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

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Abstract

The coupling of models is a commonly used approach when addressing the complex interactions between
15 different components of earth systems. We demonstrate that this approach can result in a reduction of errors in wave forecasting, especially in dynamically complicated coastal ocean areas, such as the southern part of the North Sea – the German Bight. Here, we study the effects of coupling of an atmospheric model (COSMO) and a wind wave model (WAM)*,* which is enabled through implementing wave induced drag in the atmospheric model. The numerical simulations use a regional North Sea
20 coupled wave-atmosphere model as well as a nested-grid high resolution German Bight wave model. Using one atmospheric and two wind wave models simultaneously allows for studying the individual and combined effects of two-way coupling and grid resolution. This approach proved to be particularly important under severe storm conditions as the German Bight is a very shallow and dynamically complex coastal area exposed to storm floods. The two-way coupling leads to a reduction of both surface wind
25 speeds and simulated wave heights. In this study, the sensitivity of atmospheric parameters, such as wind speed and atmospheric pressure to the wave-induced drag, in particular under storm conditions and the impact of two-way coupling on the wave model performance is quantified. Comparisons between data from *in-situ* and satellite altimeter observations indicate that two-way coupling improves the simulation of wind and wave parameters of the model and justifies its implementation for both operational and
30 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 usually considered as spatially uniform over water. In reality however, the wind waves extract energy and momentum from the atmosphere as they grow under the influence of wind. This effect is greater for young sea states and high wind speed in comparison to decaying sea and calm atmospheric conditions. Under such conditions, the drag coefficient cannot be considered as independent from the sea-state and as uniform in time and space. This dependence needs to be accounted for in coupled atmosphere-wave models. Jenkins *et al.* (2012) demonstrated that the wave field alters the ocean's aerodynamic roughness and the air–sea momentum flux depending on the relationship between the surface wind speed and the propagation speed of wave crests (the wave age). Based on high resolution coupled simulations, Doyle (1995) demonstrated that young ocean waves increase the effective surface roughness, decrease the 10-m wind speed, and modulate heat and moisture transports between the atmosphere and ocean. As a result of this boundary layer modification Doyle (1995) concluded that the mesoscale structures associated with cyclones are perturbed. The impact of sea surface roughness was investigated in studies by Bao *et al.* (2002) and Desjardins *et al.* (2000). As shown by Lionello *et al.* (1998), the two-way wave-atmosphere coupling attenuates the depth of the pressure minimum. In particular, non-linearities increase under extreme conditions, which can modify the intensity of storms due to feedbacks between waves and the atmosphere. This feedback needs to be accounted for in coupled models as strong winds cause the drag coefficient of the sea surface to increase leading to a reduction of wind speeds and modification of wind directions (Warner *et al.*, 2010). These effects feed back into the airflow, wind speed, and turbulence profile in the boundary layer. Zweers *et al.* (2010) showed that the used atmospheric model overestimates the surface drag for high wind speeds. At the same, the simulations underestimated the intensity of hurricane winds. Zweers *et al.* (2010) proposed an approach of calibrating the boundary layer parameterization using a one-way coupled model. They tested a new parameterization that decreased the surface drag for two hurricanes in the Caribbean. This new drag parameterization leads to much stronger forecasted hurricanes, which were in good agreement with observations.

The coupling between atmospheric and wind wave models was first introduced operationally in 1998 by the European Centre for Medium-Range Weather Forecasts (ECMWF). The method based on the theoretical work of Janssen (1991) contributed to an improvement of both atmospheric and surface wave forecasts on the global scale. Waves were recently considered in operational coupled model systems, such as that of Meteo-France (Voldoire *et al.,* 2013). Breivik *et al.* (2015) incorporated the effects of surface

waves onto ocean dynamics via ocean side stress, turbulent kinetic energy due to wave breaking, and the Stokes–Coriolis force in the ECMWF system.

The effect of coupling on model predictions becomes more important (Janssen et al. 2004) with increasing the grid resolution, which therefore emphasizes the need for coupling on the regional scales. Spatial and temporal changes in the wave and wave energy propagation are not yet sufficiently addressed in high-resolution regional atmospheric models. The shallow water terms in the wave equations (depth and current refraction, bottom friction and wave breaking) play a dominant role near coastal areas, especially during storm events, where the wave breaking term prevents unrealistically high waves near the coast. The spray caused by breaking waves modulates the atmosphere boundary layer. Air-sea interaction is also of great importance in regional climate modelling. Rutgersson et al. (2010, 2012) introduced two different parameterisations in a European climate model. One parameterisation uses roughness length and includes only the effect of a growing sea, as proposed by Janssen (1991). The other, uses wave age and introduced the reduction of roughness due to swell. In both cases, these parametrisations affected the long-term averages of atmospheric parameters notably and demonstrated that the swell has an important impact on mixing in the boundary layer is. Järvenoja and Tuomi (2002) emphasized the necessity to use wind data with fine temporal discretization in the wave model in the Baltic Sea and found the impact of the coupled model on the meteorological part of the model can mainly be seen in predicted surface winds. For the Mediterranean Sea, Cavaleri *et al.* (2012) found that reduced wind speeds were compensated by a limited deepening of the pressure fields of atmospheric cyclones. Lionello *et al.* (2003) demonstrated the importance of the atmosphere-wave interaction by studying the sea surface roughness feedback on momentum flux. In addition, a coupled ocean–atmosphere–wave–sediment transport (COAWST) modelling system has been developed for the coastal ocean (Warner et al, 2010, Kumar *et al.*, 2012). For the Balearic Sea, Renault *et al.* (2012) compared atmospheric and oceanic observations and showed that the use of COAWST improved their simulations, especially for storm events. Recently, high resolution, regional, and fully coupled models have been further developed, as shown by Katsafados *et al.* (2016) who used the Mediterranean Sea as an example. They focused on air–sea momentum fluxes in conditions of extremely strong and time-variable winds and demonstrated that by including the sea-state dependent drag coefficient, effects on wave spectrum and their feedback on momentum flux lead to improved model predictions. For the southern North Sea (the German Bight area), Staneva *et al.* (2016) showed the effect of wave-induced forcing on sea level variability and hydrodynamics, although wave-atmosphere interaction processes were not considered.

Model outputs can be validated against *in-situ* and space-based observational data from satellite altimetry. Analyses of the differences between altimeter and *in-situ* measurements over longer time intervals provide an estimate of the accuracy of altimeter data relative to *in-situ*-data assumed as ground-truth.

Significant wave heights derived from satellite altimetry have been compared to wave height measurements from several wave-riders in Passaro *et al.* (2015). Fenoglio-Marc *et al.* (2015) consider the complete satellite mission duration to derive an estimation of the accuracy for significant wave height and wind speed.

In this study, we aim at a quantification of the effects of coupling of the wave and atmospheric model, also during extreme storm events. We compare simulations from between coupled and stand-alone models that we validate with newly available space-based observational data. 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 the computed sea-surface roughness back to the atmospheric model. Then, we statistically assess the impact of the two-way coupling and validate the two setups against available *in-situ* and remote sensing data. Our novel contribution here is that we simultaneously run (via a coupler) a regional North Sea coupled wave-atmosphere model together with a nested-grid high resolution in the German Bight wave model (one atmospheric model and two wind wave models). Using this configuration allows us to study the individual and combined effects of (1) model coupling and (2) grid resolution, especially under severe storm conditions, which is a challenging aspect for wave modelling at the German Bight because it is a very shallow and dynamically complex coastal area.

The paper is structured as follows. First, we describe the models used, the coupling and specification of different model setups, period of model integration, and available data for validation in section 2. Afterwards, we validate the models against satellite and *in-situ* measurements in section 3. Section 4 discusses the impact of two-way coupling. The final section summarizes our findings and also provides an outlook for future research.

2. Model description and set-up

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, see also http://www2.cosmo-model.org/). Its climate model COSMO-CLM (CCLM) is used by the Climate Limited-area Modelling Community (http://www.clm-community.eu/). 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 with generalized terrain following vertical

coordinates. The model uses the primitive momentum equations. The continuity equation is replaced by a prognostic equation for perturbation pressure (i.e., pressure deviation from a reference state representing a time-independent dry atmosphere at rest, which is prescribed as horizontally homogeneous, vertically stratified and in hydrostatic balance).

In our setup, we use a spatial resolution of ~10 km and 40 vertical 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 database for the North Sea (Geyer, 2014) covering the period 1948-2013 with a spatial resolution of ~24 km (0.22°) and a temporal resolution of six hours.

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 maintained 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.* (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 wave model for the North Sea with a spatial resolution of ~5 km (Fig. 1a), and a finer wave model for the German Bight with a resolution of ~900 m (Fig. 1b). These models (described in Staneva *et al.,* 2015) use a directional resolution of $15°$ and 30 frequencies with an equidistant relative resolution ranging from 0.04 to 0.66. The boundary values for the North Sea model are taken from the regional model EWAM (European WAM) of the German Weather Service (DWD). The forcing wind data are provided by CCLM (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 sea state dependent roughness length, according to Janssen (1991), has already been implemented into WAM-4.5.4. Thus for the present study, the model only needed to be adapted for the 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) from the European Centre for Research and Advanced Training in Scientific Computation (CERFACS) and MCT (the Model Coupling Toolkit) that was developed by Argonne National Laboratory in the USA. Details of properties and usage of the coupler OASIS3 can be found in Valcke

(2013). Exchanged fields between the atmospheric and wave models in this study are wind and sea surface roughness length. For the coupling with OASIS3 the modifications in the atmospheric model are as in Ho-Hagemann *et al.* (2013), and in the wave model WAM as in Staneva *et al.* (2016).

