J., L. Cavaleri, M. Donelan, K. Hasselmann, S. Hasselmann and P.A.E.M. Janssen, (1994). Dynamics and modelling of ocean waves. Cambridge University Press, Cambridge, UK, 560 pages.

Kumar, N., Voulgaris, G., Warner, J. C., and Olabarrieta, M. (2012). Implementation of the vortex force formalism in the coupled ocean-atmosphere-wave-sediment transport (COAWST) modeling system for inner shelf and surf zone applications. Ocean Modelling, 47, 65-95.

Lillibridge, J. L., R. Scharroo, S. Abdalla, and D. C. Vandemark (2014), One- and two-dimensional wind speed models for Ka-band altimetry, J. Atmos. Oceanic Technol., 31(3), 630–638, doi:10.1175/JTECH-D-13-00167.1.

Passaro, M., Fenoglio-Marc, L., Cipollini, P. (2015). Validation of Significant Wave Height From Improved Satellite Altimetry in the German Bight, Geoscience and Remote Sensing, IEEE Transactions on, 53, 4, 2146-2156.

Rockel, B., Will, A., and Hense, A. (2008). The Regional Climate Model COSMO-CLM (CCLM), Meteorol. Z., 17, 347–348.

Rutgersson, A., Sætra, Ø., Semedo, A., Carlsson, B., Kumar, R. (2010). Impact of surface waves in a regional climate model. Meteorologische Zeitschrift, 19(3), 247-257.

Rutgersson, A., Nilsson, E. O., Kumar, R. (2012). Introducing surface waves in a coupled wave-atmosphere regional climate model: Impact on atmospheric mixing length. Journal of Geophysical Research: Oceans, 117(C11).

Scharroo, R., Leuliette, E.W., Lillibridge, J.L., Byrne, D., Naeije, M.C., Mitchum, G.T., (2013). RADS: consistent multi-mission products. Proc. of the Symposium on 20 Years of Progress in Radar Altimetry.

Smith, W.H.F., Scharroo, R., (2015). Waveform aliasing in satellite radar altimetry. IEEE TGRS 53 (4), 1671–1681.

Staneva J., Wahle, K., Günther, Stanev, E. (2016). Coupling of wave and circulation models in coastal-ocean predicting systems: a case study for the German Bight. Ocean Sci., 12, 797–806.

Stockdale, T. N., Anderson, D. L. T., Alves, J. O. S., & Balmaseda, M. A. (1998). Global seasonal rainfall forecasts using a coupled ocean–atmosphere model. Nature, 392(6674), 370-373.

Valcke S., (2013) The OASIS3 coupler: a European climate modelling community software, Geosci. Model Dev., 6, 373-388.

Valcke S, Craig T, Coquart L (2013) OASIS3-MCT User Guide, OASIS3-MCT 2.0. Technical Report, TR/CMGC/13/17, CERFACS/CNRS SUC URA No 1875, Toulouse, France.

Voldoire, A., Sanchez-Gomez, E., y Mélia, D. S., Decharme, B., Cassou, C., Sénési, S., ... Déqué, M. (2013). The CNRM-CM5. 1 global climate model: description and basic evaluation. Climate Dynamics, 40(9-10), 2091-2121.

Warner, J. C., Armstrong, B., He, R., & Zambon, J. B. (2010). Development of a coupled ocean–atmosphere–wave–sediment transport (COAWST) modeling system. Ocean modelling, 35(3), 230-244.

