Authors Response to the Reviewers' comments

Rev.# 1

J.W. de Vries (Referee)
hans.de.vries@knmi.nl
Received and published: 29 July 2016

Dear Hans de Vries,
Thank you for reviewing our manuscript and for the constructive comments and suggestions. In the revised manuscript your comments and suggestions for improvements have been carefully considered.

The subject of this manuscript is the 2-way coupling of atmospheric and wave models in the German Bight. Atmospheric forcing is supplied to the wave models, and the wave model sends back the surface roughness to the atmospheric model. The results of 2-way coupling are compared to 1-way coupling for a 3-month period that includes one of the most severe storms, named Xaver, in the last decades.
The subject is highly relevant and the technique promises a seizable improvement of wave forecasts in especially shallow areas with complex topography. And the authors indeed show an overall improvement of wave forecasts and also in particular for the Xaver storm.

Authors: Thank you for this nice appraisal.

It is, however, sometimes difficult to get to the message the authors try to convey. One of the reasons are the many errors in the english language, especially incorrect or missing articles, inconsistency between singular and plural, inconsistency in tenses, and missing commas. The manuscript should therefore be carefully checked and corrected.

Authors:
The revised manuscript has been carefully checked by a native speaker; typos and errors in the English language have been corrected.

Chapter 3, on results, is very fragmented and lacks a clear wrap-up and conclusion at the end. Moreover, especially Section 3.1 is very long and deals with a number of more or less separate items. It would help to put these in separate subsections.
Sometimes the conclusions are contradictory to what the figures or tables suggest.

Authors:
We agree and the revised manuscript has been re-structured. Chapter 3 with the results has been spitted in two new Sections: Chapter 3 dealing with validation and Chapter 4 in which we discuss the impact on wave-atmosphere coupling (one-way versus two-way). The new Section 3: "Validation" has also been divided into three sub-sections describing separately and providing more analyses on 3.1: the validation of altimeter data against in situ data (this is a completely new part in the revised manuscript); 3.2: model validations against satellite data and 3.3: model

validation against in situ measurements. We think that the manuscript is now better structured and reads easier.

Comments in more detail:

1. Introduction

The reference Lionello (2003) is not in the references list. But the remark about what it states seems very odd here. The formulation suggests that the 2003 paper already describes the current work.

Authors: The Introduction section has been re-structured and carefully revised (following also a similar comment of the Reviewer's #2). The state-of the art has been better presented. More information about the previous studies has been provided (incl. Lionello, 1998, 2003). The novelty in our work compared with previous studies has been described and arguments for performing our study have been presented.

Towards the end, Staneva et al. (2016) is referenced. I would say that the subject of this paper has more relevance to the present paper than just the fact that wave heights are overestimated or the description of the used models. I would expect a discussion on coupling just waves and the atmosphere and including also circulation. And in the end you will probably want to couple all three together.

Authors: We agree and in the revised manuscript a comprehensive discussion about the coupling between waves and hydrodynamics (referring also to our recent developments in Staneva et al., 2016) have been included. The perspectives and future plans towards implementing a filly coupled atmosphere-wave-circulation model, based on the developments and findings described here, as well as those by the wave-hydrodynamic coupling studies, have been discussed.

2.4 Integration Period and Data Availability

At the end, you refer to Figure 1b for the wave rider buoys, but they are in Figure 1c.

Authors: We apologize for this mistake, and we refer to the correct figure in the revised manuscript. Additionally, we removed the satellite tracks from Figure 1 (old Fig. 1b). The new Figure 1 shows only the domain and bathymetry of the model areas.

3.1 Validation of models

As in the final paper the tables will be close to the text, you might consider leaving out the values themselves here. It would make the text more easily readable.

Authors: We agree and removed the values that are given in the Table from the text in the discussion of the validations. We additionally reformulated this description in Section 3, making it clearer by stressing on major conclusions from each sub-section.

Line 221: "due to the reasons explained above" is not clear which reasons you are aiming at.

Authors: We agree and changed the text accordingly. Similar comment has also been given mentioned by the second reviewer, the revised text was re-phrased and we clearly refer to the introduction part.

Line 230: Change "It is well known that..." into "Passaro et al. (2014) established that...".

Authors: The suggested revision has been made.

Line 240: "... wave heights are in good agreement." I do not agree. In the calm case, both models underestimate the wave height by approximately 1 m over a large part of the track.

Authors: The suggested revision has been made. We discussed the comparisons between the model and satellite altimetry wave heights and commented on the discrepancies in Section 3.2.

Line 242: "... however,[!] the reduced wave height...". Change "however" into "although". Differences between the models are much smaller than the difference with the observations.

Authors: The suggested revision has been made. We agree with this comment – the differences between the model runs are most significant and indeed smaller than between model and observations. This has been now revised in Section 3 and also stressed in the discussion section.

Line 246: The peak of the storm, at least the highest wave heights, are at the edge of the domain of the wave model. Any differences with observations will therefore strongly be influenced by the boundary conditions. And, actually, Figure 3b does not show a maximum, just an increasing wave height towards the North.

Authors: We agree with the comment and the discussion of the comparisons (the results in Fig. 6 a in the revised manuscript) has been re-phrased, making it clearer. The maximum that we referred is observed by the satellite data. Indeed for the both model runs, the wave height increases northward. This finding has been commented on in Section 3.2.

The comparison of these two tracks is a very useful illustration. You must have looked at the other tracks as well. Without giving any details here, it would be relevant to say something of the general picture that emerges from that. Does it agree with these two examples, or are there also other features there?

Authors: We looked at many other tracks, and the results were similar to the ones for the calm situation. In general, the measured wind speeds were in slightly better agreement with the modelled ones as seen also from the statistics in Table 1. The track for storm Xaver was the only one taken under such extreme conditions. This discussion has been added in Section 3.2.

More or less the same remark on the comparison with the wave buoys. You show Helgoland and Westerland, but you should at least mention whether the results for Fino and Elbe are similar.

Authors: We have also looked at the comparisons between in situ and modelled data for FINO-1 and Elbe stations. Those comparisons look similar to what we show. The general picture and the conclusions agree. We added additional discussion to Section 3.3.

Line 280: As the results for both wave models are different in shallow water, what does that mean for the 2-way coupling? Should you not get sea surface roughness from the model that includes wave breaking?

Authors: We agree with the comment that it is difficult to differentiate between effects coming from wave breaking and from two-way coupling. This point has been thoughtfully discussed in Section 3.3 and additional references have been provided.

Line 289: "were provided by the DWD" is a remark that should be in Section 2.4.

Authors: The suggested revision has been made.

Line 296: "Even though differences ... decrease ..." That is not what I see. Differences in biases in Table 2 are not really different between 50 and 100 m and the difference in standard deviation is even larger.

Authors: We apologize for this incorrectness and fully agree with the comment. Only the bias slightly decreases. The description of those results has been corrected in the revised manuscript, and we made the explanations clearer.

Line 303: The word "either" gives a choice between two possibilities. So it is not correct where you want to combine 4 things.

Authors: The suggested revision has been made.

Line 307: It would help to give RMSE also in Table 3, if you refer to that instead of the standard deviation.

Authors: That was a mistake in writing and we changed 'rmse' into 'standard deviation' in the text.

3.2 Impact

The first paragraph suggests that in 1-way coupling the coupling to the waves is too strong. If you would decrease this coupling, e.g. by a smaller Charnock constant, would that not give similar results for the waves? Then, what is the added value of the 2-way coupling?

Authors:

We agree that by calibrating the parameters one can achieve better results compared to the measurements even using only a one-way coupled experiment (e.g., as in Zweers et al., 2002). This has been discussed in the introduction in the revised manuscript. However, the aim of our work was also to perform a process oriented study by considering the feedback of the surface roughness by the sea state dependence of the surface stress via the two-way atmosphere-wave coupling. These developments are needed for future extension of the coupled model system by integrating atmosphere-wave–current interactions to further investigate the effects of coupling, especially during extreme storm events.

You claim that the argument you infer from Figure 5 for wind speed differences is supported by the effect on wind stress (Figure 6). But the wind stress has a rather straightforward relation to the wind speed, so this is really the same argument. Just the fact that the wind stress is more that quadratic in the wind speed makes the effect only seem stronger.

Authors: We agree and the suggested revision has been made. In the revised manuscript we removed the redundant figure with the horizontal patterns of wind stress rmse and bias (Figure 6 in the first submission).

Line 332: "... which tends to fill the low" is not what Janssen and Viterbo (1996) claim. They claim that the disturbance will grow less, what is not the same.

Authors: We agree and this has been re-phrased in the revised manuscript.

Line 336: "... indicates a shift of the pressure low minimum". That should be easily seen directly in the pressure fields. Why then an indirect argument?

Authors: We agree with the comment. More information has been added in the discussion of the pressure filed in Section 4.

Line 340: "such effects". What effects?

Authors: The suggested revision has been made. We changed this into 'to observe this impact'.

Figures:
The use of figures with several subfigures is not always an advantage. Some of the graphs, especially time series in Figures 3, 4 and 8 are already small and will be smaller even and more difficult to read in a printed version. The authors might want to split some apart.

Authors: We agree and the organization of the figures has been changed in the revised manuscript. The sub-plots have been split in different figures. The figure patterns were made larger. Additionally, the quality of the individual figures has been improved. Some of them have been re-ordered following the logics in the text.

Figure 1: The explanation is not logical: first 1c and then 1b.
Figure 1b: I am not sure if a figure with all of the tracks is useful. They are not at the same time, and it is rather obvious that the pattern would look like that.
Figure 1c: The name Westerland is unreadable.

Authors: We agree – actually we removed Figure 1b with the satellite tracks from Figure 1. The size of the figures has been changed and their quality improved.

Figure 2: Units are missing on the wind speed scale.

Authors: The suggested revision has been made. We added the missing units to the figures caption and in the figure.

Figure 3: The subfigures are not really similar enough to combine all of them. 3c and 3d could be taken together, but the way in which they are presented now suggests that

3a belongs to 3c and 3b to 3d.
As 3c and 3d are mentioned first in the text, they should be before 3a and 3b.
It would be useful to limit the area of Figure 3a to the same area as Figure 3b. Now a comparison is difficult.
It would help to indicate the buoys in 3a and 3b.
The color yellow in 3c and 3d is hardly visible.

Authors: The suggested revision has been made. We made two separate figures out of it: first one with the comparison of measurements and model results and a second one with the distribution of Hs in the model area. We also separated the figures for the different events.
The quality and presentation of the figures (lines, colors, fonts) has been improved. The Figures have been then re-numbered.

Figure 5: The use of "bias" and "rmse" in this figure is confusing, as there terms are mostly used to indicate the difference with observations. Suggestion: "average difference" and "RMS difference". Also in Figure 6.
The figure might be explained more clearly. Either in the subscript, or in the text.

Authors: The suggested revision has been made. We introduced the terms as suggested in the text and in the figures caption and tried to explain more clearly what is shown in the figures caption.

Rev.# 2

Authors: Thank you for the review of our manuscript.
We appreciate the constructive comments and will revise the manuscript in accordance with the reviewer's comments.

Manuscript "An atmosphere-wave regional coupled model: improving predictions of wave heights and surface winds in the Southern North Sea by Kathrin Wahle et al. evaluates the effect of model coupling on the accuracy of modelled wave field in coastal areas. Model coupling especially for short-term forecasting purposes is a very topical issue and it is nice to see that the progress includes also coastal modelling. However, the authors state in several places that coupling of atmosphere and wave models is not novel in itself and that coupled models have been run operationally in many forecasting centres for decades. A reader would expect more detailed analysis of the effects of coupling on the coastal modelling, which is the novelty of this paper. Also, the analysis of the results should be done more carefully. In several places there are statements that are not entirely supported by the Figures presented (cf. specific comments). The paper is fairly well structured, but the formulations and language require some further attention. I also recommend that the language is checked by a native speaker.

Authors: We agree. The manuscript has been revised and the analyses of the model results were more precisely presented. Deeper discussion and more information are provided of the role of two-way coupling on the coastal model results. Following the similar comments of the Reviewer #1 this Section has been re-organized (see also the answers to Reviewer #1 comments about that).

The revised manuscript has been carefully checked by a native speaker, typos and errors in English language have been corrected.

Some specific comments:
Section 1. Introduction: This section could be better structured and written. Explicit statements of what the authors are studying in this paper could be put in one place, preferably at the end of this section. Also the references to previous studies should be better formulated. Now it seems just a list of different coupled models presented in earlier studies. Please highlight their connection to the present study.

Authors: We agree with the comments and the suggested revisions have been done. The introduction part has been re-organized following this suggestion. Earlier works have been better formulated and new references added. The discussion on what we are studying in this manuscript, stressing on the novelty compared to the early studies is given now in one paragraph.

Section 2.3: Please give a short description of how the coupling was done, not just a reference to article by Ho-Hagemann et al.

Authors: The suggested revision has been done in Section 2.3 of the revised manuscript.

Section 2.4, line 206: Here should probably be a reference to Fig. 1c, not 1b

Authors: We apologize for the mistake and refer now to the correct figure. The old Fig.1b has been removed from Figure 1.

Section 3.1, line 221: "reasons explained above" - Should it be "due to earlier explained reasons" and please give a reference to the section, where this explanation is given or explain it here.

Authors: We agree. The text has been modified and we provided clearer statements.

Section 3.1: Did you compare the altimeter data against the Waveriders? How good is the accuracy of the altimeter data in the North Sea? And how was the match-up done between altimeter data and model data (distance in space and time, averaging, etc.)?

Authors: We completely agree that additional information is needed. In the revised manuscript we introduce reference to previous studies in the introduction. We also included a new sub-section (now Section 3.1) dealing with comparisons of altimeter data against in-situ measurements to estimate the accuracy of altimeter data. Analyses and new figures demonstrating these comparisons have been also included in the revised version.
We also included a discussion about the match-up of altimeter and model data in our study in Section 3.2.

What is the number of matched model-measured pairs for each altimeter and buoy?

Authors: For the altimeter data these numbers are given in Table1 (about 7000 for each of them). For the buoys there are about 4000 matched pairs. These numbers have been also now given in Sections 3.2 and 3.3, correspondingly, of the revised manuscript.

Section 3.1, line 239-240: "In both cases measured and modelled wave heights are in good agreement" - is this really so? There seems to be quite big differences between the modelled and measured values along the track. Please be more precise.

Authors: The suggested revisions have been done. The validation results have been more precisely discussed in Section 3.2 and additional arguments and explanations presented.