We perform one-way and two-way coupled simulations. In the one-way coupled model, the atmospheric model provides wind data for the North Sea wave model via OASIS. This is equivalent to the familiar forcing of a wave model by 10 m wind fields. We will refer to the results of these simulations as COSMO-1wc and WAM-NS-1wc, where '1wc' and 'NS' stand for 'one-way coupled' and 'North Sea', respectively. In the two-way coupled model, the North Sea wave model is forced with winds provided by the atmospheric model and the sea surface roughness lengths are sent back to the atmospheric model, which in return might change the wind speeds. We will refer to the results of these simulations as COSMO-2wc and WAM-NS-2wc, respectively. The coupling time step is 3 minutes for all the simulations. This short time step is a great advantage when modelling fast moving storms in comparison to using stand-alone wave models forced by winds, which are usually available in hourly time steps.

The high resolution German Bight wave model, which also runs simultaneously with CCLM and North Sea WAM, is forced in two simulations by the CCLM wind and the boundary data provided by the North Sea WAM set-up. We will refer to the two differently forced setups as WAM-GB-1wc and WAM-GB-2wc. In the second experiment roughness information is sent to the atmospheric model by WAM-NS-2wc, while it is not in the first experiment. Compared to previous atmosphere-wave coupling research, our study is novel as we are able to simultaneously run a high resolution coastal model (the German Bight one) that uses winds and lateral forcing provided by the coupled regional atmosphere (COSMO-2wc) and wave (WAM-NS-2wc) models.

2.4 Study Period and Data Availability

The coupled wave-atmosphere model system described in the previous section was used to simulate a three-month period from October to December 2013. This period was chosen because it includes the time when the storm Xaver passed over the study area on the 6th of December, 2013. This was one of the most severe storms of the last decade, which 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. At the German Bight, the arrival of Xaver coincided in time with a high tide. Because of the high tide and wind gusts of greater than 130 km/h, an extreme weather warning was given to the coastal areas of north-western Germany (Deutschländer *et al.*, 2013). This storm event was also exceptional because of its long duration of nearly two days. The surge height reached ~2.5 m, with its maximum at low tide. During Xaver, two surge maxima were observed (Staneva *et al.*, 2016). Fenoglio-Marc *et al.* (2015)

200   described the first surge maximum as a wind-induced maximum. They found that the surge derived from the tide gauge records at Aberdeen and Lowestoft stations, had only one maximum, reaching the eastern North Sea coastal areas (anticlockwise propagation) approximately ten hours later than at Lowestoft (easternmost UK coast). This caused the second storm surge maximum, which was detected by the measurements in the German Bight. As demonstrated by Staneva *et al.* (2016), the wave-induced

205   mechanisms contributed to a persistent increase of the surge after the first maximum (with slight overestimation after the second peak).

In the present study, we perform statistical analyses for the whole integration period and investigate the period of the extreme storm event Xaver in more detail. The distribution of wind speeds and directions over the selected period as seen in the waverider data from the *in-situ* platform FINO-1 (see Fig. 1b for its

210   location) is shown in Fig. 2. North-westerly winds are generally dominant, but strong winds (higher than 20 m/s) came from the west and southwest as the Xaver storm moved eastwards. South-easterly and north-easterly winds are rarely observed at the FINO-1 station.

To validate our experiments, we use wind speed and significant wave height data measured by satellite altimeters SARAL/AltiKa, Jason-2 and CryoSat-2 over the North Sea (see Fig. 3 with the tracks of the

215   different satellites over the three-month study period). The first two carry classical pulse-limited altimeters that operate in a low resolution mode (LRM), while the CryoSat-2 instruments operate in an LRM or in Delay Doppler Altimetry (DDA) mode. The CryoSat-2 data used here were extracted from the RADS database (Scharroo *et al.,* 2013), where CryoSat-2 data acquired in DD mode in our region was processed to generate pseudo-LRM data (PLRM). Accuracy and precision of PLRM data are slightly

220   lower than LRM and SAR data (Smith and Scharroo, 2015). The altimeter satellites observe along their ground-track offshore up to a few kilometres from the coast (Fig. 3). Their ground track pattern and repeat period are different for each of the three missions, as the same location is revisited by each mission every 27, 10, and 350 days (Chelton *et al.*, 2001). The SARAL/AltiKa data are of special interest in our study because this satellite passed over German Bight during the storm Xaver when the surge was at its

225   maximum (Fenoglio-Marc *et al.,* 2015). The *in-situ* wave data from four directional waveriders at German Bight are provided by the Federal Maritime and Hydrographic Agency (BSH) (see Fig. 1b for the buoy locations). The wind speed measurements close to the shore of the Island of Sylt, near the Westerland buoy location, and on the island of Helgoland are provided by the DWD. At station FINO-1 (see Fig. 1b for its location), there were also wind speed measurements available at 50 and 100 m above

230   sea level for the selected period.

3. Validation of the results

3.1 Altimeter data

The long revisiting time of the same location and the global coverage could be considered as intrinsic characteristics of the satellite altimetry. Therefore, a longer interval of analysis is needed when analysing the agreement between altimeter and *in-situ* measurements, collected from waveriders and anemometers. The tracks during the study period for the three different satellites are illustrated in Fig. 3. Wind speed and significant wave height data measured at FINO-1 station during the 5-day period (2-7 December, 2013) are shown in Fig. 4. The nearest point observations of the satellite altimeter SARAL/Altika, as it passed over the region at 5:45 on December 6th (see also Fenoglio-Marc *et al.*, 2015) are specified with the blue mark also in Fig. 4. The wave height and wind speed measured by the SARAL/Altika altimeter (blue symbol) during the Xaver storm are in good agreement with *in-situ* observations.

The differences between the altimeter and *in-situ* measurements over longer time intervals provide an estimate of the accuracy of the altimeter data relative to the in-situ-data assumed as ground-truth. Fenoglio-Marc *et al.* (2015) considered both wave height and wind speed derived from DDA, (also called SAR altimetry) located at a distance to coast greater than 10 kilometres and showed that comparison to *in-situ* observations from the same *in-situ* stations network in the German Bight gave standard deviations between 30 and 15 cm for wave height; 1.6 m/s and 1.8 m/s for wind speed. They also found a good consistency between pseudo-conventional (PLRM) and SAR in the open ocean, with root mean square*RMS* differences of 21 cm, and 0.26 m/s for wave height and wind speed respectively. *In-situ* analysis showed a higher accuracy for SAR compared to PLRM. As a demonstration, Fig. 5 shows the scatterplots for FINO-1 and CryoSat-2 SAR and PLRM measurements. For the wind speed the accuracy of SAR and PLRM is similar and the standard deviation (*STD*) between the two data sets is 1.9 m/s. For the significant wave height (Fig. 5a), we observe a higher accuracy in SAR than in the standard PLRM retracking (*STD* is 18 and 30 cm, respectively). The accuracy in the significant wave height from PLRM increases (*STD* is 19 cm) when a dedicated retracking procedure is applied (Fenoglio-Marc *et al.*, 2015). Figure 5b shows an underestimation of wind speed of altimetry relative to the *in-situ* data (slope is below 0.8 in all cases).

3.2 Altimeter-model comparisons

In this section, we quantify the performance of one-way *versus* two-way coupling by comparing the output of the atmospheric and wave models against remotely sensed data. Table 1 gives the statistics of the differences (bias and standard deviations) between the model and altimeter-derived values of wave

height and wind speed over the selected three-month period. The numbers of matched pairs (approximately 7000) of observations and simulations are also given in Table 1 for the different satellites.

270   For all three satellites, the standard deviation in the two-way coupled model is smaller than in the one-way coupled model. For Jason-2 and SARAL/Altika, the bias in the two-way coupled model is nearly halved compared to the bias in the one-way model. Measured values are lower than the modelled values in the one-way and two-way experiments.

For Cryosat-2, on the contrary, the measured values are higher than the modelled values on average for

275   both the wave height and wind speed. The biases between the CryoSat-2 data and the two-way model simulations (see the red shaded values in Table 1) are larger than the biases between the CryoSat-2 data and the one-way model runs. Fenoglio-Marc *et al.* (2015) also found that the CryoSat-2 derived wave height data overestimate the wave model data from the DWD. However, they found the opposite for the wind speed. i.e. the CryoSat-2 derived wind speed underestimates the COSMO winds from the DWD

280   data. This disagreement is due to the different data that have been used to force the atmospheric models by DWD and this study. Particularly challenging for the significant wave height (*SWH)* detection are coastal data, due to land and calm water interference in the altimeter footprint, and low sea states, due to an extremely sharp leading edge in the waveform that is consequently poorly sampled (Passaro et al., 2015). The wind speed instead is derived from the backscatter coefficient, which is related to the

285   amplitude of the waveform.