Figures

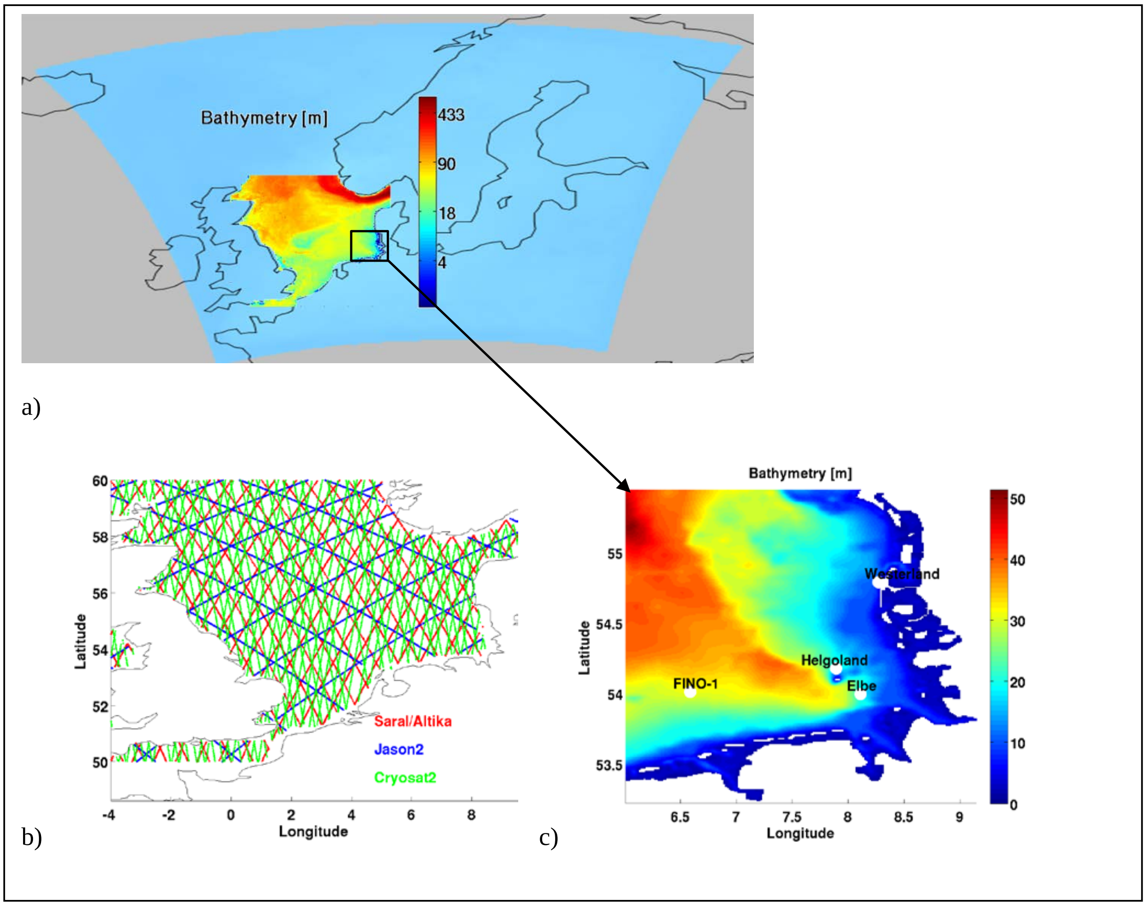