Section 3.1, line 245-246: "the two-way coupled model results are closer to the measurements" - This is true for latitudes 54-55 and 57-58, but around latitude 56, the one-way coupled model seems to be closer to measurements. More detailed analysis is required.

Authors: We agree with the comment about the discussion of the comparisons with the measurements. More detailed analyses have been added in Section 3.2 about the spatial (latitudinal) distribution of the satellite date and model simulations. Critical discussion on the results has been included.

Fig. 3: Why not use the same altimeter track to compare the performance on low-wind and storm conditions?

Authors: The choice of tracks to compare the performance (Figure 5 and Figure 6 in the revised manuscript), also following the comments of the reviewer #1, has been discussed in Section 3.2 in the revised manuscript.

Section 3.1, lines 266-267: "Throughout the period WAM-NS-1wc shows the highest significant wave height" - This is true for Helgoland, but not for Westerland, where

WAM-GB-1wc occasionally has higher values.

Authors: We agree with the comment and this has been added in the revised manuscript. Additional analyses are provided making now the description in Section 3 more precisely.

Section 3.1, lines 283-284 and Fig. 4d: What actually happens on December 5th in the Westerland in WAM-GB-1wc. Why is it behaving completely differently from the other setups? Nothing in the wind field seems to be supporting this kind of behaviour.

Authors: We apologize for the mistake, which we made while plotting WAM-GB-1wc run (blue line in Fig.4). The figure has been plotted correctly (Figure 7 in the revised manuscript).

Figure 4: Would it be possible to mark the locations of the wave buoys to figures 4a and 4b. Although their locations are shown in Fig. 1, it would be easier for the reader to evaluate the model performance, if the locations would also be marked here.

Authors: Following the Reviewer #1 suggestions, the organization of the figures has been changed in the revised manuscript. The different sub-plots have been split into separate figures. The patterns in the new Figures were made larger. Additionally, the quality of the individual figures has been improved. Some of them have been re-ordered following the logics in the text. Figure 4 a,b is Figure 8 and Fig. 4c,d – Fig. 7.

Figure 8: Please use scales that show the whole range of the presented values of the chosen periods.

Authors: As described in the text the wave age is calculated as the quotient of phase and friction velocity it gets very high values by calm weather conditions when the wind speed is very low. Therefore, we introduced a wave age limit in the plots making the time variability and the ranges clearer. Additional information and description on the wave age plots has been added in Section 4.

~~An atmosphere-wave regional coupled model: improving predictions of wave heights~~ **Wave-atmospheric modelling, satellite and** ~~surface winds~~ ***in situ* observations in the Southern North Sea: the impact of horizontal resolution and two-way coupling**

Kathrin Wahle[1], Joanna Staneva[1], Wolfgang Koch[1], Luciana Fenoglio-Marc[2], Ha T. M. Ho-Hagemann[1], Emil V. Stanev[1]

[1]Institute of Coastal Research, Helmholtz-Zentrum Geesthacht, Germany

[2]Institute of Geodesy and Geoinformation, University of Bonn, Germany

Correspondence to: Kathrin.wahle@hzg.de, Phone: +49 4152 871559

Abstract

~~Reduction~~The coupling of models is a commonly used approach when addressing the complex interactions between different components of earth systems. We demonstrate that this approach can result in a reduction of errors in wave forecasting~~ errors is a challenge~~, especially in dynamically complicated coastal ocean areas, such 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 (COSMO) and a wind wave model~~,~~ (WAM), which ~~in the present study~~ is enabled through an introduction of wave induced drag in the ~~atmosphere model. This, on one side,~~ atmospheric model. The numerical simulations use a regional North Sea coupled wave-atmosphere model as well as a nested-grid high resolution German Bight wave model. Using one atmospheric and two wind wave models in parallel allows for studying the individual and combined effects of the two-way coupling and grid resolution. This approach proved to be particularly important under severe storm conditions because German Bight is a very shallow and dynamically complex coastal area exposed to storm floods. The two-way coupling leads to a reduction of ~~the~~both surface wind speeds~~, and on the other side, to a reduction of~~ 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~~, is studied. Additionally,~~ and the impact of two-way coupling on 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 quantified. Comparisons between data from *in -situ* and satellite altimeter 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 of the model and justifies its implementationsimplementation 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, the wind waves extract energy and momentum from the atmosphere ~~while~~as they ~~are growing~~grow under ~~the~~ wind. This effect is ~~the largest~~greater for young sea states and high wind ~~speeds. One can thus consider~~speed, in comparison to decaying sea and calm atmospheric conditions. Under such conditions, the drag coefficient ~~as sea~~cannot be considered as independent from the sea-state ~~dependent~~ and ~~non-~~uniform in time and space. This dependence needs to be accounted for in ~~the coupled atmosphere-wave models.~~coupled atmosphere-wave models. Jenkins *et al.* (2012) demonstrated that the wave field alters the ocean's aerodynamic roughness and air–sea momentum flux, depending on the relationship between the surface wind speed and propagation speed of the 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 speeds and modulate the heat and moisture transports between the atmosphere and ocean; and concluded that as a result of this boundary layer modification, the mesoscale structures associated with the cyclone are perturbed. The impact of sea surface roughness has been investigated in studies by Bao *et al.* (2002) and Desjardings *et al.* (2001). As ~~stated~~shown 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~~ (1998), the two-way wave-atmosphere ~~and the waves.~~coupling attenuates the depth of the pressure minimum. In particular, under extreme conditions, non-linearities increase and the intensity of ~~the~~ storms ~~could~~can be modified~~.~~ due to feedbacks between waves and the atmosphere. This ~~has to~~ feedback must be accounted for ~~by the coupling~~ in coupled models because strong winds cause ~~an increase of~~ the drag coefficient of the sea surface to increase, which leads to ~~a~~wind speed reduction ~~of the wind speed and also to~~and modification of the wind direction (Warner *et al.*, 2010). These effects feed back into the airflow, wind speed and turbulence profile in the boundary layer. Zweers *et al.* (2002) illustrated that the surface drag was overestimated in the atmospheric weather prediction model for high wind speeds, and the intensity of hurricane winds was underestimated in the simulations; they proposed an approach of calibrating the boundary layer parameterization using the one-way coupled model. They tested a parameterization that decreased the surface drag for two hurricanes in the Caribbean and demonstrated that the new drag parameterization leads to much stronger forecasted hurricanes, which were in good agreement with observations. Two-way coupling of wave and atmospheric models is an alternative approach for development of a fully coupled ocean-atmosphere modelling system, as it enhances the description of interactions and exchanges in the atmospheric boundary layer. Accurate modelling of the boundary layer is of utmost importance for long range predictions.

~~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~~by the European Centre for Medium-Range Weather Forecasts (ECMWF). The method, which ~~uses~~is based on 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~~ Waves have been recently considered in operational coupled ~~in 1997 accounting for effects of wind, heat, precipitation and sea surface temperature in either model (Stockdale et al. 1998). Recently,~~ model systems, such as for Meteo-France (Voldoire *et al.* 2012). Breivik *et al.* (2015) incorporated the effects of surface waves onto ~~the~~ ocean dynamics via ~~surface~~ocean side stress, turbulent kinetic energy due to wave breaking, and the Stokes–Coriolis force ~~into~~in 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, 2012) introduced two different parameterisations in a European climate model. One ~~of them was using~~

~~the~~parameterisation uses roughness length and ~~including~~ includes only the effect of a growing sea~~ only~~, as ~~introduced~~proposed by Janssen (1991~~), and another one using the~~). The other, uses wave age and ~~introducing~~introduced the reduction of roughness due to swell~~ (see also Rutgersson et al. 2012).~~ . In both cases~~ they found a significant impact of~~ , these parametrisations had high impact on the long-term averages of atmospheric parameters and ~~also~~demonstrated that the ~~impact of~~ swell ~~waves~~impact 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~~significant.

With increasing grid resolution, the impact of coupling on model predictions becomes more important (Janssen *et al.* 2004), thus emphasizing the need for coupling on the regional scales. Spatial and temporal changes in the wave and wave energy propagation are still insufficiently addressed in high-resolution regional ~~full coupled models are also subject to further development. Katsafados et al. (2016) did set up such a system for~~ 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. The wave breaking term prevents unrealistically high waves near the coast. The spray caused by breaking waves modulates the atmosphere boundary layer.

Järvenoja and Tuomi (2002) emphasized the necessity to use wind data with fine temporal discretization in the wave model, part of the regional coupled atmosphere-wave model at the Baltic Sea, to ensure that the latter reacts physically correctly to rapidly changing winds. No significant difference caused by the coupling, except for the surface wind speeds, has been found in the meteorological model. For the Mediterranean Sea, however, Cavaleri *et al.* (2012) found that reduced wind velocities was compensated by 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, 2012, Kummar *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 ~~and~~as an example. They focused on air–sea momentum fluxes in conditions of extremely strong and time-~~varying~~variable winds. They demonstrated ~~more realistic representation of the momentum exchanges in the wave-atmosphere coupled modelling system~~that by including the sea-state dependent drag coefficient~~: the~~, effects on wave spectrum and ~~its~~their feedback on ~~the~~ momentum flux lead to ~~improvements of~~ improved model predictions. For the southern North Sea (the German Bight area), Staneva *et al.* (2016) demonstrated the role of wave-induced forcing on sea level variability and hydrodynamics, although the effects of wave-atmosphere interaction processes were not considered.

~~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.~~Model outputs can be validated against *in-situ* and space-based observational data from satellite altimetry. The accuracy of the 1-Hz wave height and wind speed derived from altimetry has been estimated in previous studies by comparison with in situ-data assumed as ground-truth over intervals of few years. Analysis of the differences between altimeter and *in-situ* measurements over longer time intervals provides an estimation of the accuracy of altimeter data relative to in situ-data assumed as ground-truth. Significant wave height derived satellite altimetry has been compared to wave height measured by several wave-riders in Passaro *et al.* (2015). Fenoglio-Marc *et al.* (2015) considers the complete satellite mission duration to derive an estimation of the accuracy for significant wave height and wind speed. The standard deviation is between 40 cm and 15 cm for conventional altimetry (Passaro *et al.*, 2015) and between 30 and 15 for SAR altimetry (Fenoglio-Marc *et al.*, 2015). Slightly different results are also obtained depending on the retracker methods used for the altimeter data processing. Higher accuracy is found in open sea (e.g. 15 cm at FINO3 platform) then near coast (34 cm at Helgoland). They showed that the standard deviations depend on the location of both measurements and on the retracking processing used.

Our objective here is to quantify the effects of coupling between the waves and atmosphere model, especially during extreme storm events. We present intercomparisons between coupled and stand-alone models and validate these models 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 ~~back to the atmospheric model~~ the computed sea-surface roughness~~. We can then~~ back to the atmospheric model. Then, we statistically ~~access~~assess the impact of the two-way coupling and validate the two setups against available *in situ* and remote sensing data. ~~By introducing the interaction of wind waves and atmosphere we aim at further reduction of modelling errors.~~

~~Novel~~Our novel contribution here is ~~the simultaneous run using the~~simultaneously running (via a coupler ~~of~~) a regional North Sea coupled wave-atmosphere model together with a nested-grid high resolution German Bight wave model (one atmospheric model and two wind wave models). Using this ~~setup~~configuration allows us to study the individual and combined effects of (1) model coupling and (2) grid resolution, especially ~~in~~under severe storm conditions, which is challenging for ~~the~~ wave modelling ~~in the~~at German Bight ~~since~~because 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~~by describing the models used, ~~as well as~~ the ~~technical~~ coupling~~. It also contains the~~ and specification of different model setups, period of model integration and available data for validation~~.~~ in Section 2. Validation of the models against satellite and *in situ* measurements are described in Section 3. A discussion on ~~model results and sensitivity experiments~~the impact of two-way coupling is ~~given~~provided in Section ~~3~~4. The paper ends with a summary and an outlook ~~to~~for future ~~works.~~research.

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~~, see also http://www2.cosmo-model.org/). Its climate ~~mode~~model COSMO-CLM (CCLM) is ~~developed and applied~~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 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~~., pressure deviation ~~of pressure~~ from a reference state representing a time-independent dry atmosphere at rest, which is prescribed ~~to be~~as horizontally homogeneous, vertically stratified and in hydrostatic balance).

In our setup, we use a spatial resolution of ~~about 10km~~~10 km 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~~database for the North Sea (Geyer, 2014) covering the period 1948-2013 with a spatial resolution of ~~about~~ ~24 km (0.~~22°)~~22°) 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~~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 ~~kept~~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.*, 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 wave model for the North Sea with a spatial resolution of ~~about~~ ~5 km (Fig. 1a), and a finer wave model for the German Bight with a resolution of ~~about~~ ~900 m~~.~~ (Fig. 1b). These models, which 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 EWAM (European WAM) of the German Weather Service (DWD~~) EWAM (European WAM).~~). The forcing wind data are provided by ~~the atmospheric model~~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 WAM model code already contains the calculation of~~. The sea state dependent roughness length, according to Janssen (1991), has already been implemented into the WAM-5.4.5, thus for the present study, the model only ~~had~~needed to be adapted for usage with the OASIS3-MCT coupler (see Section 2.3).

2.3 Coupling of Models

The 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~~from the European Centre for Research and Advanced Training in Scientific Computation (CERFACS) and MCT (the Model Coupling Toolkit) ~~which~~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 atmospheric model are as in Ho-Hagemann *et al.* (2013), and in the wave model WAM as in Staneva *et al.*, (2016). 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. simulations. In the one-way coupled mode onlymodel, the atmospheric model sendsprovides wind data tofor the North Sea wave model via OASIS. This is thus equivalent to the familiar forcing of a wave model by 10m10 m wind fields. We will refer to the results of this simulationthese simulations as COSMO-1wc and WAM-NS-1wc, respectively, where '1wc' and 'NS' staystand for 'one-way coupled' and 'North Sea'., respectively. In the two-way coupled modemodel, the North Sea wave model sends back is forced with winds provided by the atmospheric model and the sea surface roughness lengths obtained fromare sent back to the atmospheric model wind forcing , which in return might reducechange the 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 simulationthese simulations as COSMO-2wc and WAM-NS-2wc, respectively. The coupling time step in either simulationfor all simulations is 3 minutes. This small couplingshort time step is a biggreat advantage forwhen modelling fast moving storms compared to an uncoupled run, where wind fields , in comparison to using stand-alone wave models forced by winds, which are usually available hourly at the most hourly.