To perform a spatial comparison between model simulations and the satellite data, we analysed individual tracks over the North Sea, and two of these are shown in Figures 6 and 7. The satellite altimetry observations along the ground-track at the time of the overflight at the German Bight last ~38 sec. The selected SARAL/AltiKa passes are very diverse, as one was taken under calm conditions (Fig. 6) and the

290   other during the storm Xaver (Fig. 7), which therefore provided an opportunity to compare measured and modelled wave heights and wind speeds along the satellite tracks under different atmospheric and wave conditions illustrated in Figures 6 and 7. Under calm conditions, differences between the results of the one- and two-way coupling are very small (Fig. 6a). Both models (WAM-NS-1wc and WAM-NS-2wc) overestimate the measured wave height (red line) over a large part of the track. However, the increase of

295   modelled wave height with increasing latitude appears to be consistent with the northward wind speed increase observed by the satellite data and simulated in the two simulations (Fig. 6b). During the storm Xaver, the difference between the wave height in the WAM-NS-1wc and WAM-NS-2wc simulations (Fig. 7a) increases up to 1 m in the southern North Sea. The altimeter-derived quantities fluctuate greatly. However, the two-way coupled-model results are closer to the satellite data, in comparison to the ones in

300   WAM-NS-1wc, except for the latitude of ~56$^\text{o}$ N, where the significant wave height from the satellite measurements has a local peak. The modelled significant wave height (black lines) is much smoother than

the satellite observations (red line), which can be explained by the fact that the model is not capable to resolve the small scales seen in the satellite observations. The corresponding wind speed does not grow at this latitude, neither for the measured nor the modelled wind speeds. It is noteworthy that both model experiments missed the peak in measured SWH above 58° N (Fig. 7a). The modelled wind speed well fits the altimeter-derived data during calm conditions in both experiments (COSMO-1wc/2wc, Fig. 6b). Northwards of 55° N, the wind speed is higher than 10 m/s, while the wind speed in the two-way coupled experiment (COSMO-2wc, full line) is slightly lower than in COSMO-1wc. During the storm Xaver, the measured wind data fluctuate ~18 m/s, whereas the modelled data show much higher values of ~20 m/s, reaching ~22 m/s at ~57° N and 59° N (Fig. 7b). This confirms the findings of Fenoglio-Marc *et al.* (2015), who had compared the same altimeter data with ERA-Interim, NOAA/GFC and COSMO/EU winds. They suggested that the low wind speeds derived from the altimeter are caused by an overestimation of the atmospheric attenuation of the radar power in the Ka-band. In fact a larger attenuation correction would result in a too large backscatter coefficient and hence a reduced wind speed (Fenoglio-Marc *et al.,*2015) 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). Similar analyses along all tracks over the study period agree with the two examples demonstrated in Figs. 6 and 7. In general, the measured wind speeds were in slightly better agreement with the two-way coupled model results, which was also demonstrated by statistics presented in Table 1. The track during the time of storm Xaver was the only track taken under such extreme conditions.

3.3 Validation against in-situ measurements

Analyses of the temporal variability of the significant wave heights in the German Bight under stormy conditions allow us to investigate not only the impact of two-way coupling but also the role of the horizontal resolution. Figure 8 illustrates the time variability of the significant wave height (top) and the wind speed (bottom) at the Helgoland and Westerland stations (see for locations Fig. 1b) from observations (black line) and the different model runs during the storm Xaver.

The wind fields in both locations are very similar in the COSMO-1wc/2wc model runs; the peak of the storm is reduced from 26 to 22 m/s. By comparing the model and measured wind speed, it is noticeable that the modelled wind speeds grow too early and too high at all locations at the beginning of the storm (see the bottom patterns in Fig. 8a,b for the Helgoland and Westerland examples). The storm characteristics are matched well at Helgoland but are slightly underestimated at Westerland. Still, the overall model performance at Westerland is satisfactory, considering the strongly fluctuating wind

335 measurements. Similar behaviour is observed for the Elbe and Fino-1 (not shown here) wave buoy stations.

Throughout this period, the highest values of significant wave heights are simulated by the WAM-NS-1wc experiment. The lowest values, and closest to the observations, are from the WAM-GB-2wc simulations (Fig. 8). At the beginning of December, during the calm atmospheric conditions, all model
340 results are similar and fit relatively well with the *in-situ* measurements. The differences in the wave growth between the different model simulations become notable after the storm onset. During the peak of the storm, the WAM-NS-1wc simulation overestimates the measured wave heights by ~3 m at the Helgoland station (water depth 30 m, Fig. 8a) and by ~4 m at the shallow water of the Westerland station (water depth 13 m, Fig. 8b). Compared to the in-situ measurements, this peak occurs earlier in all
345 simulations due to the time discrepancy between wind data and model time steps. The wave heights predicted by the WAM-GB-2wc are agree with the observations best, especially for the Westerland station (Fig 8b, the red-line).

The influence of spatial resolution on the simulated characteristics can be clearly seen in the time series at the deep water buoy at Helgoland, for which the differences between simulated wave heights during the
350 storm Xaver reach ~1 to 1.5 m in the corresponding North Sea and German Bight simulations (Fig. 8a). This buoy is located in an area of large gradients in water depth (Fig. 1b), where the high resolution model uses a finer bathymetry at coastal areas with a rather complex shore (such as at Helgoland) leading to a better simulation of wave heights.

At the shallow Westerland buoy station (Fig. 8b) the differences are additionally enhanced by the depth-
355 induced wave breaking in the German Bight model. This can also be seen in the snapshots of wave height in the North Sea and German Bight models at the peak of the storm (Fig. 9 a, b). Shoreward of the 15 m isobaths, the wave heights drop from 6 to 4 m in the German Bight model. In contrast, for the North Sea model, the 6 m high waves reach the south-eastern coast. The WAM-NS-1wc model run underperforms in comparison to the WAM-NS-2wc simulation at Westerland. This underperformance further proves the
360 importance of two-way coupling for the coastal German Bight areas, where the model wind speed is even higher (by ~2 m/s) than at Helgoland. We admit that it is difficult to differentiate between the effects due to wave breaking and two-way coupling because both contribute to reducing the wave height under extreme weather conditions. Wave breaking plays a dominant role in very shallow water, especially during storm events, by preventing unrealistically high waves near the coast. For deep waters, the sea
365 surface roughness feedback due to the two-way coupling plays a very important role (Fig. 8a). The importance of the two-way coupling is clearly demonstrated by comparing the WAM-GB-2wc (the blue line) and WAM-GB-1wc (the red line) in Fig. 8. For all stations, the simulated SWH in WAM-GB-2wc is reduced, especially during the Xaver peak, and is closer to the measurements.

The wind speeds are validated against measured data from FINO-1 in 50 m and 100 m height over the whole modelling period (Table 2). We find better agreement in the two-way coupled run. The bias in wind speed is negative for the one-way coupled setup, i. e. the modelled wind speed is overestimated. The bias is significantly reduced due to the lower wind speed in the two-way coupled model. The *RMS* difference is ~3 m/s in either case, but slightly reduced for the full coupled setup.

For a more quantitative validation of the WAM-GB-1wc/2wc results, we use four buoys (see Fig. 1b for their locations) in water depths of 13 to 30 m. Table 3 gives the statistics for significant wave height (*SWH*) over the whole period (there are ~4000 matched pairs). For the four buoys and regardless of the type of coupling, the bias for *SWH* is slightly negative, i.e.*,* the modelled data over predict the measured values. The simulated significant wave heights are lower and the bias between the measurements and model results are significantly reduced in the WAM-GB-2wc experiment. The standard deviation of the significant wave height of the two-way coupled simulation is similar to that of the one–way coupled simulations. Only for the FINO-1 station, the standard deviation is increased by ~2.5% in the two-way coupled model run.

4 Impact of the two-way coupling

In the following discussion, the impact of coupling is analysed for the North Sea focusing on the spatial patterns under different physical conditions. The three-month average of the significant wave height and wind speed are reduced significantly (Fig. 10) for the two-way coupling compared to the one-way coupling. This reduction results from an extraction of energy and momentum from the atmosphere by waves. The average difference in wave height (Fig. 10a) is ~20 cm, which is a reduction of ~8% of the three-month mean value (~2.3 m). The *RMS* difference between the two simulations (Fig. 10b) is ~40 cm in the central North Sea. For the wind speeds, the averaged difference (Fig. 10c) is ~30 cm/s when averaged over the model area, corresponding to a reduction in wind speed of ~3% of the three-month mean value (~10 m/s). The *RMS* difference (Fig. 10d) between the two-way and one-way coupled simulations over the whole North Sea area is ~80 cm/s. The spatial patterns in the averaged differences in Fig. 10 can be explained by the dominant westerly winds (Fig. 2). As the wind comes from land (Great Britain) and strikes the North Sea, the differences in the wind speed between the two models are larger closer to the coast because of differences in sea surface roughness. Moving further east, the atmospheric boundary layer adapts in both cases to the winds over sea, and there is less difference between the one- and two-way coupled models. For the wave height, the averaged differences close to the western coasts and in the English Channel are small because the fetch is too short for the waves to evolve.

The differences in the mean sea-level pressure between COSMO-1wc/2wc for the storm Xaver period is analysed in Fig. 10. At the peak of the storm (Fig. 11a) the mean sea level pressure is ~900 hPa over Norway and ~1000 hPa over the North Sea. Compared to the one-way coupled setup, the pressure increased by ~50-100 Pa in the southeast (Fig. 11b). The slightly decreased pressure in the remaining part of the model area indicates a shift of the pressure low minimum, confirming the results of Cavaleri *et al.* (2012), who found similar patterns in the Mediterranean Sea under developing cyclones. As noted by Janssen and Viterbo (1996), the timescale of the wave impact on the atmospheric circulation is in the order of five days. However, our model area is too small to observe this impact. It is more plausible that our results are caused by wave-mean flow interactions in the atmosphere. This effect of wave coupling on the atmospheric circulation will be analysed thoroughly in future experiments.