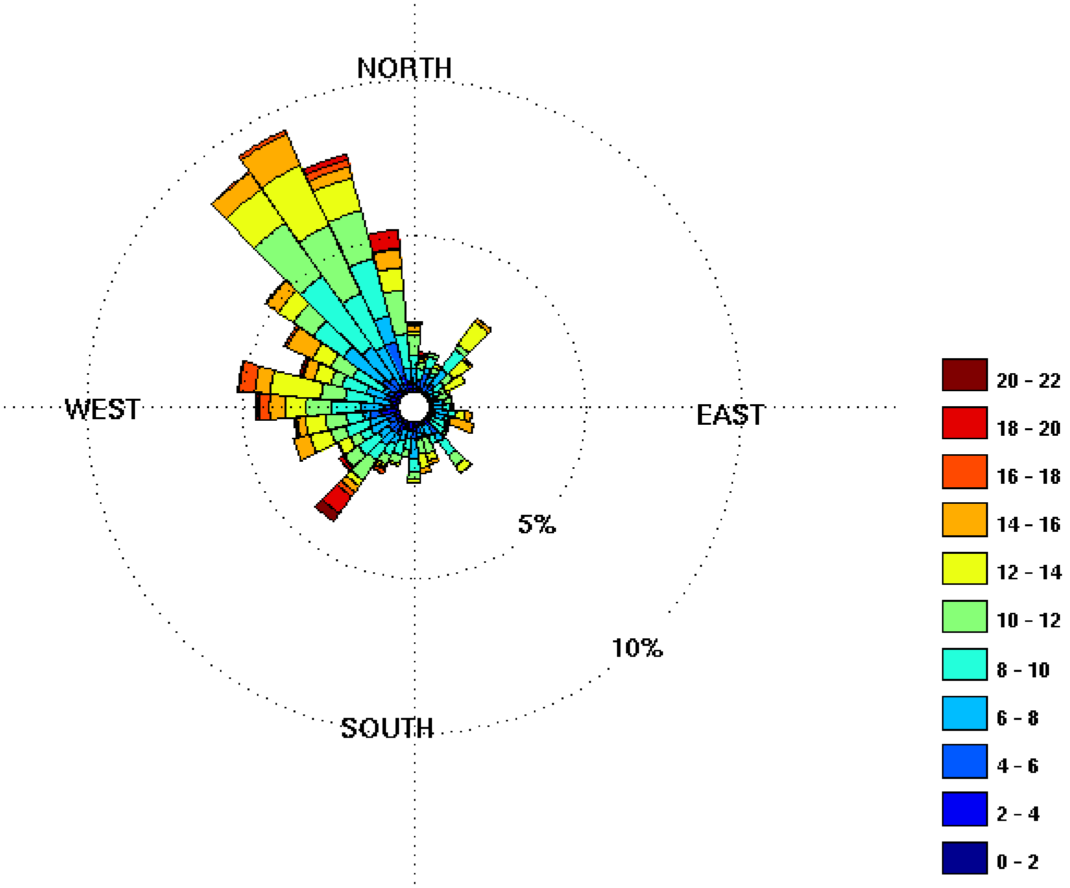