The high resolution German Bight wave model, which also runs simultaneously with the CCLM and North Sea WAM, is forced in the two simulations by the respectiveCCLM wind and the boundary data. provided by the North Sea WAM set-up. 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 in the second experiment. This study is novel, compared to previous atmosphere-wave coupling research, because with the OASIS coupler 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 2.4. IntegrationStudy Period and Data Availability

~~The~~ The coupled wave-atmosphere model system described ~~models were~~ in the previous section was used to simulate ~~the~~a three~~-months-~~month period from October to December 2013. This period was chosen ~~since~~because it includes ~~on December 6th~~ the time when the storm ~~'Xaver'~~ Xaver passed over the study area on the 6th of December, 2013. This was one of the most severe storms of the last decade~~. 'Xaver'~~, 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. ~~Exceptional was also the long duration of~~ It reached its lowest sea level pressure on the 5th of December at 18 UTC over Norway (~970 hPa, Figs. 2 and 3). At German Bight, the arrival of Xaver coincided in time with high tides. Because of the high tides 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 ~~of~~ was also exceptional because of its long duration of nearly two days. ~~The German Bight coast was affected by three surges due to the storm coming almost constant from Northwest.~~The surge height reached ~2.5 m, with its maximum at low water time. During Xaver, two surge maxima were observed (Staneva *et al.*, 2016). Fenoglio-Marc *et al.* (2015) described the first surge maximum as a wind-induced maximum. the tide gauge records which was detected by measurements on German Bight. As demonstrated by Staneva *et al.* (2016), the wave-induced processes contributed to a persistent increase of the surge after the first maximum (with slight overestimation after the second peak).

In ~~our~~the present study, we perform ~~a~~ statistical analysis for the whole period of integration and investigate the ~~stormy~~ period of extreme storm event Xaver in more detail. ~~Figure 2 shows~~ The distribution ~~over the selected period~~ of wind speeds and directions ~~at the *in*~~ over the selected period as seen in the waverider data from the *in situ* platform FINO-1 ~~data station~~ (see ~~Figure 1c~~Fig. 1b for its location~~).~~) is shown in Fig. 2. North-westerly winds are generally dominant, but ~~during 'Xaver'~~ strong winds ~~are also coming~~(higher than 20 m/s) came from the west and ~~south-west~~southwest as the Xaver storm moved eastwards. ~~For the validation of our experiment~~South-easterly and north-easterly winds are rarely observed at the FINO-1 station.

To validate our experiments, we ~~used~~use wind speed and significant wave height data measured by ~~altimeter satellites~~ satellite altimeters SARAL/AltiKa, Jason-2 and CryoSat-2 over the North Sea~~.~~

(see Fig. 3 with the tracks of the different satellites over the three-month study period). The first two carry on-board a classical pulse-limited altimeter ~~which~~that operates in a low resolution mode (LRM), while the CryoSat-2 instrument operates in an LRM or in Delay Doppler ~~(DD~~Altimetry (DDA) mode. The CryoSat-2 data used here ~~have been~~were extracted from the RADS database (Scharroo *et al.* 2013), where CryoSat-2 data acquired in DD mode in our region ~~has been~~was 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~~observe along their ground-track offshore up to a few kilometres from the coast (~~see Figure 1b~~Fig. 3). Their ground track pattern and ~~the~~ repeat period are different for each ~~mission, for~~of the three missions~~ above~~, as the same location is revisited by each mission every 27, 10, and 350 days ~~respectively~~ (Chelton *et al.*, 2001). The ~~data from~~ SARAL/AltiKa data ~~is here~~are of special interest ~~since~~in our study because this satellite passed over ~~the~~ German Bight during the storm ~~'Xaver'~~Xaver when the surge was at ~~his~~its maximum (Fenoglio-Marc *et al.* 2015). ~~Additionally, we used~~The *in situ* wave data from four directional ~~Datawell wave riders in the~~ waveriders at German Bight ~~operated~~are provided by the Federal Maritime and Hydrographic Agency (BSH) (see ~~Figure 1b for satellite tracks).~~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 ~~available~~ above sea level for the selected period.

~~1. Results~~

3. ~~3.1~~ Validation of ~~models~~the results

~~To~~*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 statistically analyzing the agreement between the 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 Time-series for the period of Xaver storm in regards to in situ wave height and wind speed measurements at the FINO-1 station, and 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 also shown in Fig. 3. 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 estimation of the accuracy of the altimeter data relative to the 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 larger 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 DDA in the open ocean, with rms differences of 21 cm, and 0.26 m/s for wave height and wind speed respectively. The cross-validation of PLRM and DDA showed for DDA a higher precision in wave height and a lower precision in wind speed (precisions for DDA were 6.6 cm and 5.8 cm/s for wave heights of 2 meter respectively). *In-situ* analysis showed a higher accuracy for DDA compared to PLRM. As a demonstration, Figure 4 shows the scatterplots for FINO-1 and CryoSat-2 DDA and PLRM measurements. For the wind speed the accuracy of CryoSat-2 DDA and PLRM is similar (std is 1.9 m/s). For the significant wave height, we observe a higher accuracy in DDA than in the standard PLRM retracking (std are 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 4b 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 ~~we compared~~ by comparing the output of the atmospheric and wave ~~model output~~models against ~~*in situ* and~~ remotely sensed data. Table 1 gives ~~for both wave height and wind speed~~ the statistics of the ~~difference~~differences (bias and standard deviations) between the model and ~~the~~ altimeter-derived values of wave height and wind speed over the selected three-month period~~, which is bias~~. The numbers of matched pairs (approximately 7000) of observations and ~~standard deviations of differences.~~ simulations are also given in Table 1 for the different satellites.

For all ~~the~~ three satellites, the standard deviation in the two-way coupled ~~setup~~model is smaller than in the one-way ~~setup.~~coupled model. Similarly~~,~~ for Jason-2 and SARAL/Altika, the bias in the two-way coupled ~~setup~~model is ~~smaller than in~~nearly halved compared to the one-way ~~setup and~~ model, due to the reasons explained in the introduction; thus, this finding is the first indication that the model offers a skill improvement. Measured values are ~~below~~ lower than the modelled ~~ones.~~values 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~~ and 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.~~experiments. In contrast, for Cryosat-2~~ instead~~, the opposite is true~~ and~~ . In other words, the measured values are ~~above~~higher than the modelled ~~ones in mean~~values on average for 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 ~~in~~between the CryoSat-2 data and 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).~~model runs. Fenoglio-Marc *et al.* (2015) also found that the CryoSat-2 derived wave height data overestimate the ~~LSM~~ wave model data from the DWD. ~~For the wind speed~~However, they ~~however~~ found the opposite for the wind speed, i.e. ~~, which is that~~the CryoSat-2 derived wind speed underestimates the COSMO ~~wind model data~~ winds from the DWD data. This ~~using both RADS PRM data and from SAR. On~~disagreement is due to the ~~other hand the coastDat2~~different data that have been 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~~ the atmospheric models by DWD and this study. This demonstrates again that a determination of wave height from satellite altimetry ~~wave height~~ is particularly challenging for waves smaller than one ~~meter~~metre (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~~a spatial 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.~~ and two of these are shown in Figures 5 and 6. The satellite altimetry observations along the ground-track at the time of the overflight at German Bight last ~38 sec. The selected SARAL/AltiKa ~~passages~~passes are very diverse~~:~~, as one was taken under calm conditions (Fig. 5) and the other pass occurred during the storm ~~'Xaver', thus providing the possibility~~Xaver (Fig. 6). Therefore, an opportunity was provided 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.~~Here, we provide a demonstration only for two tracks, but these tracks offer illustrative comparisons for calm conditions and an extreme storm event. Under calm conditions, differences between the results of the one- and two-way coupling are very small~~.~~ (Fig. 5a). Both models (WAM-NS-1wc~~/~~ and WAM-NS-1wc 2wc) overestimate the measured wave height (red line) over a large part of the track~~ (Figure 3a), however~~. However, the ~~reduced wave height~~ increased modelled wave height with latitude appears to be consistent with the northward wind speed increase observed by the satellite data and simulated ~~from the two-way coupled model is closer to the measurements.~~in the two simulations (Fig. 5b). During the storm ~~'Xaver'~~Xaver, the difference ~~of the wave height~~ between the wave height in the WAM-NS-1wc and WAM-NS-2wc simulations (Fig. 6a) increases up to ~~1m~~1 m in the southern North Sea. The altimeter-derived quantities ~~in this situation get very fluctuating but still~~fluctuate greatly. However, the two-way coupled-model results are closer to the measurements. satellite data, in comparison to the ones in WAM-NS-1wc, except for the latitude ~56 deg. 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). This result can be explained by the different post-processing of the significant wave height in the satellite data and by the statistical nature of the wave spectral model. The corresponding wind speed does not grow at this latitude, neither for the measured nor modelled wind speeds. It is noteworthy here, that the measured peak of the storm, is underestimated byin both runsexperiments and is also shifted northwards by approximately ~2 degrees (Figure 3b).

Fig. 6a). The modelled wind speed fits well with the altimeter-derived wind speed in the calm situation for both setupsexperiments (COSMO-1wc/2wc, Fig. 3a). For wind speeds of above 10m/s the lowered wind speeds from two-way coupled setup s5b). Northwards of 55 degrees approachN, the values from measurements (Figure 3a). Onwind speed is higher than 10 m/s, and the contrary,wind speed in the two-way coupled experiment (COSMO-2wc, full line) is reduced. During the storm 'Xaver'Xaver, the measured wind data are fluctuating around fluctuate ~18 m/s, whereas the modelled data show much higher values with mean of ~20 m/s, which reached ~22 m/s at latitudes ~57 and a more plausible behaviour (Figure 3b).59 degrees N (Fig. 6b). This might indicatefinding indicates 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 the low wind speeds derived from the 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). The wind speed simulated by COSMO-2wc is lowered up to 1 m/s compared to that of the COSMO-1wc. Similar analyses along all tracks over the study period agree with the two examples demonstrated in Figs. 5 and 6. 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.

Below we will analyse

3.3 Validation against in situ measurements

Analyses of the temporal variability of the significant wave heights in theat German Bight under stormy conditions. This allows allow us to investigate not only the impact of two-way coupling but also the role of modelthe horizontal resolution on the model performance. Figure 4 shows a . The comparison between data from two wave rider buoy (the location of the waverider buoys is shown in(see for locations Fig. 1) during the storm 'Xaver'1b) and model output from the coarse North Sea wave model setups (WAM-NS-1wc/2wc) and the fine German Bight onesmodel (WAM-GB-1wc/2wc).) are exemplified in Fig. 7 during the storm Xaver. Throughout thethis period WAM-NS-1wc shows, the highest values of significant wave height. are simulated by the WAM-NS-1wc experiment. The lowest simulated values originate, and closest to the observations, are from the WAM-GB-2wc output.simulations (Fig. 7). At the beginning of December, during the calm atmospheric conditions, all model results are very close but when the storm startssimilar and fit relatively well with the *in situ* measurements. The differences in the wave growth between the different model simulations become significant. after the storm onset. The peak of the storm from , as estimated by the WAM-NS-1wc simulation, overshoots the measured wave heights by about ~3 m at the Helgoland station (water depth 30m, Figure 4c30 m, Fig. 7a) and even by ~4 m at the shallow water of the Westerland station (water depth 13m, Figure 4d) whereas 13 m, Fig. 7b). This peak occurs earlier in all simulations in comparison to the *in situ* measurements, due to the time-shift in the wind data. The wave heights predicted by the WAM-GB-2wc are in a better agreement with the observations., especially for the Westerland station (Fig 7b, the red-line), in comparison to the other experiments.

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 (Fig. 1b), which explains why the differences of wave height during 'Xaver'the storm Xaver reach about ~1 to 1.5m5 m in the corresponding North Sea and German Bight simulations. (Fig. 7a). This makes clearfinding identifies the influenceimportance of different resolutions, *i.e.* different water depthsincreasing the horizontal resolution of the models in the regioncoastal areas with complex bathymetry.

At the shallow water buoy at Westerland buoy station (Fig. 7b) the differences are additionally enhanced by the 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 models at the peak of the storm (Figure 4a,Fig. 8 a, b):). Shoreward of the 15m15 m isobaths, the wave heights drop from 6 to 4m4 m in the German Bight model, whereas in. In contrast, for the North Sea model, the 6m6 m high waves reach the Southeasternsouth-eastern coast. The WAM-GBNS-1wc performs worse than underperforms in comparison to WAM-NS-2wc at Westerland, showing. This shows convincingly the importance of two-way coupling for the coastal German Bight areas, where the model wind speeds arespeed is even higher (by about 2m~2 m/s) than at Helgoland. We admit that it is difficult to differentiate between effects coming from wave breaking and from two-way coupling because both contribute to reducing the wave height by 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 the deep waters, the sea surface roughness feedback due to the two-way coupling plays a very important role (Fig. 7a). 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. 7. For all stations, the simulated WAM-GB-2wc is reduced, especially during the Xaver peak, and is closer to the measurements. 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~~ By comparing the model and measured wind speed, it is noticeable that the modelled wind speeds grow too early and too high at ~~either location~~ all locations at the beginning of the storm (see ~~again Figure 4c,d).~~the bottom patterns in Fig. 7 a,b for the Helgoland and Westerland examples). 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~~satisfactory, considering ~~how~~the strongly fluctuating ~~the~~ wind measurements~~ there are.~~. Similar behaviours are observed for the Elbe and Fino-1 wave buoy stations.

Additionally, the wind speeds ~~were~~are validated against measured data from FINO-1 in 50 m and ~~100m~~100 m 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~~We find better agreement in the two-way coupled run. The bias in wind speed is negative for the one-way coupled setup~~,~~; thus, the modelled wind ~~speeds overestimate~~speed overestimates the measured ~~ones.~~wind speed. The bias is significantly reduced due to the lower wind ~~speeds~~ in the two-way coupled model. ~~The rmse~~The root mean squared difference (RMSE) is ~~about 3m~~~3 m/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~~use four buoys (see ~~Figure 1c~~Fig. 1b for their locations) in water depths ~~from~~of 13 to 30 m. Table 3 gives the statistics for significant wave height (*Hs*) over the ~~three months~~whole period~~. In either water depth~~ (there are ~4000 matched pairs). For the four buoys and regardless of the ~~way~~type 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~~The simulated significant wave heights are ~~smaller in WAM-GB-2wc,~~lower 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~~bias between the ~~error distribution (not shown here) becomes more~~

~~symmetrical in 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 ~~cases.~~ simulation is similar to that of the one–way coupled simulations. Only for the FINO-1 station, the standard deviation is reduced by ~5% by the two-way coupled model.