Another illustration of the influence of the coupling is given by the two time series at the FINO-1 station, each about two weeks long and taken under very different conditions. One period is in November, which was rather calm and contained young and developing wind seas (Fig. 12). The other period was in December with several storms coming from the North Sea (including Xaver) with higher wave ages (Fig. 13). 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. The largest differences can be observed when the wave age (the ratio of phase velocity at the peak of the wave spectrum with friction velocity) is well below 20 and occurs before the maximum wave height has been reached (this can be well seen for Xaver, Fig. 13). Thus, the waves grow slower in the two-way coupled model. Negative differences seldom occur; only when the wave age increases rapidly (when the wind speeds approaches zero, the wave age diverges infinitely).

5.   Summary and Outlook

We developed a two-way coupled wave-atmosphere model for the North Sea including the possibility of nesting a coastal, high-resolution wave model, where the two models run simultaneously. The coupling software OASIS3-MCT that we used, allows for a parallel run of several models on different model grids. Simultaneous simulations of a regional North Sea coupled wave-atmosphere model together with a nested-grid high resolution in the German Bight wave model (one atmospheric model and two wind wave models) were performed. This enabled us to study the individual and combined effects of two-way coupling and grid resolution, especially under severe storm conditions. The sensitivity of atmospheric parameters such as wind speed and atmospheric pressure to wave-induced drag were quantified. Model intercomparisons gave encouraging results. Overall, the two-way coupled model results were in better

agreement with the *in-situ* and remotely sensed data of significant wave height and wind speed, in comparison to the one-way coupled model (COSMO drives WAM). New in this paper is the use of satellite altimetry, which provides complementary information to *in-situ* data for the validation of models. We show that comparisons between the model results and satellite-derived parameters are satisfactory, except for a known degradation of wind speed in storm conditions, which is under investigation. The two-way coupling improved the modelled significant wave heights in the German Bight, which was demonstrated by the validation against *in-situ* 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 ~8 m to ~5 m due to the coupling, which matched buoy measurements very well. The corresponding wind speeds were lowered from ~22 to ~20 m/s. In addition to 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 slight increase of the pressure field from the two-way coupled model runs. These results may also have been caused by the wave-mean flow interactions in the atmosphere. This will be the subject of subsequent work, where we will study in more depth the consequences of coupling with other atmospheric parameters at sea level and the vertical structure of the planetary boundary layer.

Staneva *et al.* (2016) addressed the impact of coupling between wave and circulation models of the German Bight during extreme storm events. They demonstrated that the coupled model results revealed a closer match with observations than the stand-alone circulation model, especially during the extreme storm Xaver in December 2013. Staneva *et al.* (2016) showed also that the predicted surge of the coupled model is significantly enhanced during extreme storm events when accounting for wave-current interaction. We demonstrated that the potential uncertainties of shallow water in the wave model are due to both: inaccurate description in the bathymetry as well as to the wave model source terms related to shallow water physics. Shallow water regions with the strongest wave-current interactions contribute to the coupled wave-atmosphere dynamics during extreme storm surge events. Depth and current refraction, bottom friction and wave breaking in the wave model play dominant roles in very shallow water. The model resolution is critical where the depth gradients are large. The improved model skills resulting from the new model developments justify further extension of the coupled model system by integrating atmosphere-wave–current interactions to further investigate the effects of coupling, especially on extreme storm events. Two-way coupling of wave and atmospheric models is an important component of a fully coupled ocean-atmosphere modelling system, as it resolves more adequately the interactions and exchanges in the atmospheric boundary layer. Accurate modelling of the boundary layer is of utmost importance for long range predictions.

470   **Acknowledgments**

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475   boundary values from the coastDat2 database for us. Markus Schultze supported us by setting up the atmospheric model and getting it started. Ha Ho-Hagemann is supported through the German project REKLIM and the Baltic Earth Programme. Luciana Fenoglio is supported by the European Space Agency (ESA) within the Climate Change Initiative (CCI). The authors are grateful for I. Nöhren for assistance with the graphics and BSH for providing the observational data.

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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). The green shaded colouring means an improvement of the two-way coupled model skills; red shading colouring means that the one-way coupled model skill are better than the ones of the two-way coupled model.

	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
Jason-2 # 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). The green shaded colouring means an improvement of the two-way coupled 585 *model skills; red shading colouring means that the one-way coupled model skill are better than the ones of the two-way coupled model.*

	windspeed [m/s] at 50m		windspeed [m/s] at 100m	
	one-way	two-way	one-way	two-way 590
mean meas.	11.03		11.85	
Averaged difference	-0.67	-0.41	-0.23	0.01
RMS difference	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). The green shaded colouring means an improvement of the two-way coupled model skills; red shading colouring means that the one-way coupled model skill are better than the ones of the two-way coupled model.