Figure 1: (a) Bathymetry (m) of the North Sea embedded in the COSMO model area (using a logarithmic scale) and (c) bathymetry (m) of German Bight as used in the WAM model. The positions of four waverider buoys used for the validation is indicated, too. (b) Tracks of all available satellite data used for validation during the selected period.



490 *Figure 2: Distribution of wind speeds (see colorbar) and directions at the FINO-1 waverider buoy for October - December 2013.*

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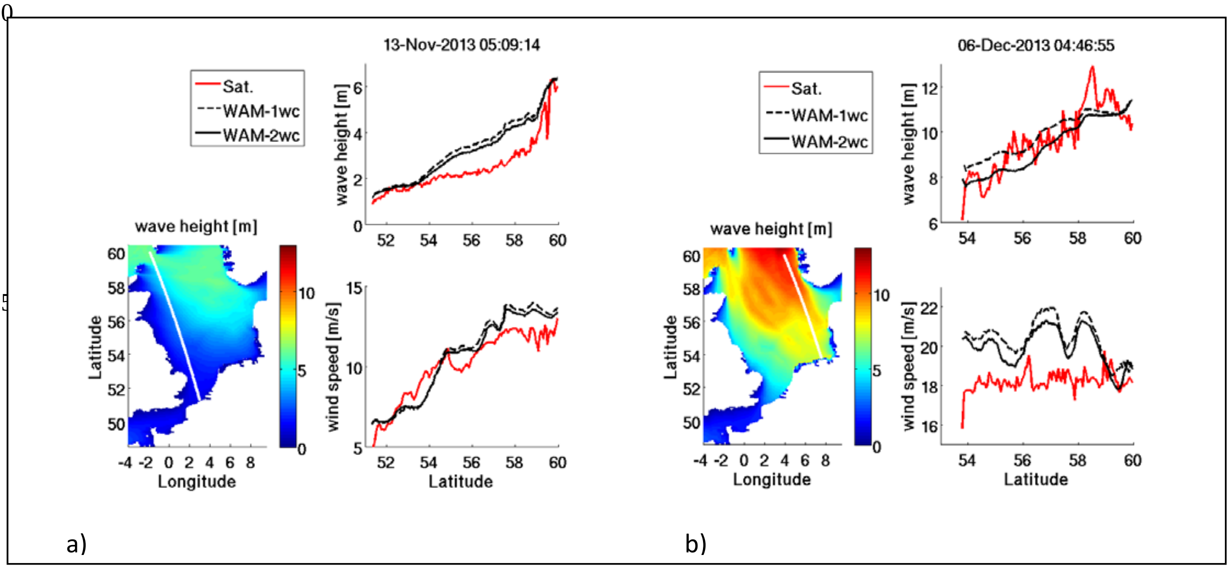