~~3.2.~~4 Impact of the two-way coupling ~~on modelling results~~

In the following discussion, the impact of coupling ~~will be~~is analysed for the North Sea focusing on the spatial patterns under different physical conditions. Three~~ months~~-month averaged significant wave height and wind speed is reduced significantly (~~Figure 5~~Fig. 9) due to the two-way coupling, which results ~~in~~from an extraction of energy and momentum by waves from the atmosphere. The average difference (bias) in wave height ~~gives values of about~~ (Fig. 9a) is ~20 cm, which is a reduction of ~~about~~ ~8% of the three-month mean value (~2.3 m). The ~~root mean squared difference (rms)~~RMSE between the two simulations (Fig. 9b) is ~~about 40cm~~~40 cm in the central North Sea. For the wind speeds, the bias (Fig. 9c) 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~~10 m/s~~) with an rmse of about 80cm~~). The RMSE (Fig. 9d) between the two-way and one-way coupled simulations over the whole North Sea area is ~80 cm/s. The spatial patterns in the bias in ~~Figure 5~~Fig. 9 can be explained by the ~~dominating~~dominant westerly winds~~.~~ (Fig. 2). As the wind ~~coming~~comes from land (Great Britain) ~~hits~~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 ~~the of~~ sea surface roughness. Moving further ~~to the~~ east, the atmospheric boundary layer adapts in ~~either case~~both cases to the winds over sea, and ~~the differences~~there is less difference between the 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~~models. For the wave height, differences in bias close to the western coasts and in the English Channel are ~~smallest since it needs~~small because some fetch is needed for the waves to evolve and ~~this~~the fetch is too short ~~here~~there.

The differences in the mean sea-level pressure between COSMO-1wc/2wc for the storm ~~'Xaver'~~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).~~Fig. 10. The mean sea level pressure at the peak of the storm (~~Figure 7a) shows~~Fig. 10a) has 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~~100 Pa in the ~~South East (Figure 7b~~southeast (Fig. 10b). 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 was ~~pointed out~~noted by Janssen and Viterbo (1996~~)~~), the timescale of wave impact ~~of waves ~~on the atmospheric circulation is ~~of~~on the order of five days. However, our model area ~~might be still be ~~is too small ~~for such effects to play a major role.~~to observe this impact. More plausible is that our results ~~might instead have been~~are caused by the wave-mean flow interactions in the atmosphere. ~~This~~This effect of wave coupling on the atmosphere circulation will be analysed more deeply in future experiments.

Another illustration of the influence of the coupling is given by the two time series at the 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~~contained young and developing wind seas (~~Figure 8a) another one~~Fig. 11). The other period was in December with several storms coming from the North Sea (including ~~'Xaver') and thus~~Xaver) with higher wave ages (~~Figure 8b~~Fig. 12). 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.~~. 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 ~~for the waves ~~before the maximum wave height ~~is~~has been reached (this can be well seen for ~~'Xaver', Figure 8b) thus~~Xaver, Fig. 12). Thus, the waves grow slower in the two-way coupled model. Negative differences ~~occur ~~seldom ~~and~~occur, only occurring when the wave age ~~rapidly ~~increases ~~(we do not consider situations where wave age exceeds 50 since there~~rapidly (when the wind speeds go to zero~~ and thus~~, the wave age goes to infinity).

5. Summary and Outlook

We ~~have setup~~developed a two-way coupled wave-atmosphere model for the North Sea, which includes the possibility of nesting a ~~local ~~coastal, high-resolution wave model; the two models perform simultaneously. This analysis was done by using the coupling software OASIS3-MCT, which ~~allowed the~~allows a parallel run of several models on different model grids. By using a coupler, simultaneous simulations of a regional North Sea coupled wave-atmosphere model together with a nested-grid high resolution German Bight wave model (one atmospheric model and two wind wave models) were performed. This allowed us to study the individual and combined effects of two-way coupling and grid resolution, especially under severe storm conditions, which is challenging for the German Bight, because it is a very shallow and dynamically complex coastal area. The sensitivity of atmospheric parameters such as wind speed and atmospheric pressure to wave-induced drag, in particular under storm conditions, were quantified. Model intercomparisons gave encouraging results~~:~~. Overall, the two-way coupled model results were in~~ a~~ better agreement with the *in -situ* and remotely sensed data of significant wave height and wind speed~~ compared~~, in comparison to the one-way coupled model (COSMO ~~forces~~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 ~~observe a general good agreement~~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 ~~also~~ 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'~~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~~which matched buoy measurements very well. ~~Nevertheless, model resolution was critical where the depth gradients were large. The~~ The corresponding wind speeds were lowered from ~~23~~~22 to ~20 m/s. ~~Besides~~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 ~~small~~slight increase of the pressure field~~. However,~~ 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 ~~the~~ coupling ~~on~~with other atmospheric parameters~~, not only~~ at sea level ~~but also~~and the vertical structure of the planetary boundary layer.

Staneva *et al.* (2016) addressed the impact of coupling between wave and circulation models of German Bight during extreme storm events. They demonstrated that the coupled model results revealed a closer match with observations than from the stand-alone circulation model, especially during the extreme storm Xaver in December 2013. This study showed that the predicted surge of the coupled model is significantly enhanced during extreme storm events when accounting for wave-current interaction. In our study, we also demonstrated that for regions such as the German Bight, the role and potential uncertainties of shallow water in the wave model are also of great importance. Shallow water regions with the strongest wave-current interactions contribute largely 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. Nevertheless, 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.

Acknowledgments

This work has been supported ~~through~~by the Coastal Observing System for Northern and Arctic Seas (COSYNA~~).~~) and as part of the Horizon2020 CEASELESS project 730030. The authors like to thank Arno Behrens for providing the boundary values for the wave model from his COSYNA results. Beate Geyer extracted 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.

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.

~~and Sensitivities, Mon.~~ Bao, J.-W., S. A. Michelson, and J. M. Wilczak, 2002: Sensitivity of numerical simulations to parameterizations of roughness forsurface heat fluxes at high winds over the sea. Mon. Wea. Rev.,130, 1926–1932.

~~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., ~~...~~ Becker, M. Nenveniste B. and Weiss, R. (2015). The German Bight: A validation of CryoSat-2 altimeter data in SAR mode. Advances in Space Research, 55(11), 2641-2656.

Desjardins, S., J. Mailhot and R. Lalbeharry, (2000).Examination of the impact of a coupled atmospheric and ocean wave system, part I, Atmospheric aspects, J. Phys.Oceanogr., 30, 385-401.

Deutschländer T, Friedrich K, Haeseler S and Lefebvre C. (2013) Severe storm XAVER across northern Europe from 5 to 7 December 2013, December, 2013 DWD report, https://www.dwd.de/EN/ourservices/specialevents/storms

Doyle, J. D., 1995: Coupled ocean wave/atmosphere mesoscale model simulations of cyclogenesis. Tellus, 47A, 766–788.

Doyle, J. D., 2002: Coupled atmosphere–ocean wave simulations under high-wind conditions. Mon. Wea. Rev., 130, 3087–3099.

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.

Jenkins A., M. Bakhoday Paskyabi, I. Ferb, A. Gupta, (2012). Modelling the effect of ocean waves on the atmospheric and ocean boundary layers. Energy Procedia 24 (2012) 166 – 175.

Muralidhar AdakudluaKatsafados 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.

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, doioi:10.1175/JTECH-D-13-00167.1.

Lionello, P.,P. Malguzzi, and A. Buzzi, (1998). Coupling between the atmospheric circulation and the ocean wave field: An idealized case, J. Phys. Oceanogr., 28, 161-177.

Lionello P, Elvini E, Nizzero A (2003) Ocean waves and storm surges in the Adriatic Sea: intercomparison between the present and doubled CO_2 climate scenarios. Clim Res 23:217–231

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.

Renault, L., J. Chiggiato, J. C. Warner, M. Gomez, G. Vizoso, and J. Tintoré (2012), Coupled atmosphere-ocean-wave simulations of a storm event over the Gulf of Lion and Balearic Sea, J. Geophys. Res., 117, C09019, doi:10.1029/2012JC007924

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. A. behrens, K. Wahle (2015). Wave modelling for the German Bight coastal-ocean predicting system, Journal of Physics, 633, pp 233-254, doi:1211, 0.1088/1742-6596/633/1/012117, ISBN: 978-3-939230-28-1.

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.

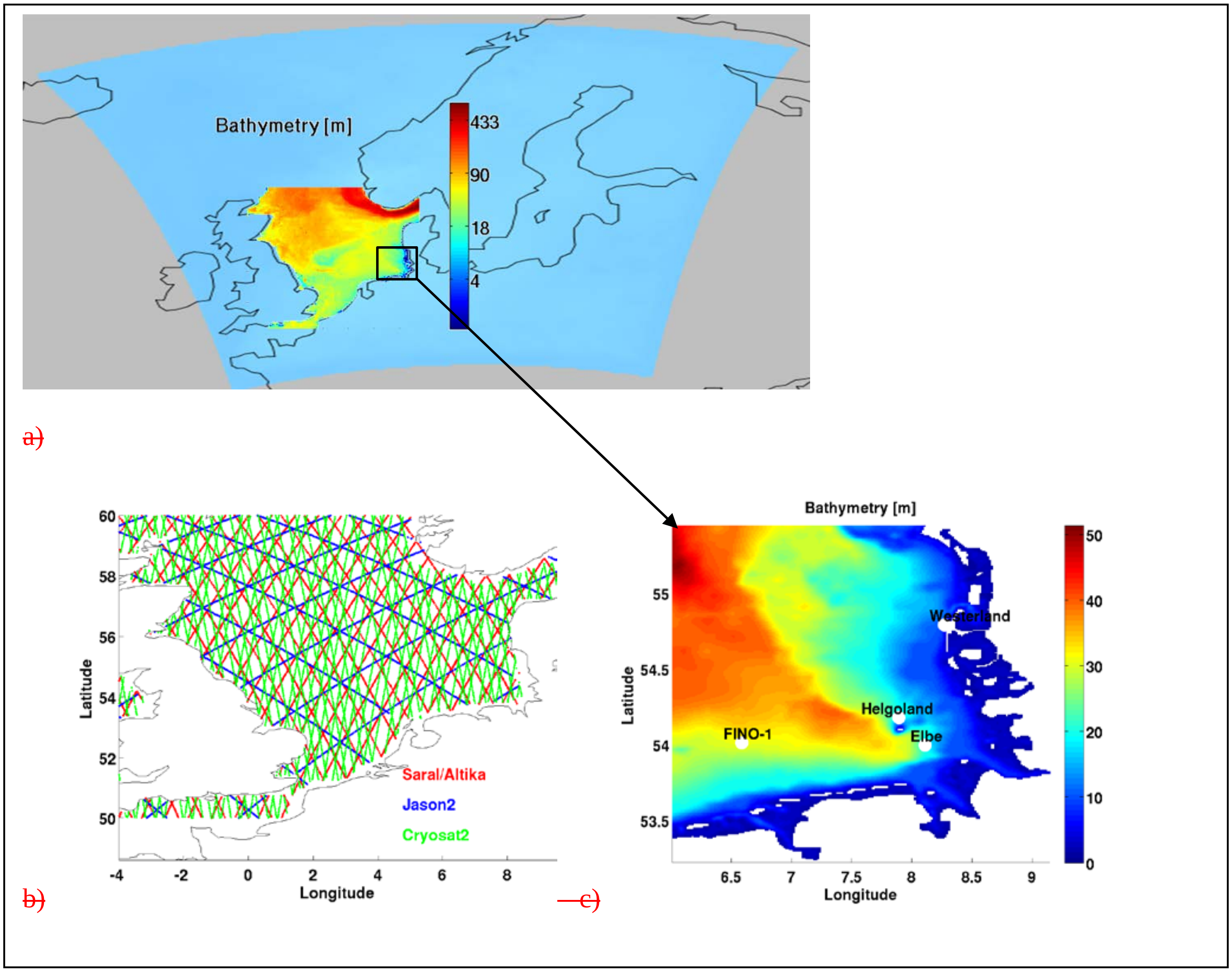
Valcke S., (2013) The OASIS3 coupler: a European climate modelling community software, Geosci. Model Dev., 6, 373-388.

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.

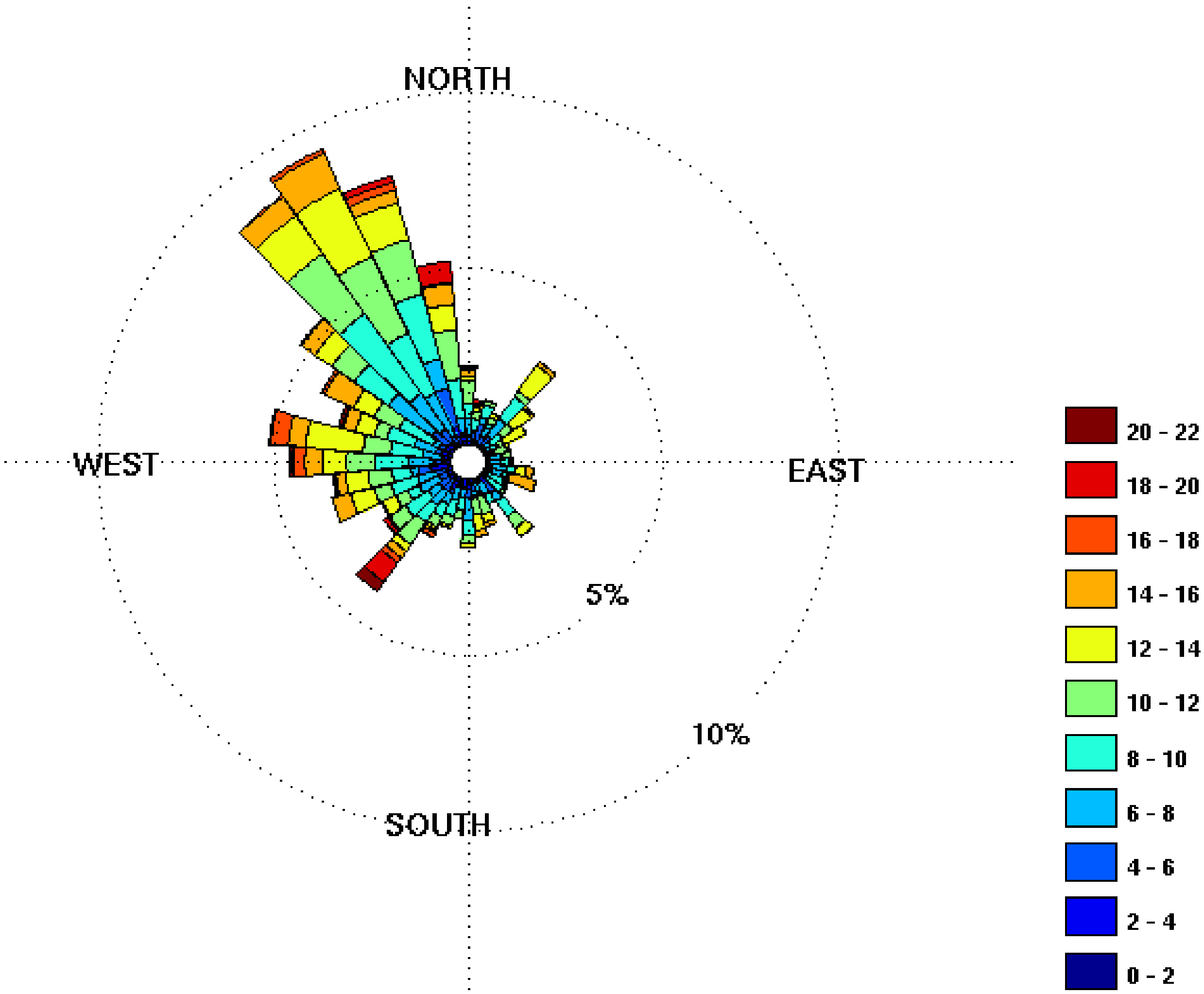
Voldoire, A., Sanchez-Gomez, E., y Mélia, D. S., Decharme, B., Cassou, C., Sénési, S., ... Déqué, M. (2013). The CNRM-CM5. 1 global climate model: description and basic evaluation. Climate Dynamics, 40(9-10), 2091-2121.