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

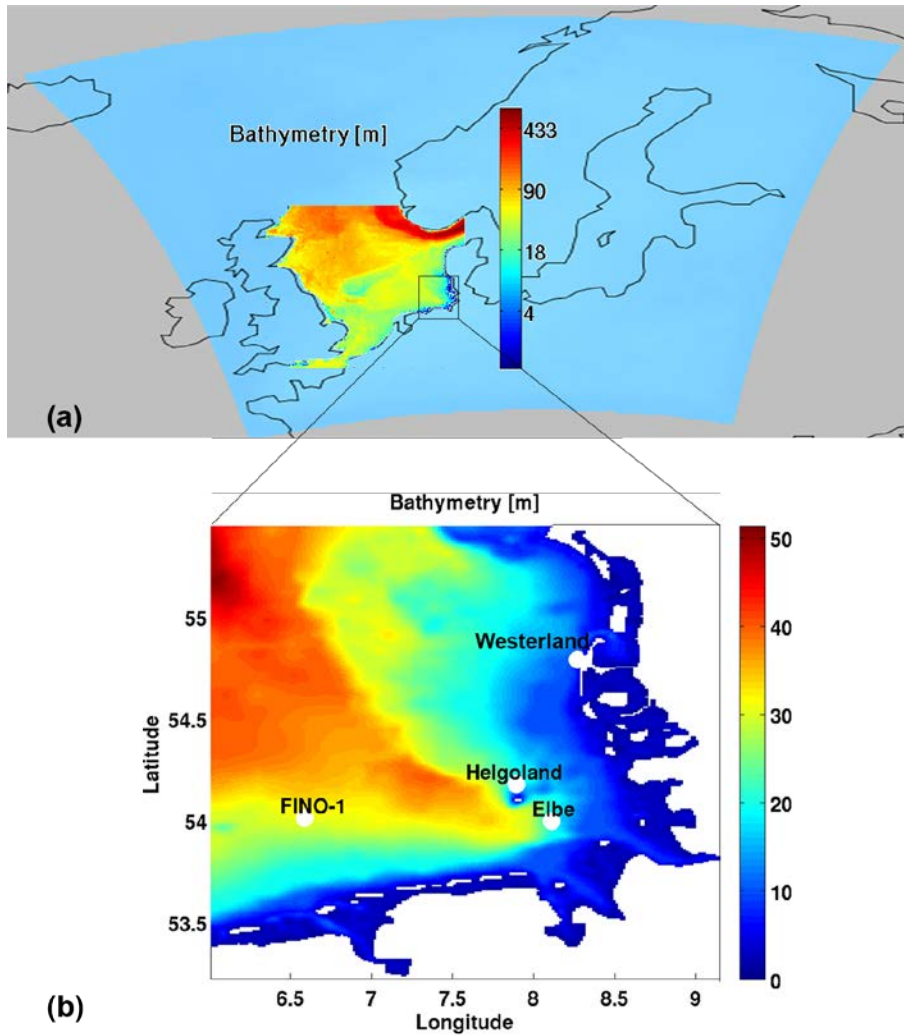
Figures

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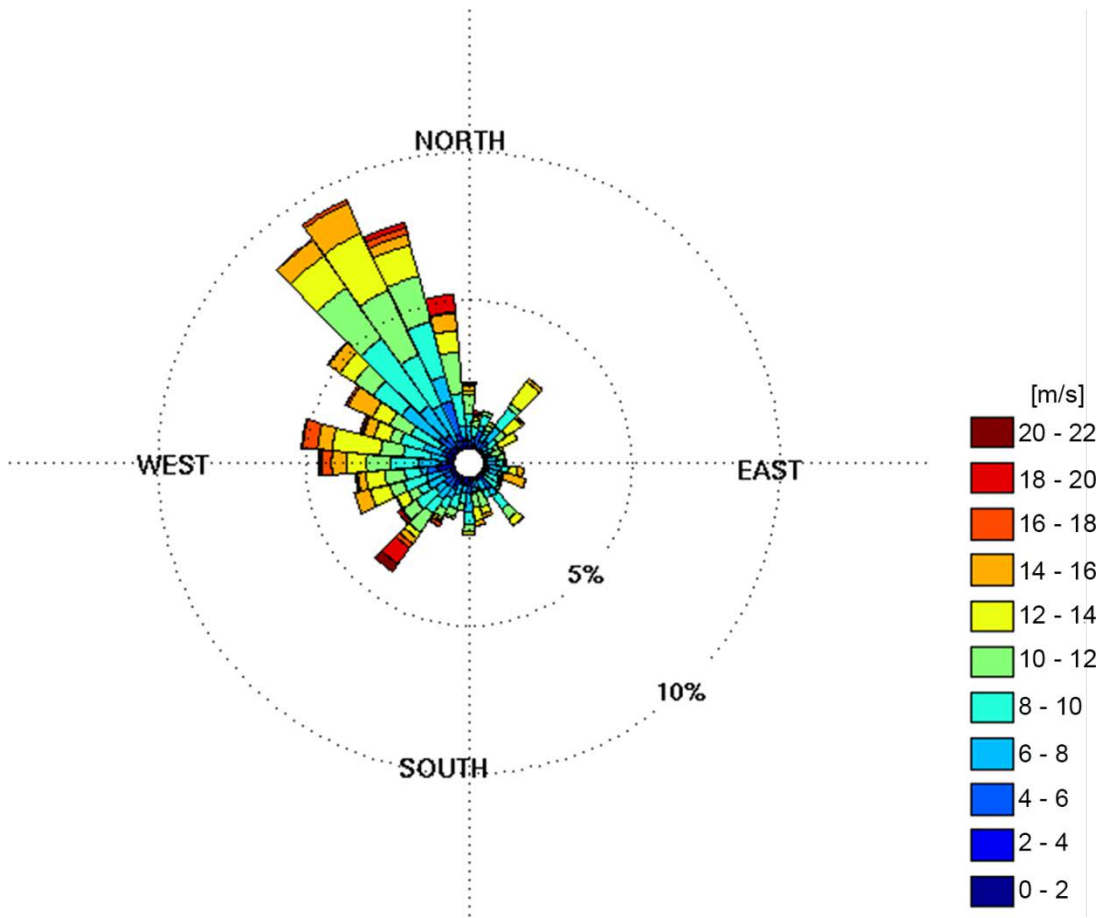
Figure 1: (a) Bathymetry (m) of the North Sea embedded in the COSMO model area (using a logarithmic scale) and (b) bathymetry (m) of German Bight as used in the WAM model. The positions of four waverider buoys used for the validation is indicated, too.

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Figure 2: Distribution of frequency and wind speeds in m/s (see color bar) and wind direction at the

FINO-1 waverider buoy for the period of 01. October, 2014 until 31 December 2013.
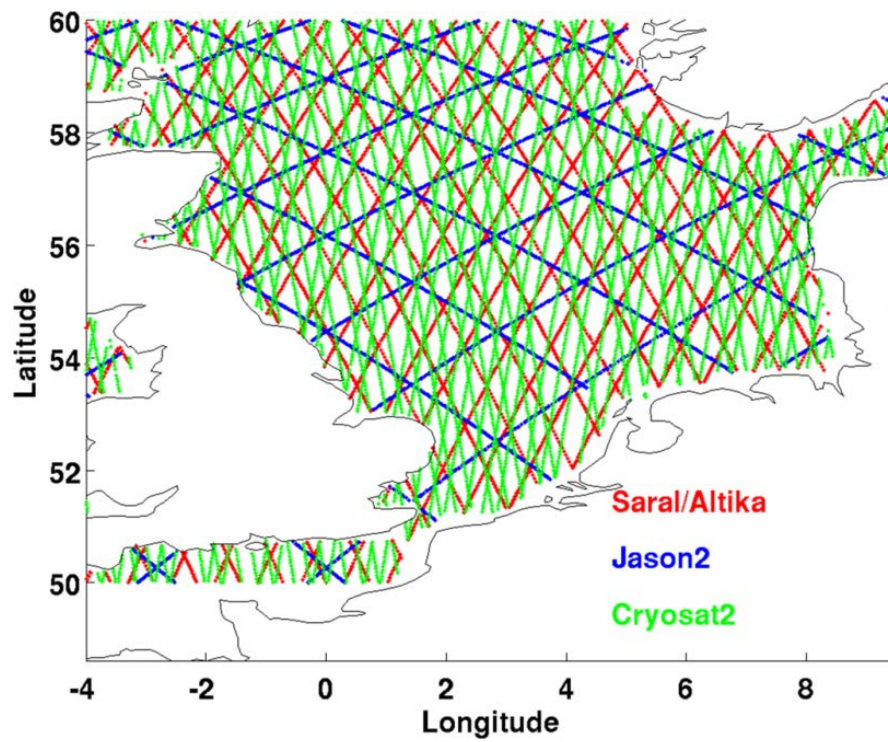
Figure 3: Tracks of all satellites during the study period (01. October, 2013 until 31 December 2013).

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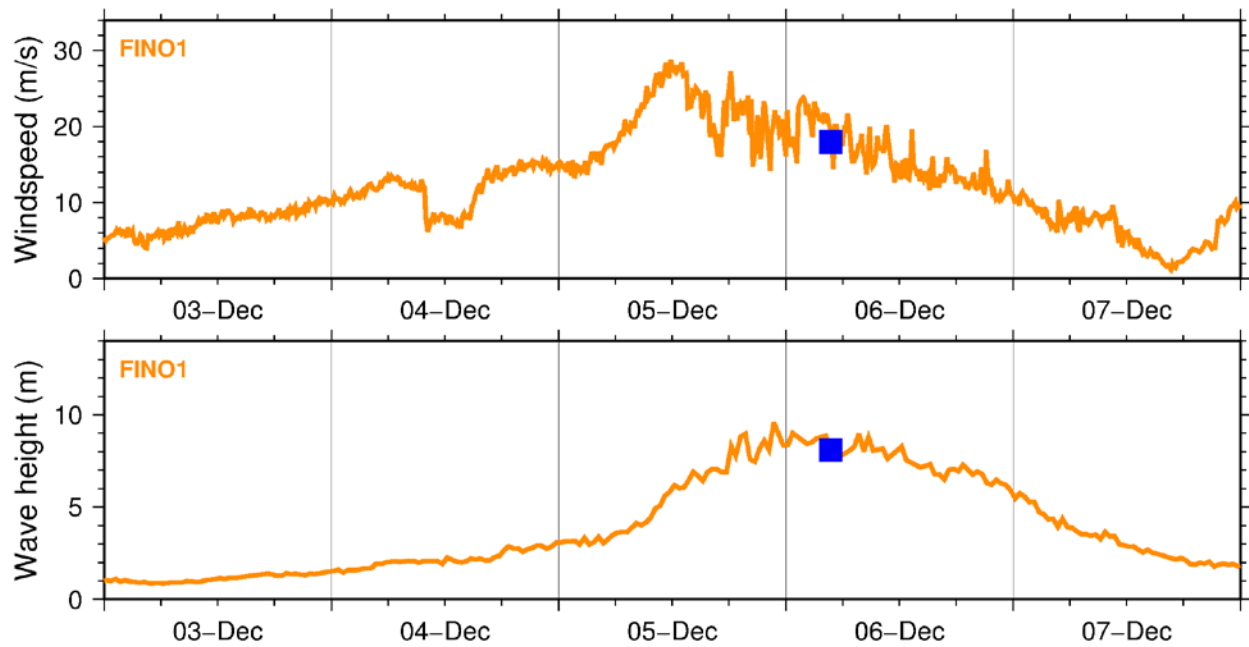
Figure 4: Time series during five days , which include the storm Xaver of the observations in station FINO-1 (orange line) together with the Saral/Altika observation (blue full square): (top) wind speed

615 (m/s) and bottom: significant wave height (m) The SARAL/AltiKa passed over the German Bight during the storm Xaver when the surge was at its maximum (the data during the overflight are ploted with a full blue mark).

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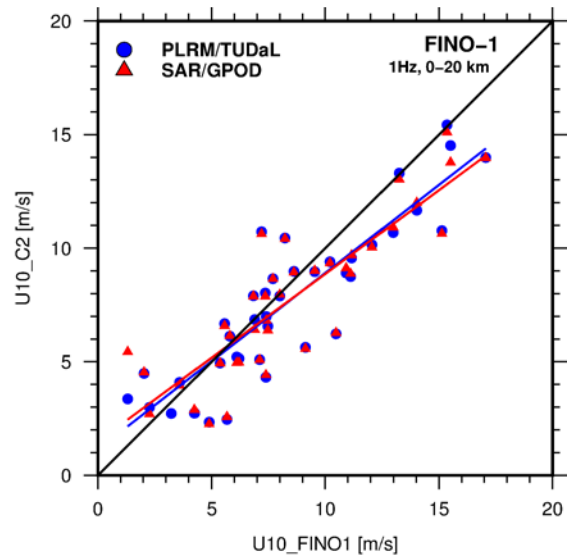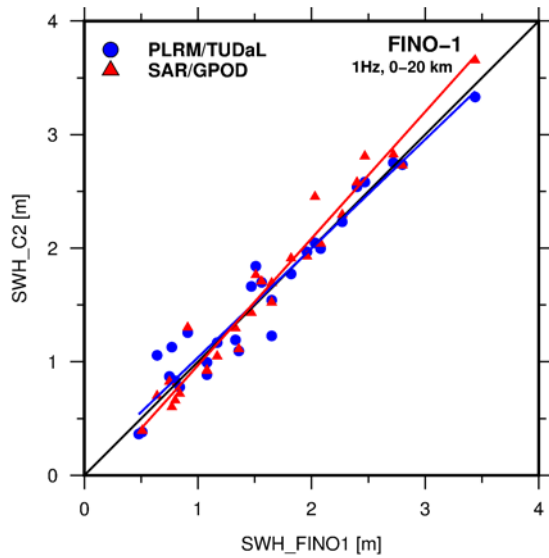
630    (a)               (b)

Figure 5. Comparison at the station FINO-1 of in-situ and altimeter-derived (a) significant wave height

and (b) wind speed of in-situ and co-located altimeter measurements at the FINO-1 station. Altimeter

data are SAR altimetry (triangle) and PLRM (circle).