Figure 3: Time series wave height (m)and wind speed (m/s) from the Saral/AltiKa data and as modelled by WAM-NS under (a) calm and (b) the storm 'Xaver' conditions. Tthe track of the satellite (the white line) is shown together with the model significant wave height at the time of the passage (lower left panel).

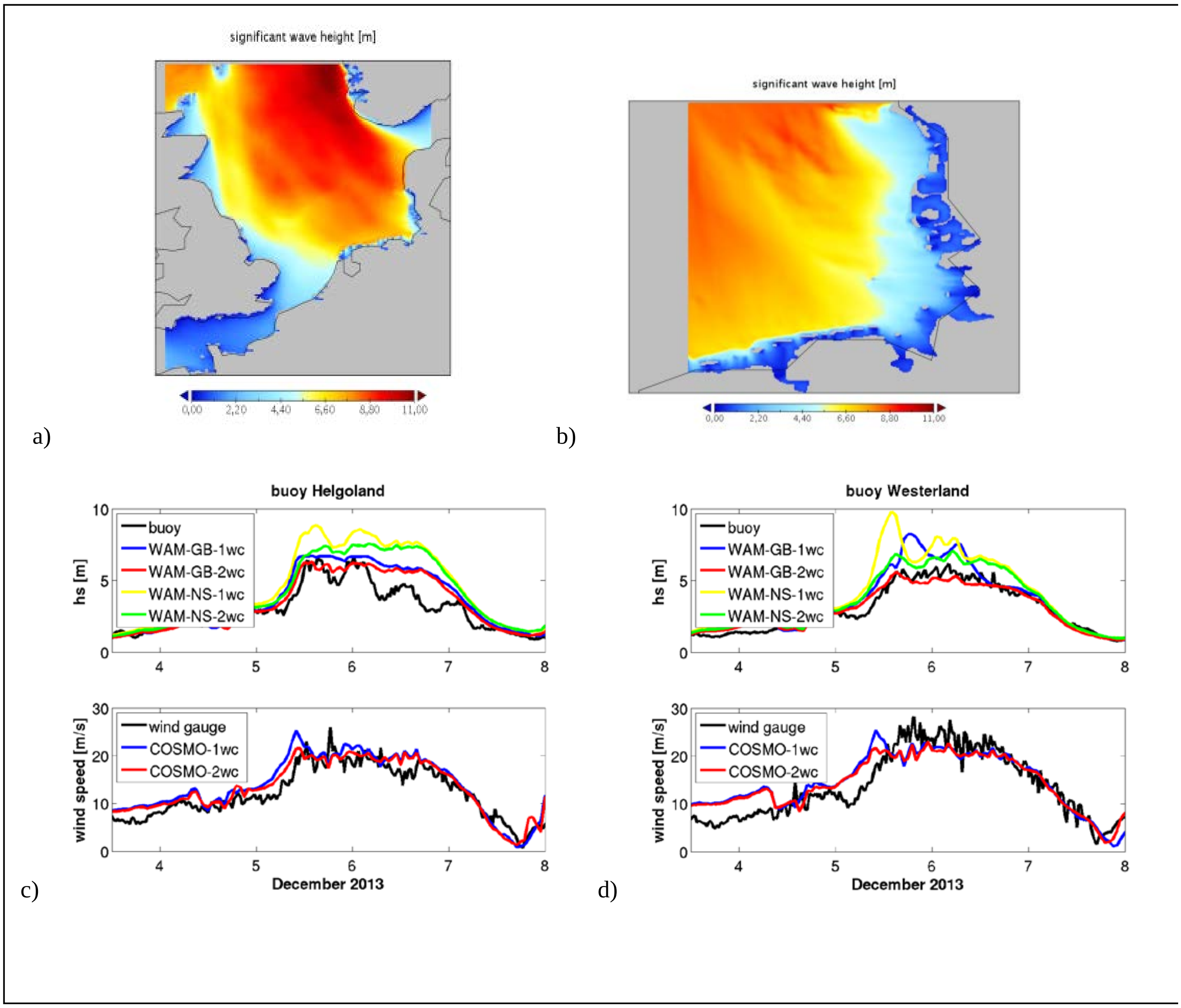

Figure 4: (a,b) Significant wave height (m) in the North Sea (a) and the German Bight (b) at the peak of the storm ‘Xaver’ (2013/12/6 9UTC) calculated by WAM-NS/GB-2wc. (c,d) Significant wave height (m,top) and wind speed (m/s, bottom) during the storm ‘Xaver’ at the buoys Helgoland (c) and Westerland/Sylt (d).