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**~~



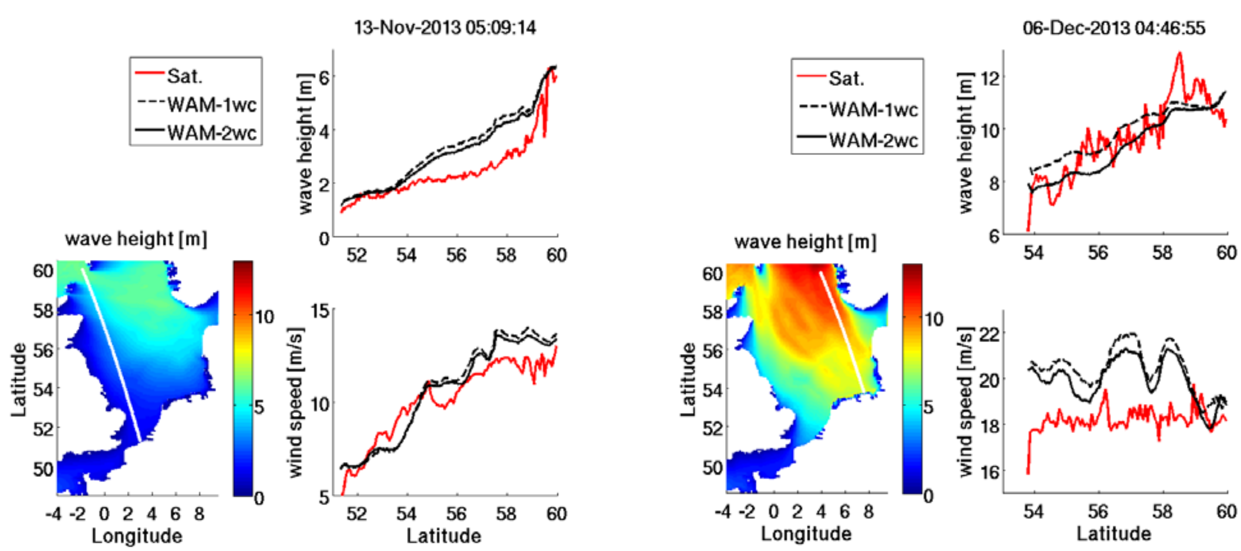
~~*Figure 1: (a) Bathymetry (m) of the North Sea embedded in the COSMO model area (using a logarithmic scale) and (c) bathymetry (m) of German Bight as used in the WAM model. The positions of four waverider buoys used for the validation is indicated, too. (b) Tracks of all available satellite data used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



1150 Zweers,N. C., V. K. Makin, J.W. de Vries, andG. Burgers (2010), A sea drag relation for hurricane wind speeds, Geophys. Res. Lett., 37, L21811, doi:10.1029/2010GL045002.

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).

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



~~a)~~ ~~b)~~

~~*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).*~~

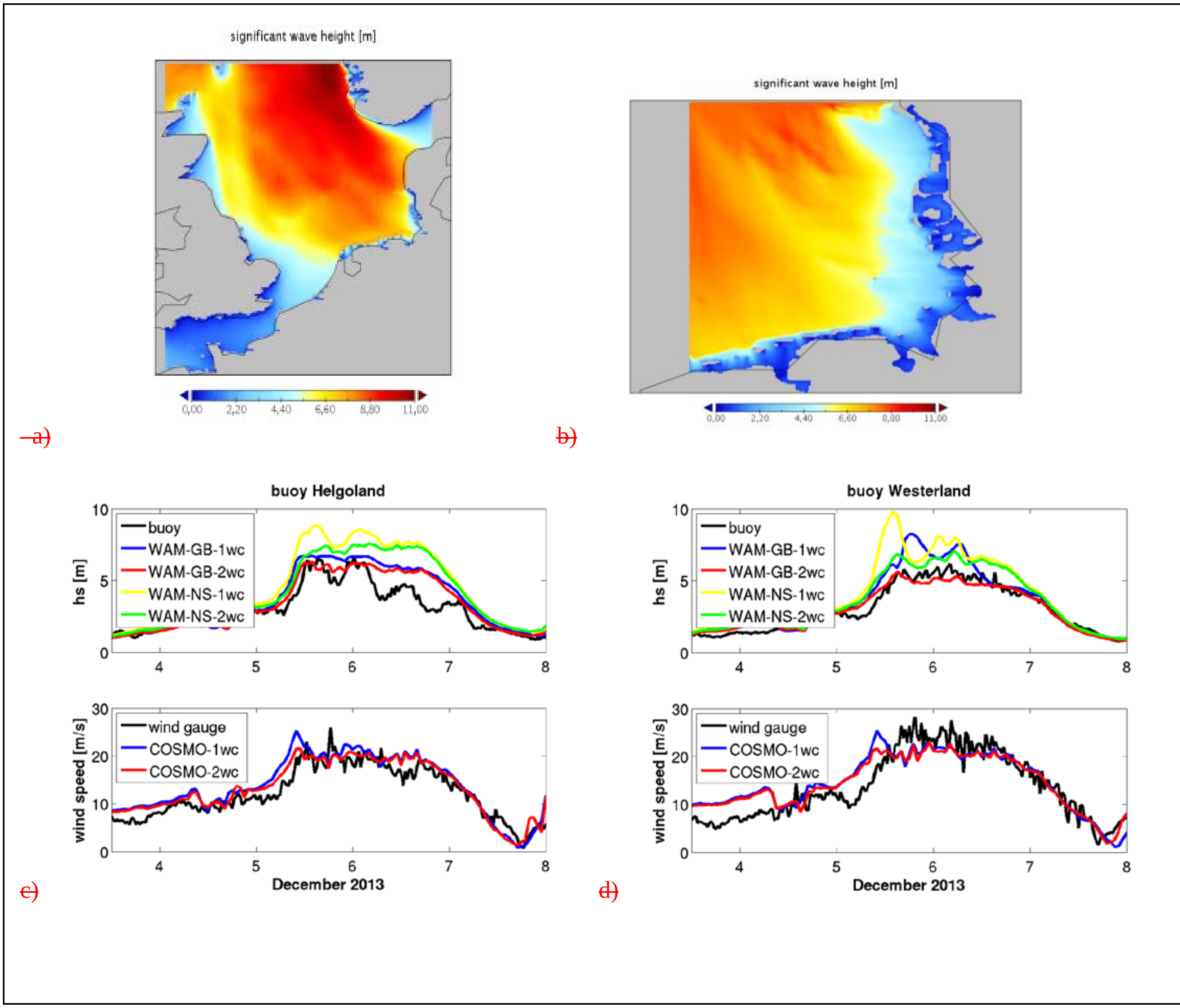
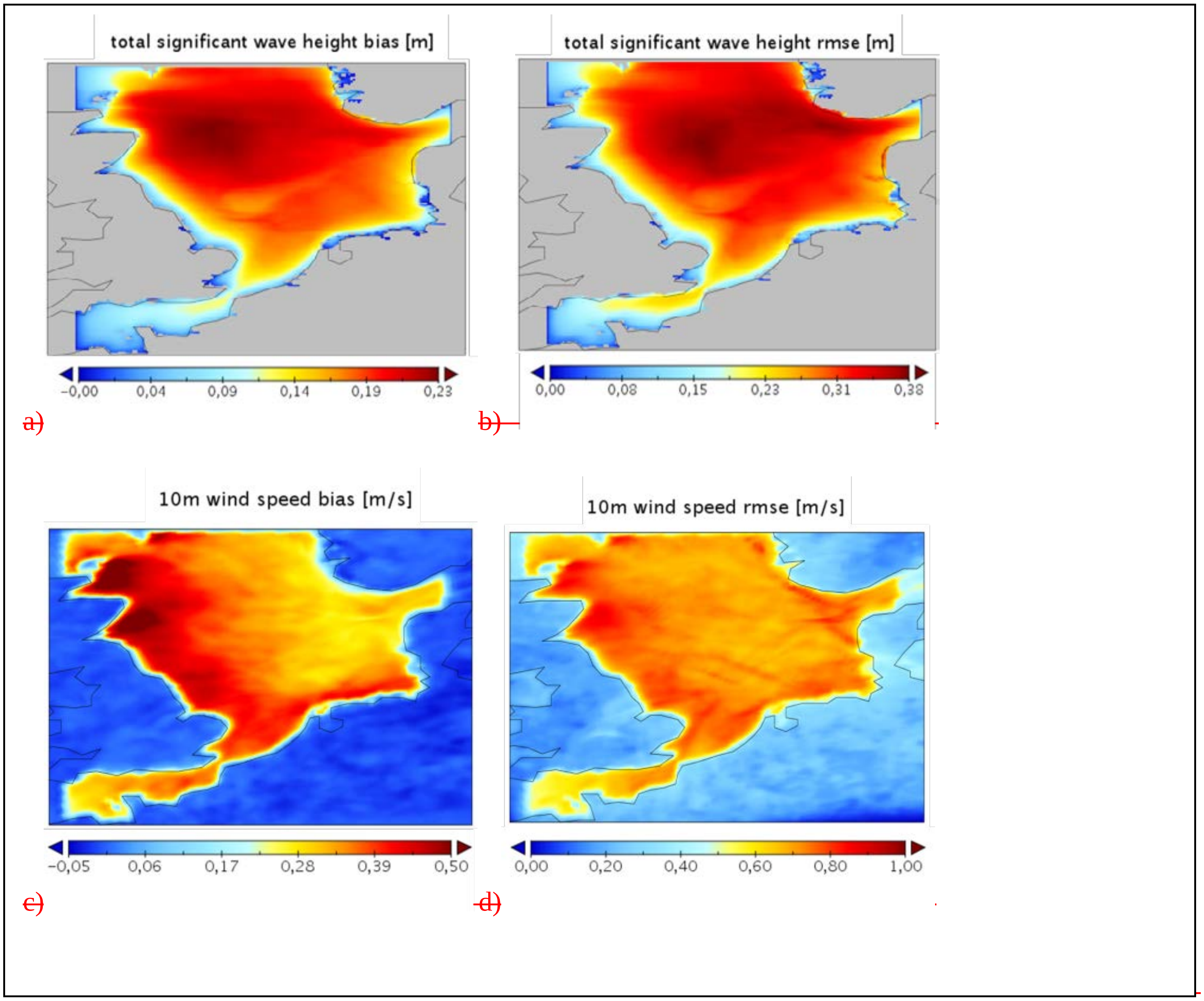


Figure 4: (a,b) Significant wave height (m) in the North Sea (a) and the German Bight (b) at the peak of the storm 'Xaver' (2013/12/6 9UTC) calculated by WAM-NS/GB-2wc. (c,d) Significant wave height (m,top) and wind speed (m/s, bottom) during the storm 'Xaver' at the buoys Helgoland (c) and Westerland/Sylt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

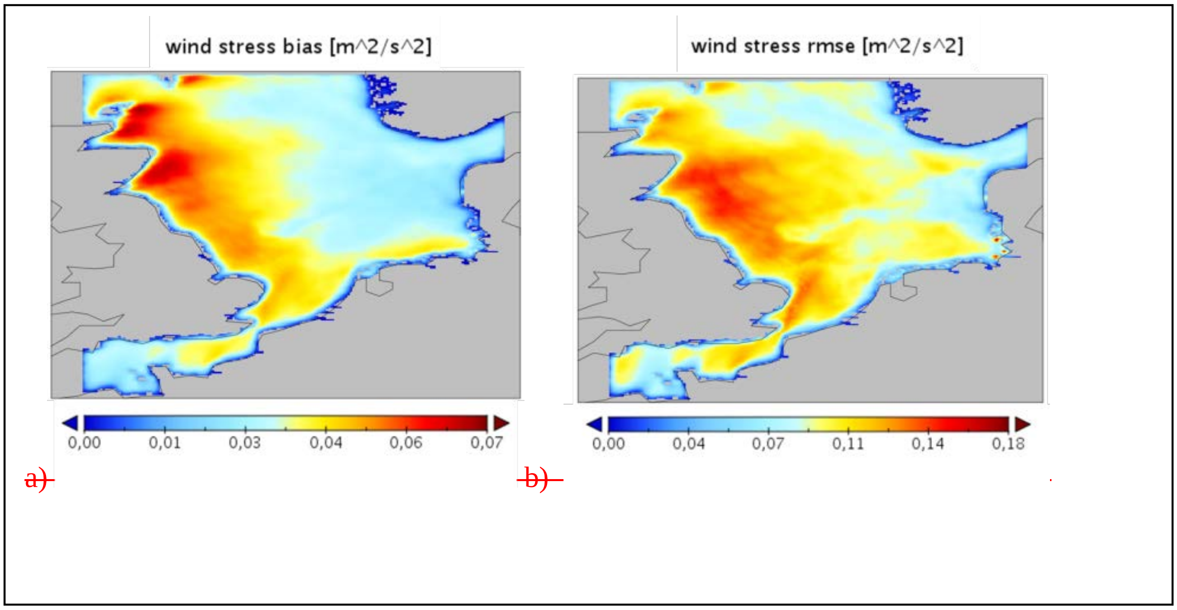


Figure 6: (a) Bias and (b) rmse of WAM/COSMO modeled wind stress when comparing one-way minus two-way coupled modeling over the whole period.