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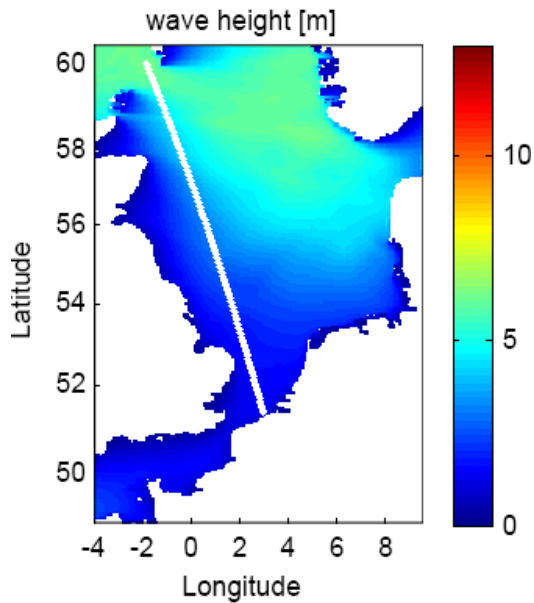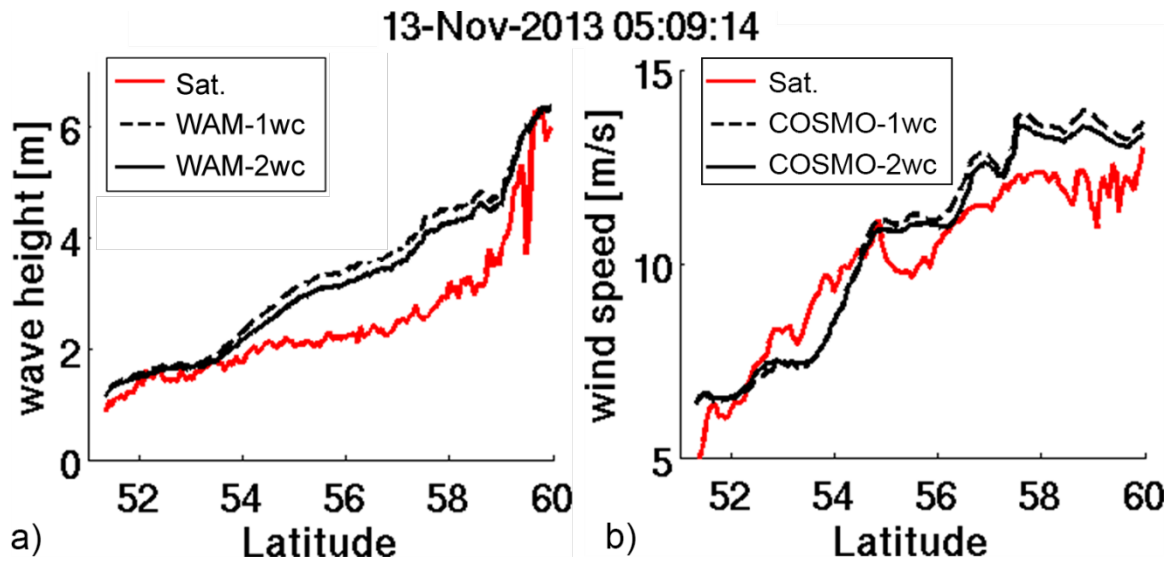
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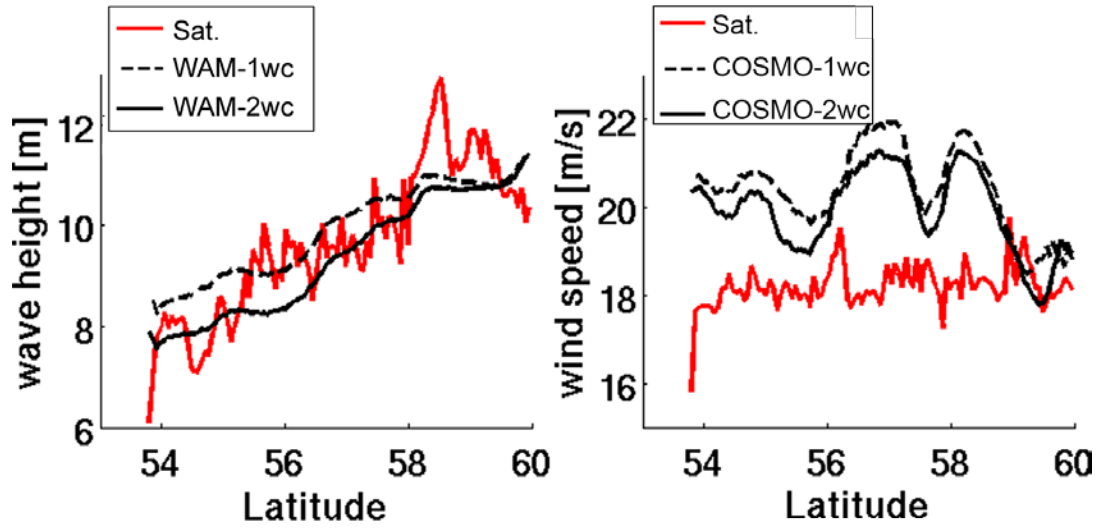
c)

Figure 6: Time series wave height (m) and wind speed (m/s) from the Saral/AltiKa data and as modelled by WAM-NS under calm weather conditions on 13 of November, 2013. The track of the satellite (the white line) is shown together with the model significant wave height at the time of the passage (bottom panel).

645

a)

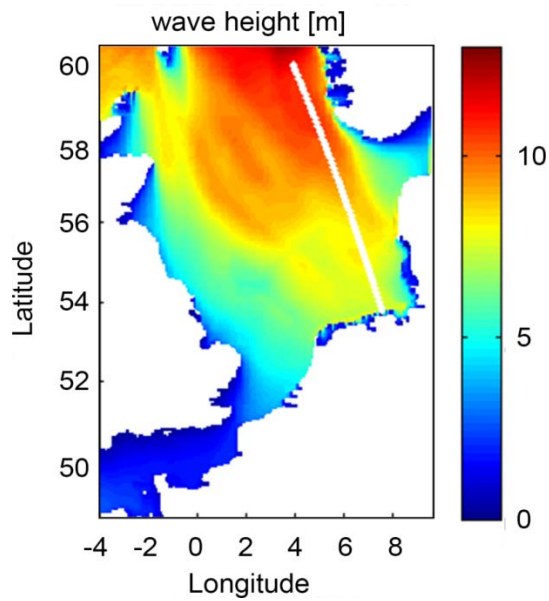
b)

650   c)

Figure 7: As Figure 6 but for the storm 'Xaver' on 06 December 2013.

(a)