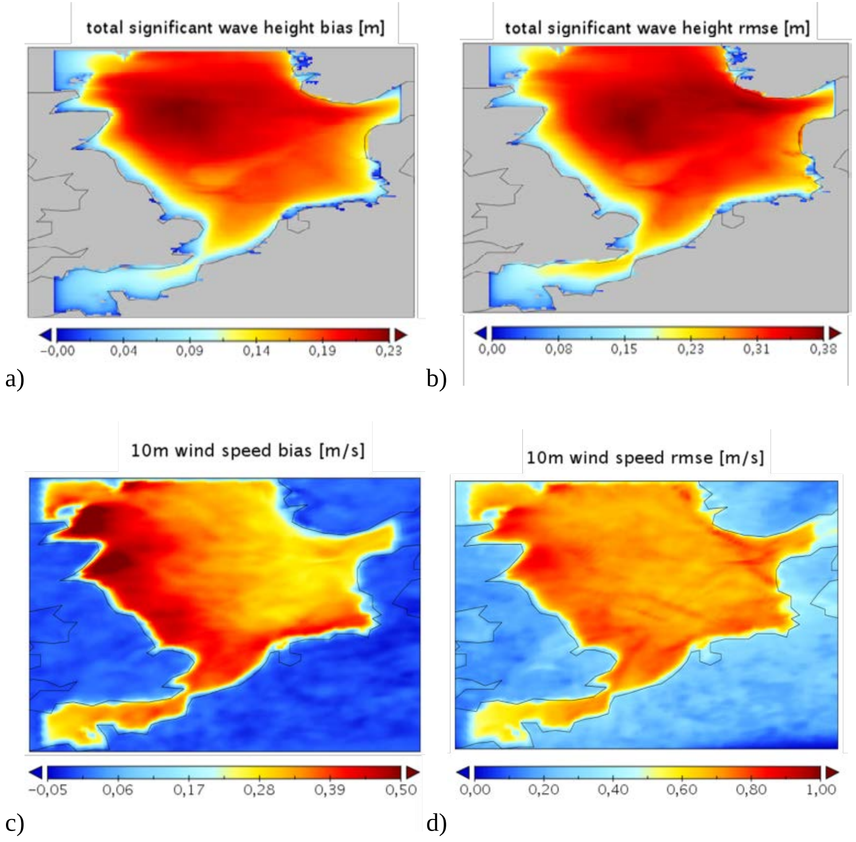

Figure 5: (a,c) Bias and (b,) rmse of WAM modeled significant wave height (m, top panel) and COSMO modeled wind speed (m/s, bottom panel) when comparing one-way minus two-way coupled modeling averaged over the whole period.

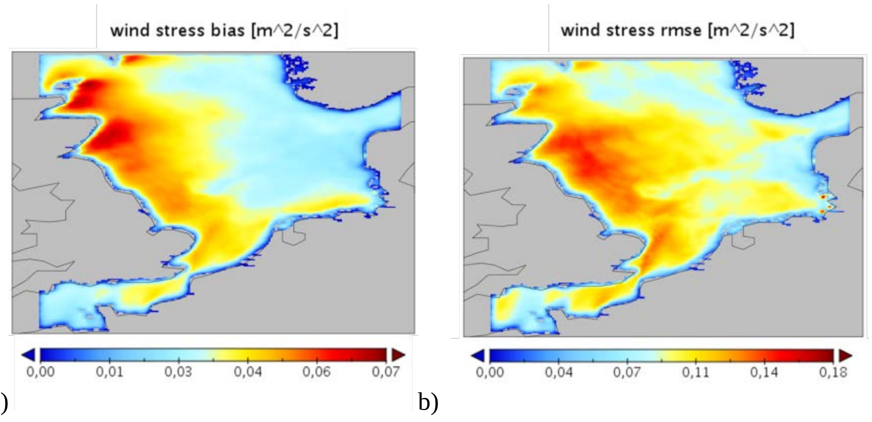

Figure 6: (a) Bias and (b) rmse of WAM/COSMO modeled wind stress when comparing one-way minus two-way coupled modeling over the whole period.

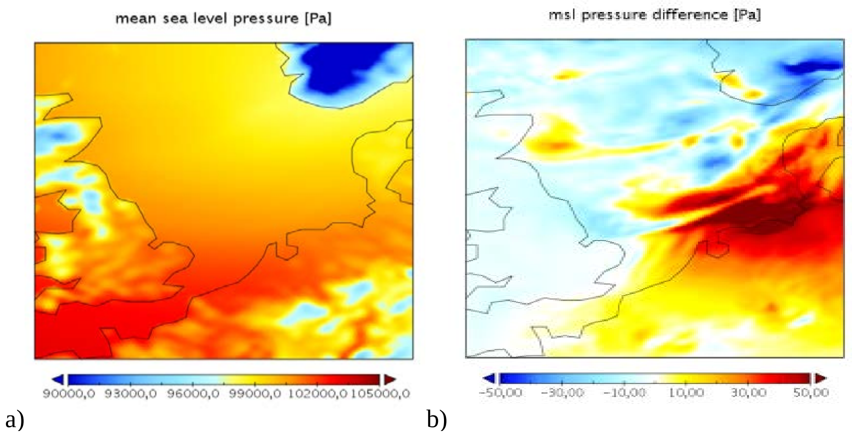

Figure 7: (a) COSMO pressure (Pa) at mean sea level height in the North Sea during storm 'Xaver' and (b) mean sea level pressure differences when comparing one-way minus two-way coupled modeling).