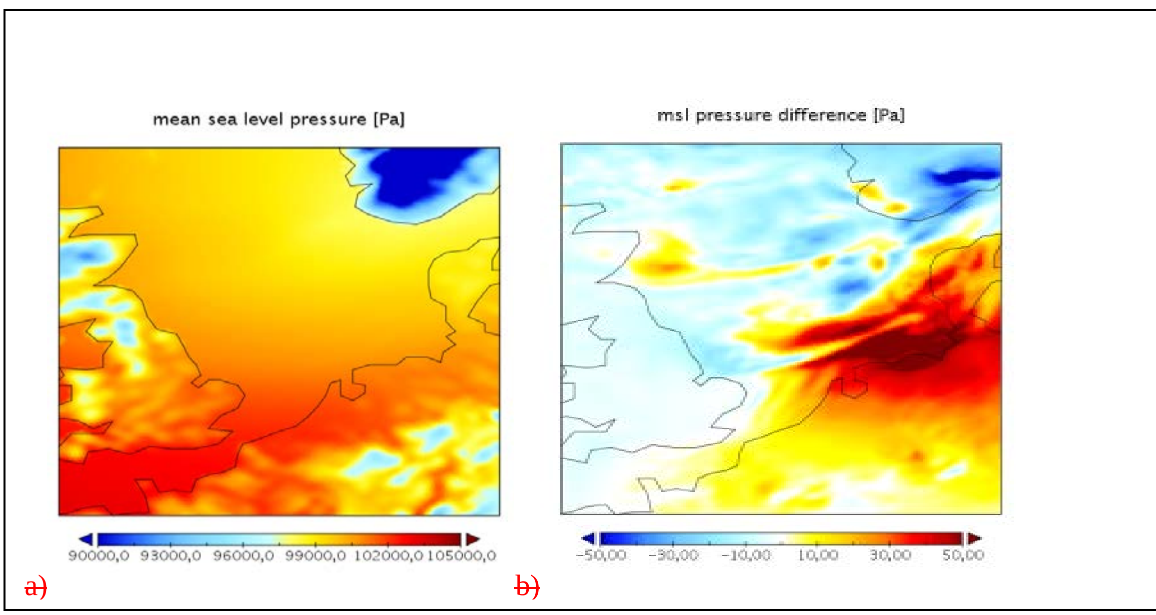
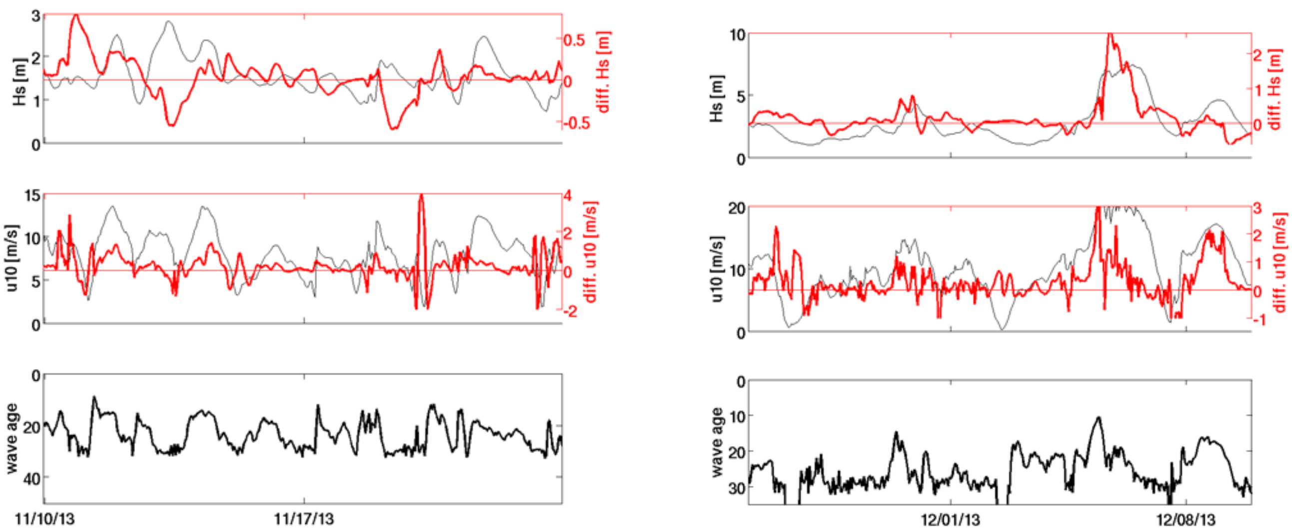


Figure 7: (a) COSMO pressure (Pa) at mean sea level height in the North Sea during storm 'Xaver' and (b) mean sea level pressure differences when comparing one-way minus two-way coupled modeling).



~~a)~~ ~~b)~~

~~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**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-oupled COSMO model data against the FINO-1 data over the whole period ured 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

Figures

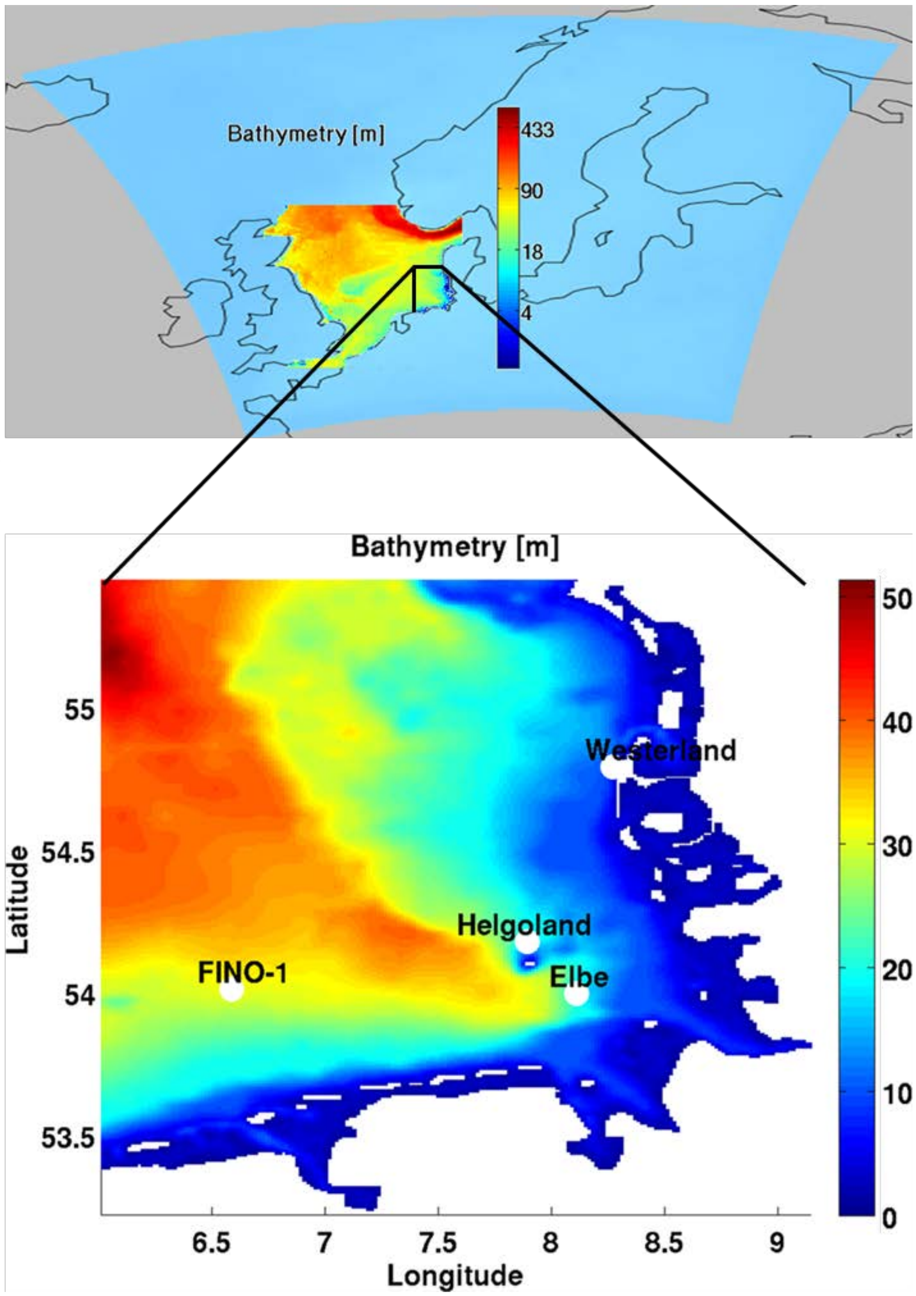


Figure 1: (a) Bathymetry (m) of the North Sea embedded in the COSMO model area (using a logarithmic scale) and (b) bathymetry (m) of German Bight as used in the WAM model. The positions of four waverider buoys used for the validation is indicated, too.

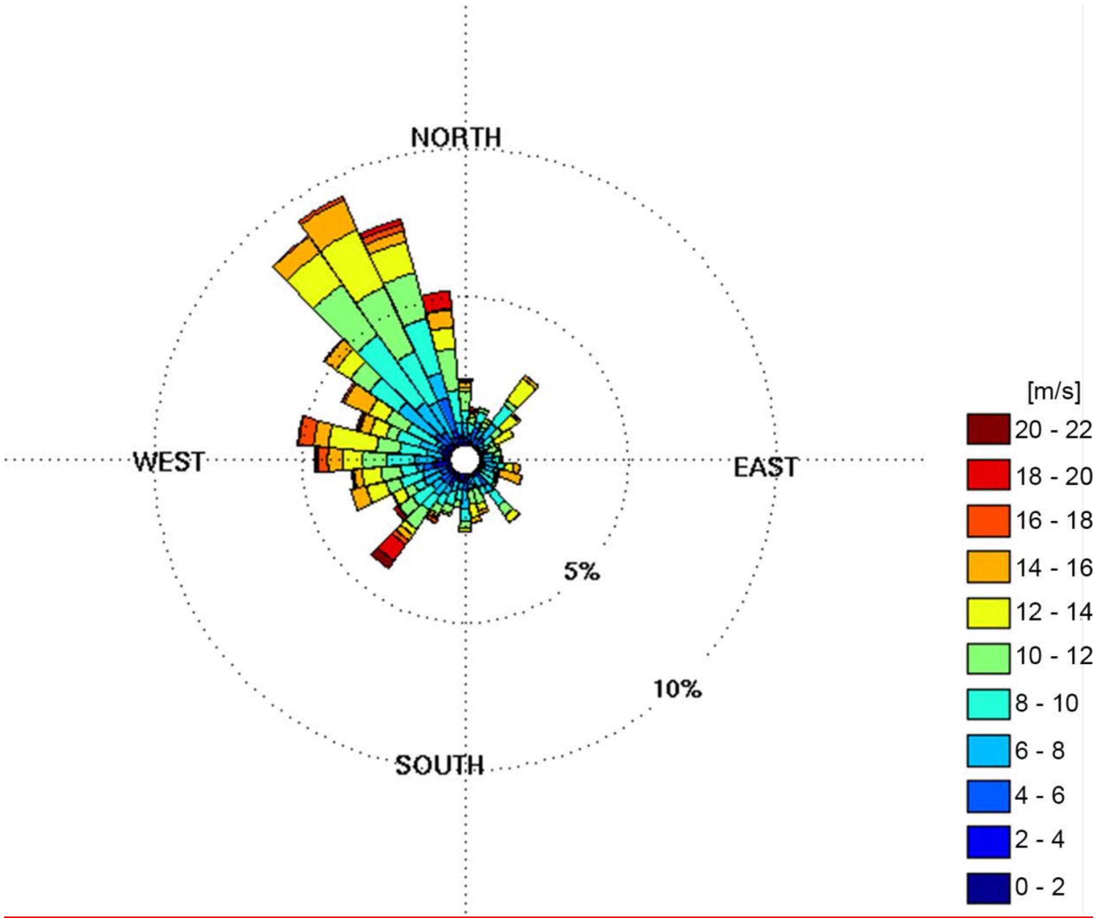


Figure 2: Distribution of wind speeds in m/s (see color bar) and directions at the FINO-1 waverider buoy for October - December 2013.