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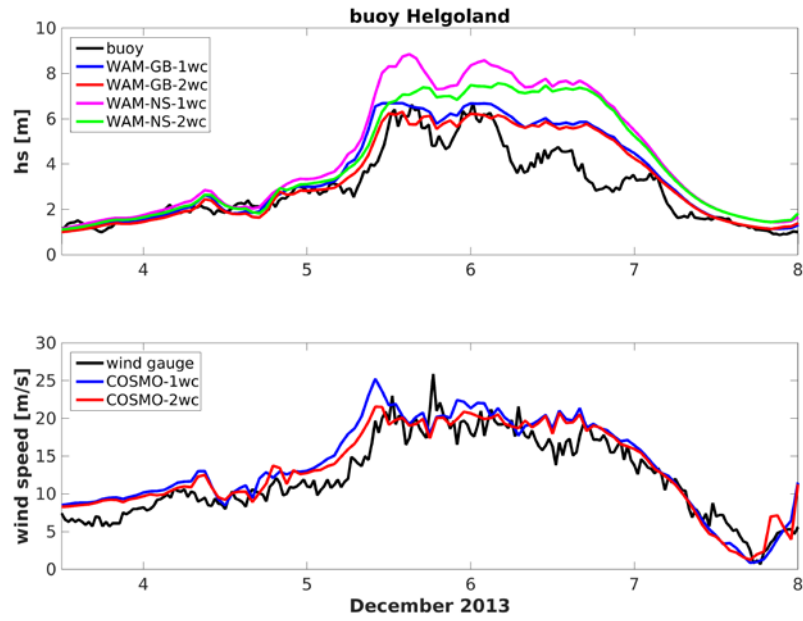
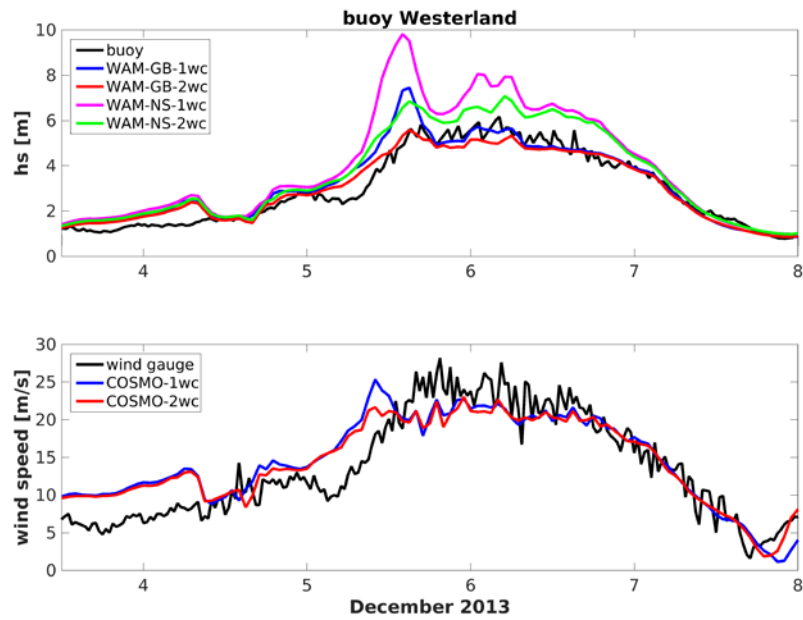
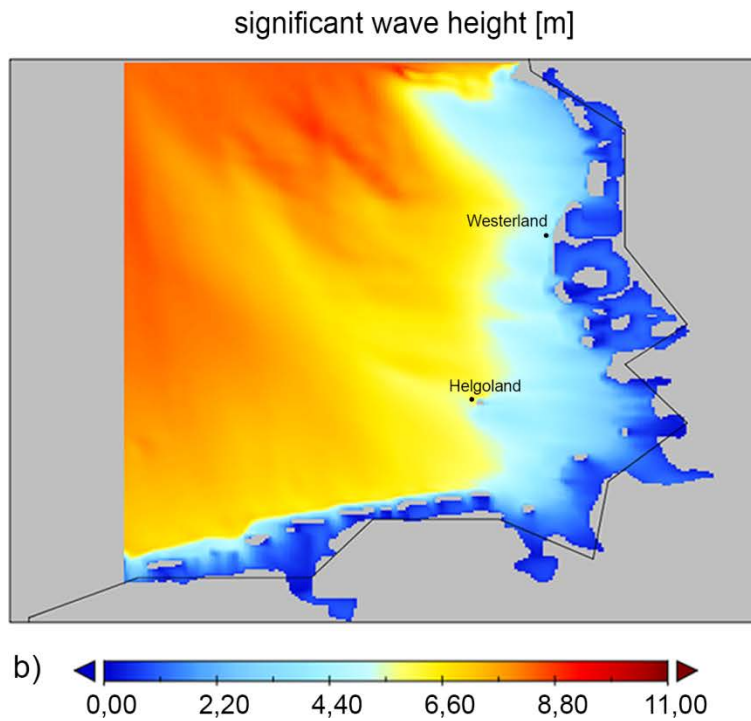
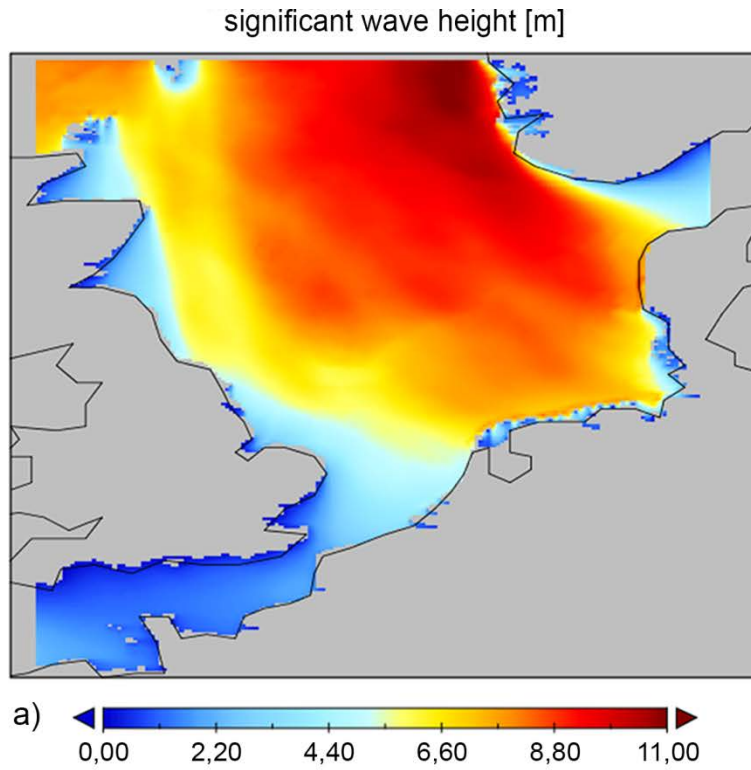

(b)

Figure 8: (a,b) Significant wave height (m, top) and wind speed (m/s, bottom) during the storm 'Xaver'

at the buoys Helgoland (a) and Westerland/Sylt (b).

660   *Figure 9: (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.

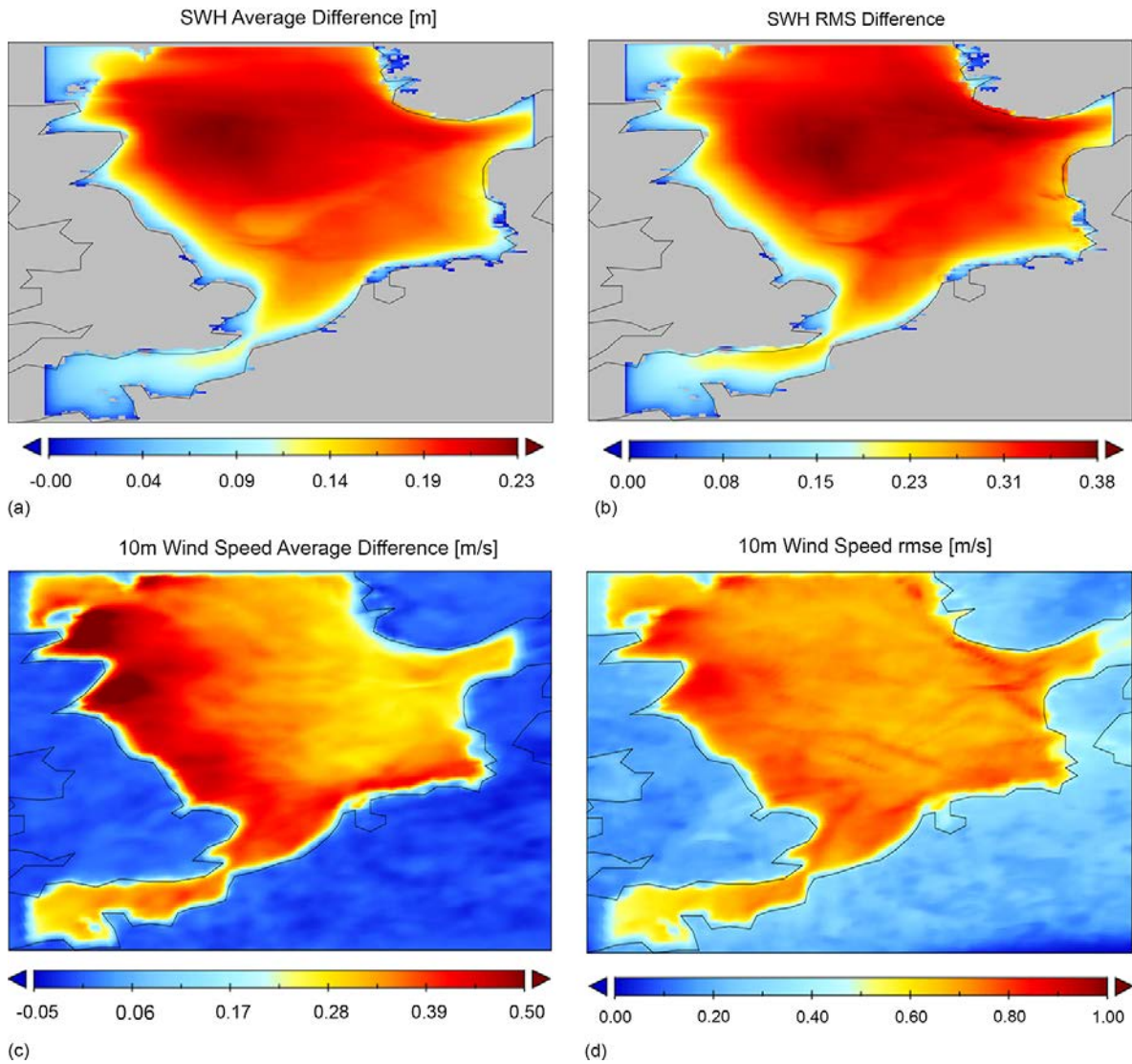
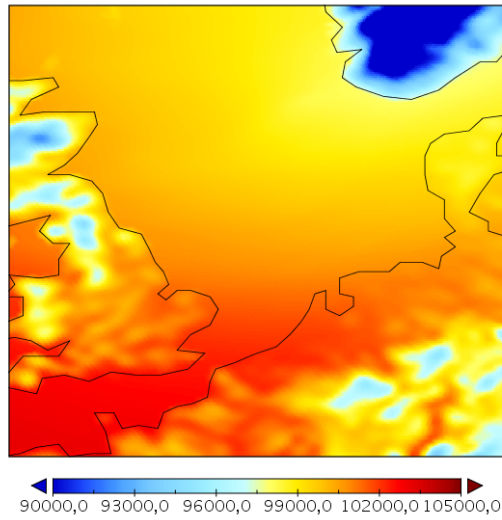