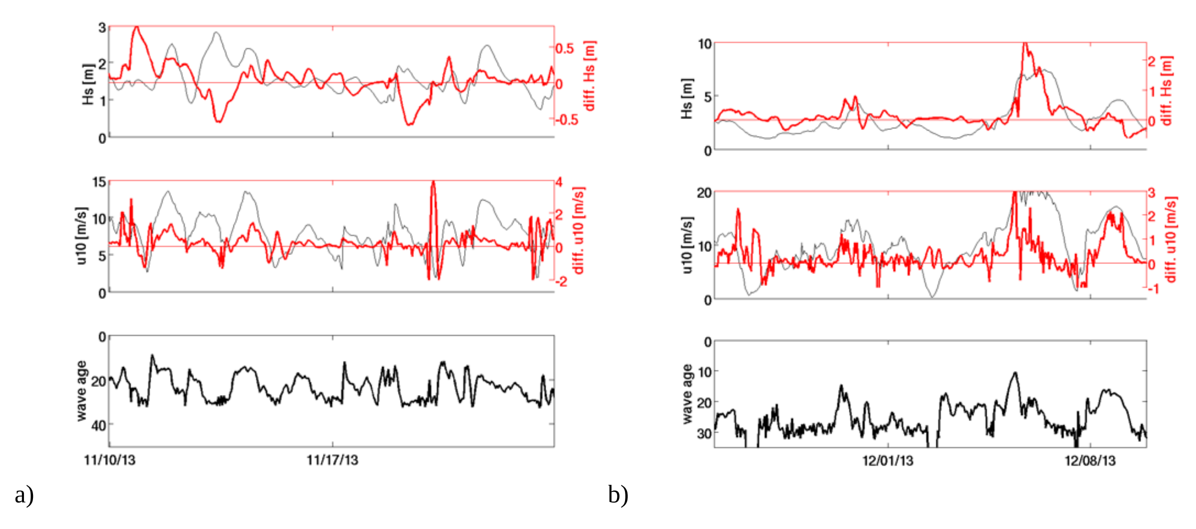

Figure 8: Time series of significant wave height (m, top), wind speed (m/s, middle) and wave age (bottom) from the two-way coupled German Bight setup at FINO-1 for (a) a rather calm period with young wind sea and (b) during the storm 'Xaver'). Red lines in the top and middle panel show the differences between the one-way and the two-way coupled models.

Table 1: Bias and standard deviation of validation of wind speed (m/s) and significant wave height (m) of the one- and the two-way coupled models against the available satellite data over the whole period (measured minus modelled).

	Significant wave height [m]		Windspeed [m/s]	
	one-way	two-way	one-way	two-way
Saral/AltiKa # 6886				
mean meas.	2.35		9.76	
bias	-0.27	-0.12	-0.64	-0.33
std. dev.	0.93	0.86	3.33	3.16
Jason2 # 6710				
mean meas.	2.38		9.62	
bias	-0.29	-0.15	-0.73	-0.40
std. dev.	1.07	1.01	3.85	3.75
Cryosat 2 # 7477				
mean meas.	2.71		10.62	
bias	0.18	0.31	0.39	0.65
std. dev.	0.90	0.87	3.33	3.18

Table 2: Wind speed (m/) bias and standard deviation of the one- and the two-way coupled COSMO model data against the FINO-1 data over the whole period (measured minus modelled).

	windspeed [m/s] at 50m		windspeed [m/s] at 100m	
	one-way	two-way	one-way	two-way
mean meas.	11.03		11.85	
bias	-0.67	-0.41	-0.23	0.01
rmse	3.26	3.17	3.33	3.22

Table 3: Significant wave height (m) bias and standard deviation of the one- and two-way coupled WAM German Bight model data against the available buoy data over the whole period (measured minus modelled).

bouy name (depth)	FINO-1(30m)		Elbe (25m)		Helgoland (30m)		Sylt (13m)	
mean meas. hs [m]	1.95		1.42		1.63		1.45	
	1-way	2-way	1-way	2-way	1-way	2-way	1-way	2-way
bias hs [m]	-0.14	-0.03	-0.07	-0.01	-0.13	-0.03	-0.15	-0.05
std. dev. hs [m]	0.45	0.50	0.49	0.49	0.54	0.55	0.59	0.59