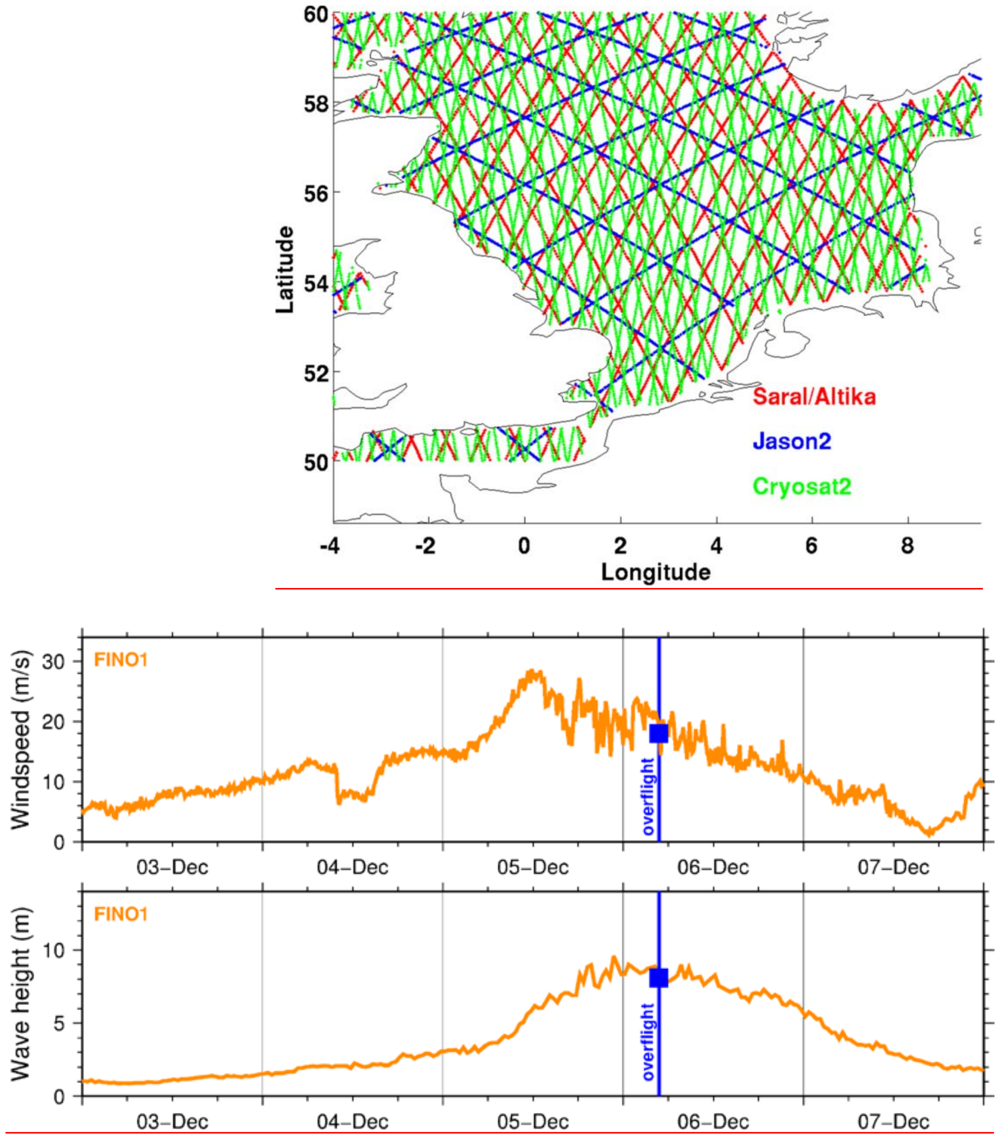


Figure 3: (top pattern) Tracks of all satellites during the study period; (middle and bottom pattern) Wind speed *(middile) and wave height (bottom) during five days* , *which include the Xaver storm at the station FINO-1.*

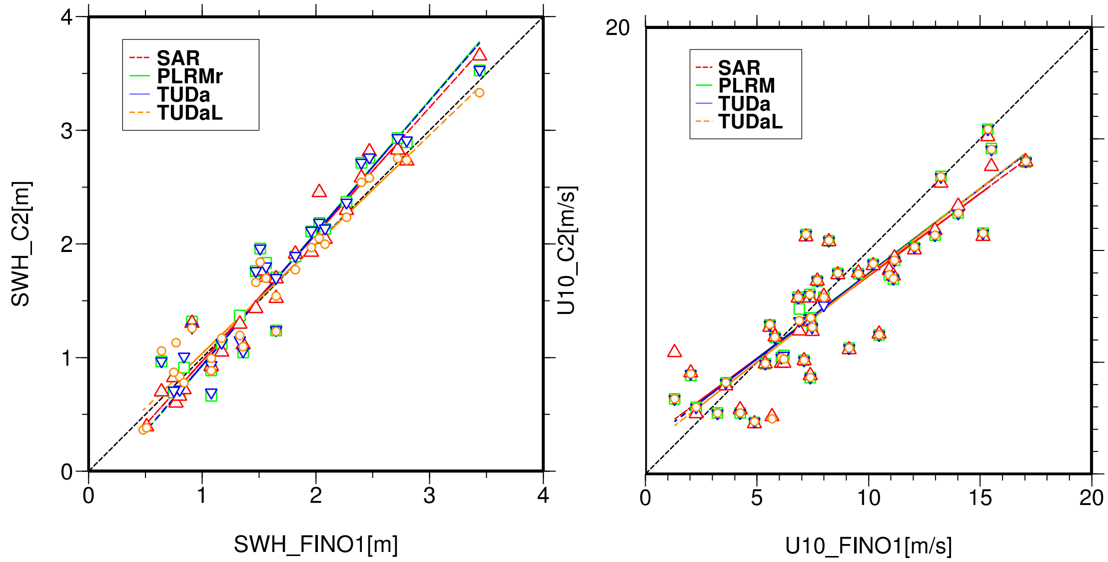
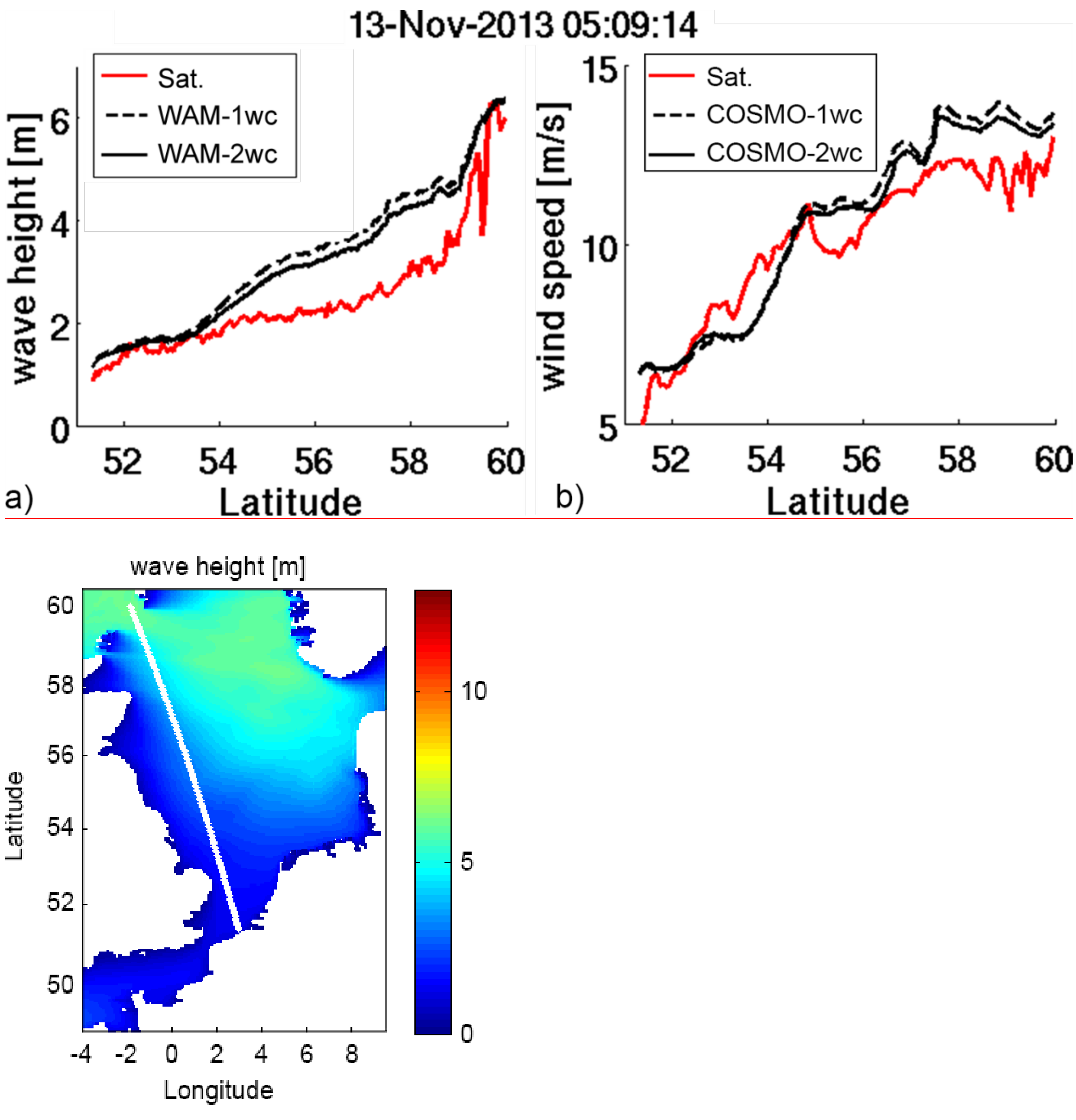
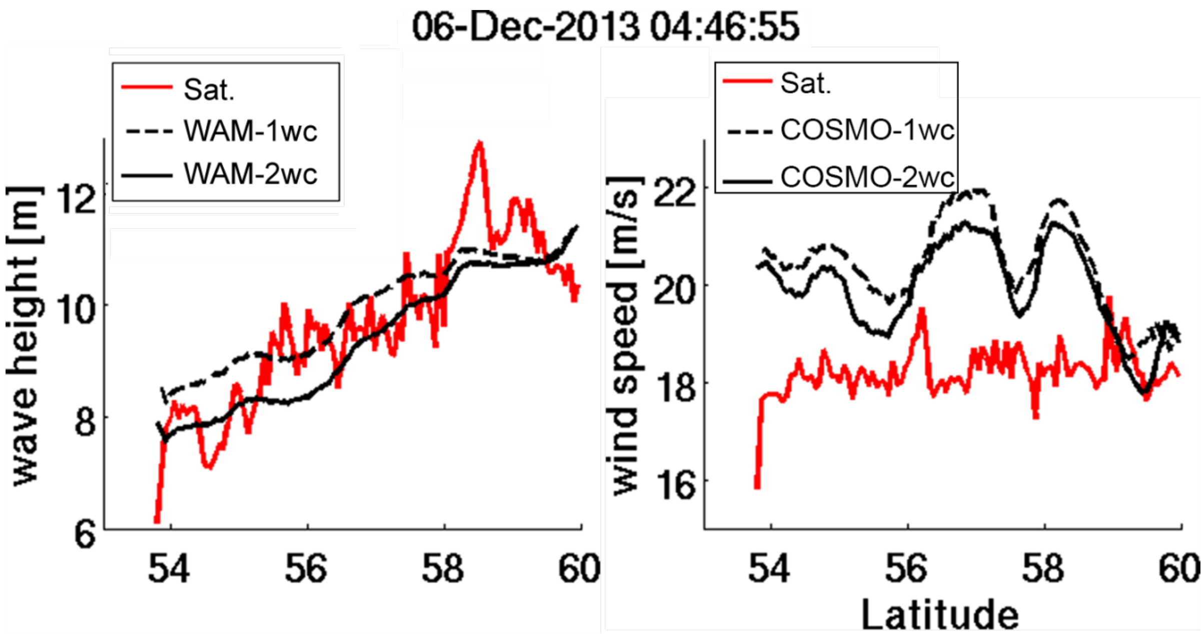


Figure 4. Comparison *of wave height (SWH, in m, left pattern) and wind speed (U10 in m7s, righ patternt) of in-situ and CryoSat-2 altimeter data. at the station FINO-1. Altimeter data used are DDA altimetry (SAR, triangle), standard PLRM (PLRMr and TUDA, square and inverse triangle) and improved PLRM (TUDaL, circle).*

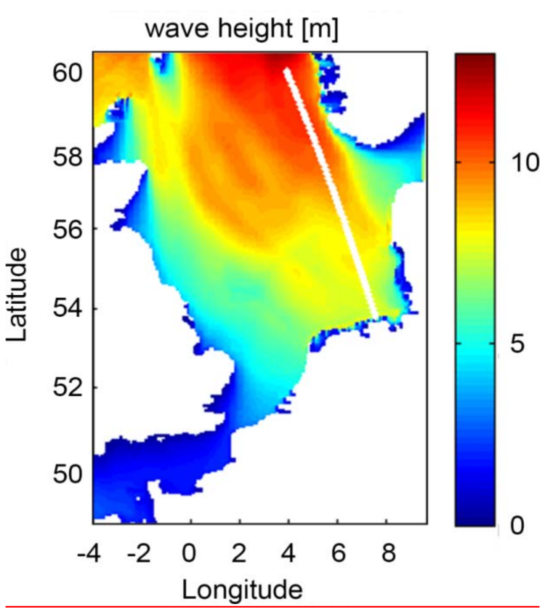


c)

Figure 5: 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).

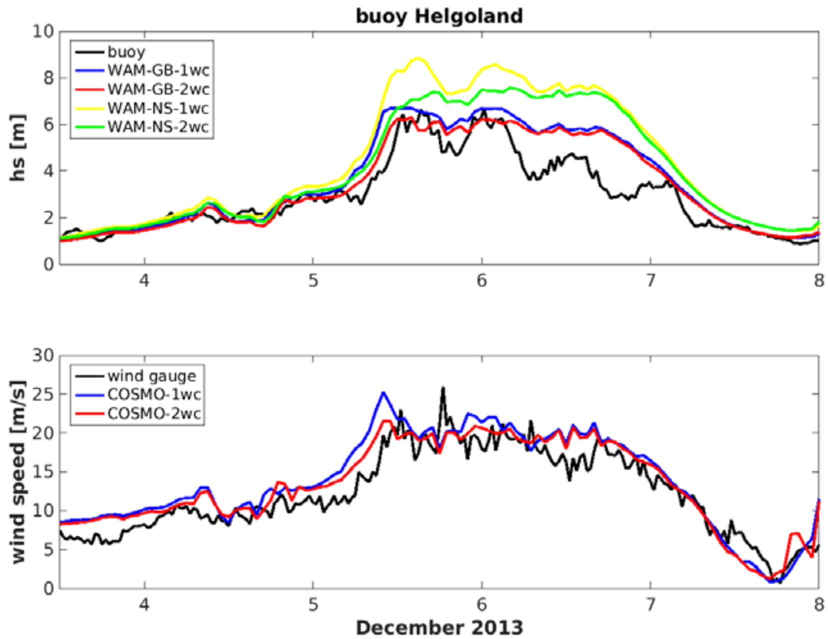


a) b)

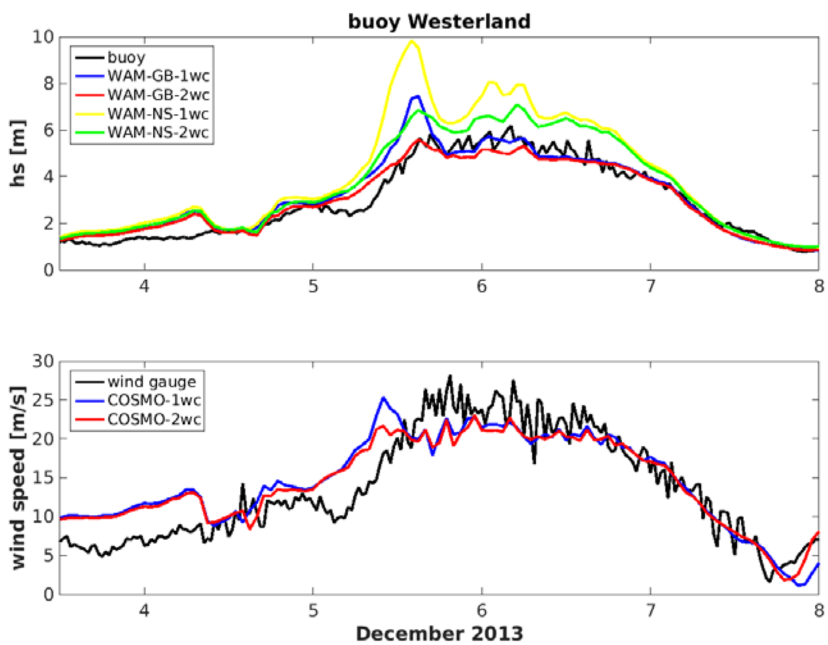


c)

Figure 6 As Figure 5 but for the storm 'Xaver' on 06 December 2013..