Figure 10: (a,c) Average difference and (b,d) rms difference (rms difference) of WAM modeled significant wave height (m, top panel) and COSMO modeled wind speed (m/s, bottom panel) when comparing one-way minus two-way coupled modeling results. The differences are calculated as averages over the whole three month period.

mean sea level pressure [Pa]

90000,0 93000,0 96000,0 99000,0 102000,0 105000,0

670   *(a)*

msl pressure difference [Pa]

−50,00   −30,00   −10,00   10,00   30,00   50,00

(b)

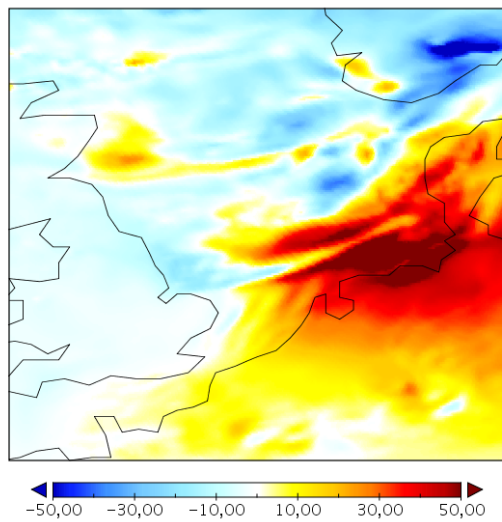



Figure 11: (a) COSMO pressure (Pa) at mean sea level height in the North Sea during storm 'Xaver' and

675   *(b) mean sea level pressure differences when comparing one-way minus two-way coupled modeling).*

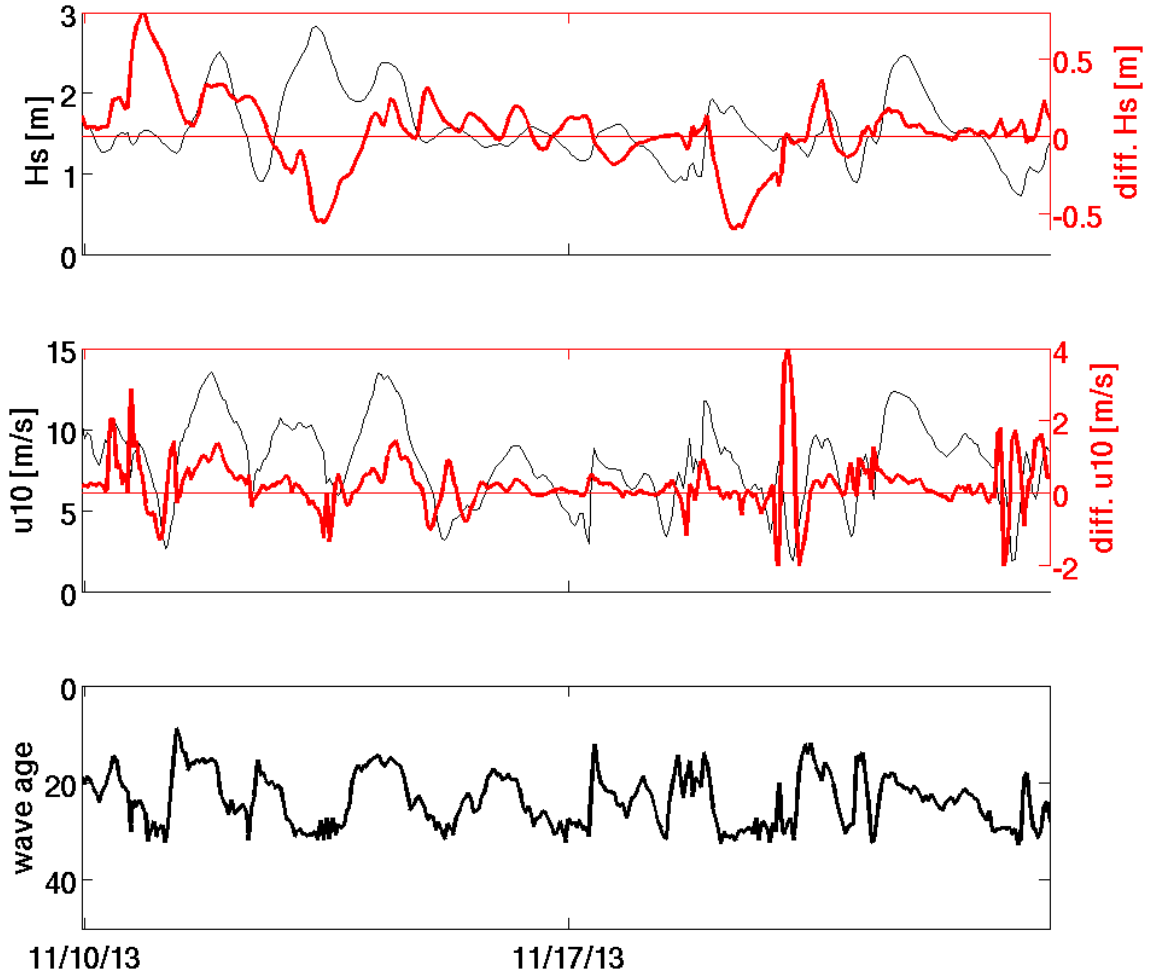



Figure 12: Time series of significant wave height (m, top), wind speed (m/s, middle) and wave age (bottom) from the two-way coupled German Bight setup at FINO-1 for (a) a rather calm period with young wind sea and (b) during the storm 'Xaver'). Red lines in the top and middle panel show the differences between the one-way and the two-way coupled models.

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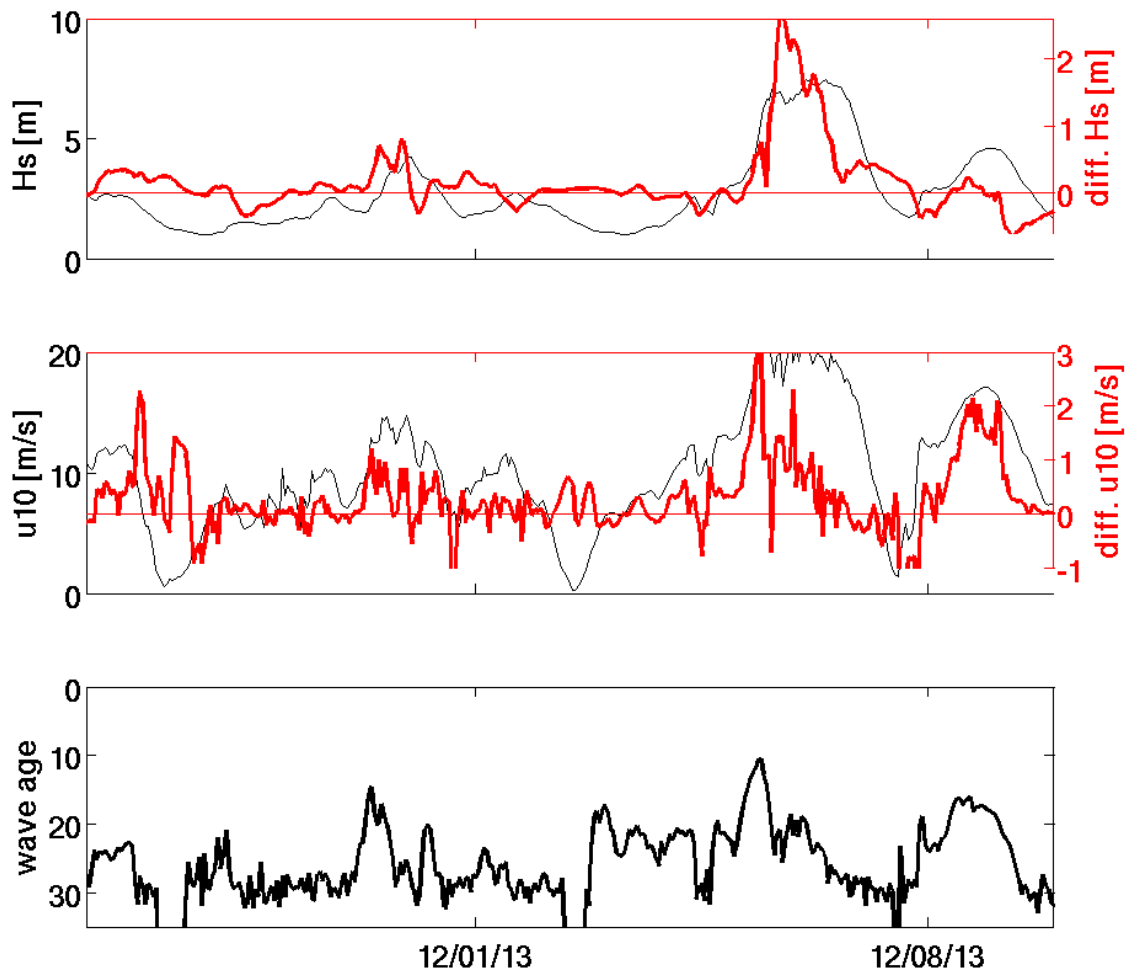
Figure 13: As Figure 12 but during the storm 'Xaver'

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