(a)



(b)

Figure 7: (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).

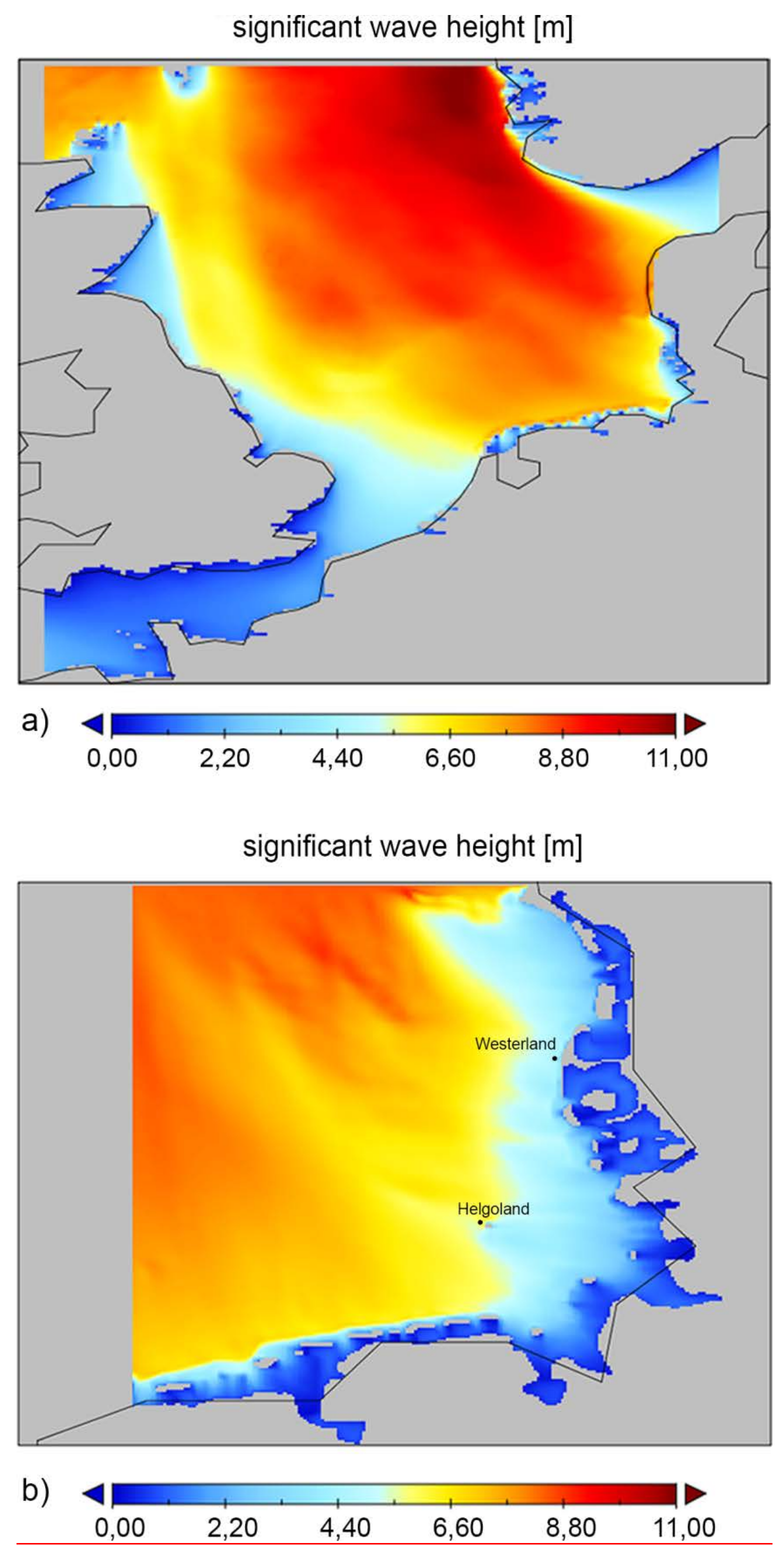


Figure 8: (a,b) Significant wave height (m) in the North Sea (a) and the German Bight (b) at the peak of the storm 'Xaver' (2013/12/6 9UTC) calculated by WAM-NS/GB-2wc.

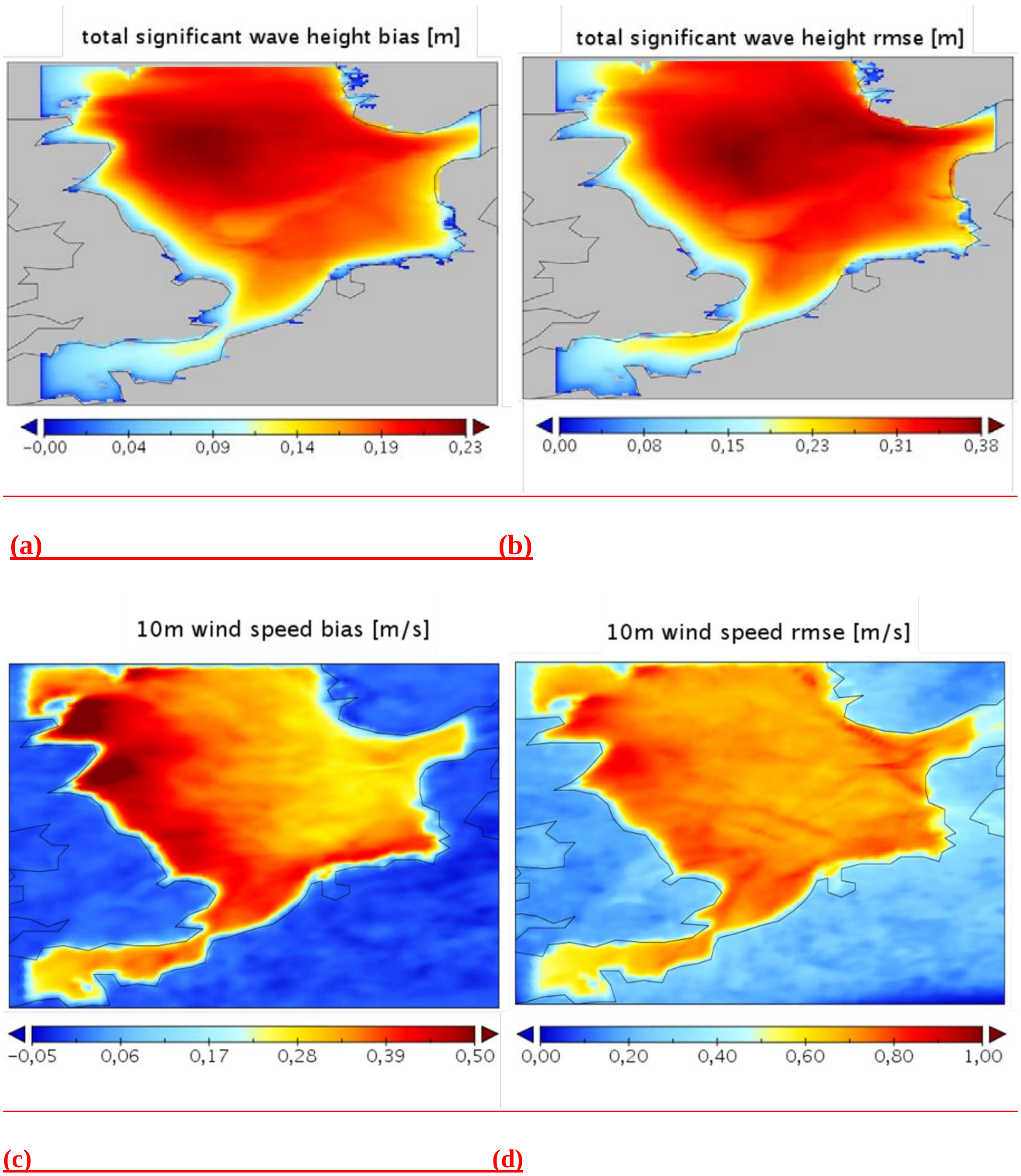
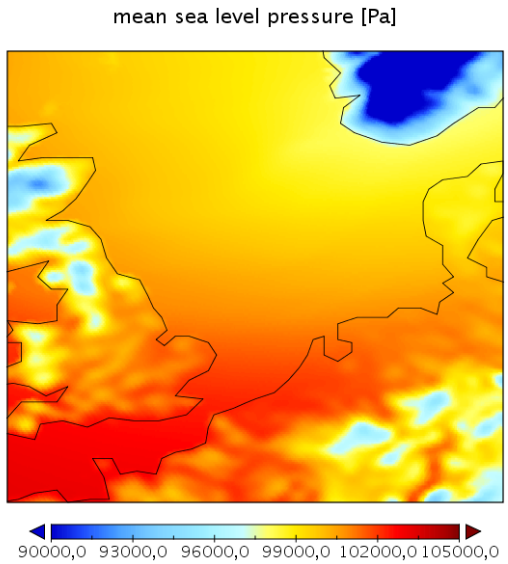
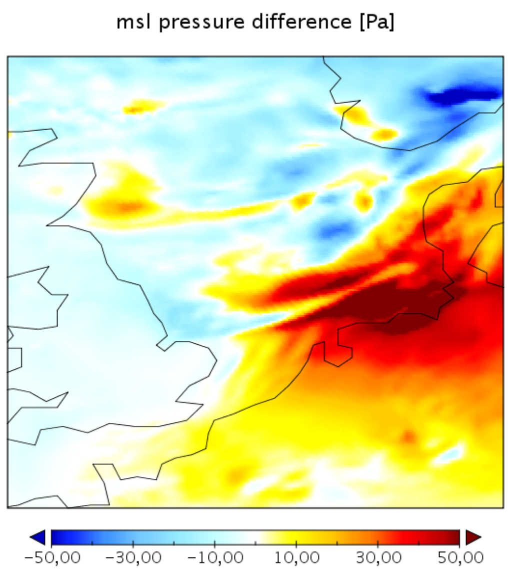


Figure 9: (a,c) Average difference (bias) and (b,d) rms difference (rmse) of WAM modeled significant wave height (m, top panel) and COSMO modeled wind speed (m/s, bottom panel) when comparing one-way minus two-way coupled modeling results. The differences are calculated as averaged over the whole three month period.



(a)



(b)

Figure 10: (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).

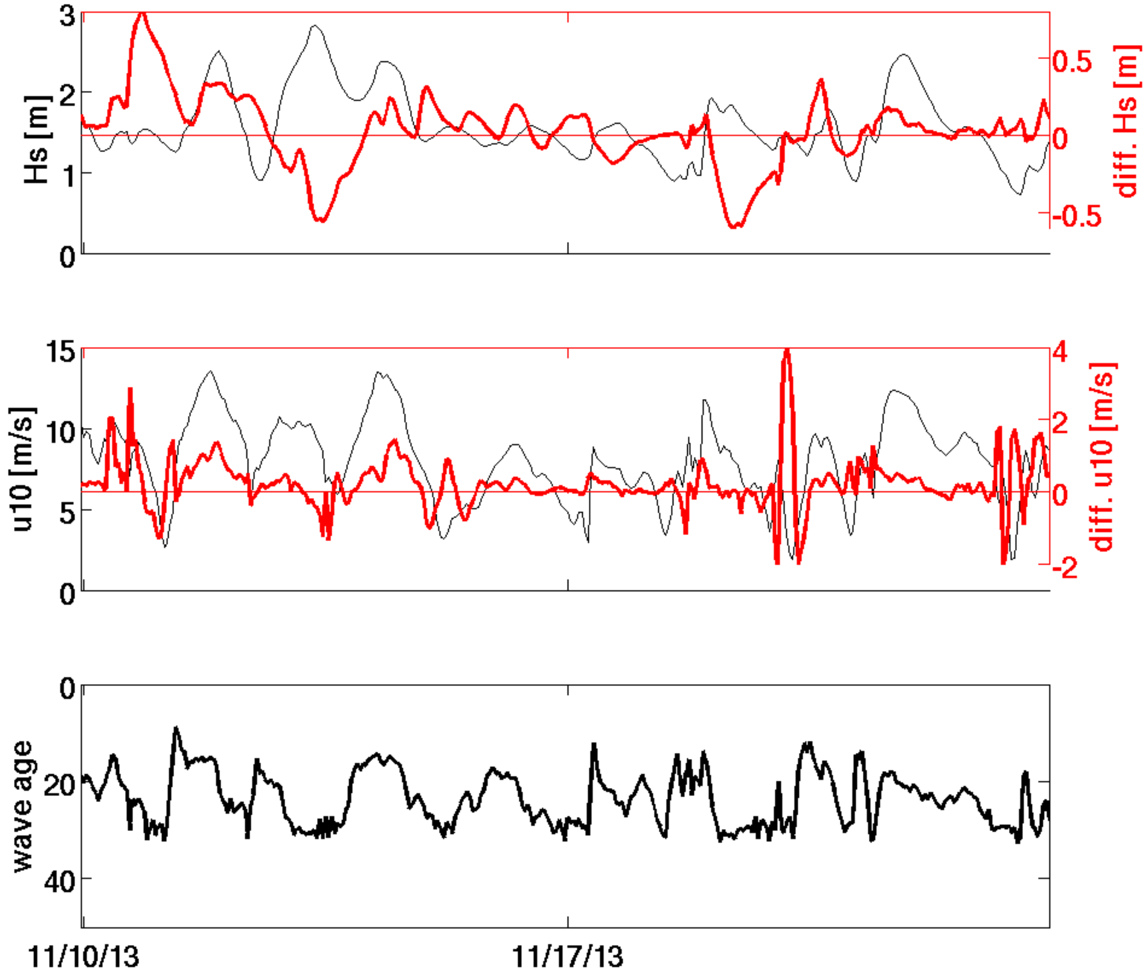


Figure 11: Time series of significant wave height (m, top), wind speed (m/s, middle) and wave age (bottom) from the two-way coupled German Bight setup at FINO-1 for (a) a rather calm period with

1330 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.

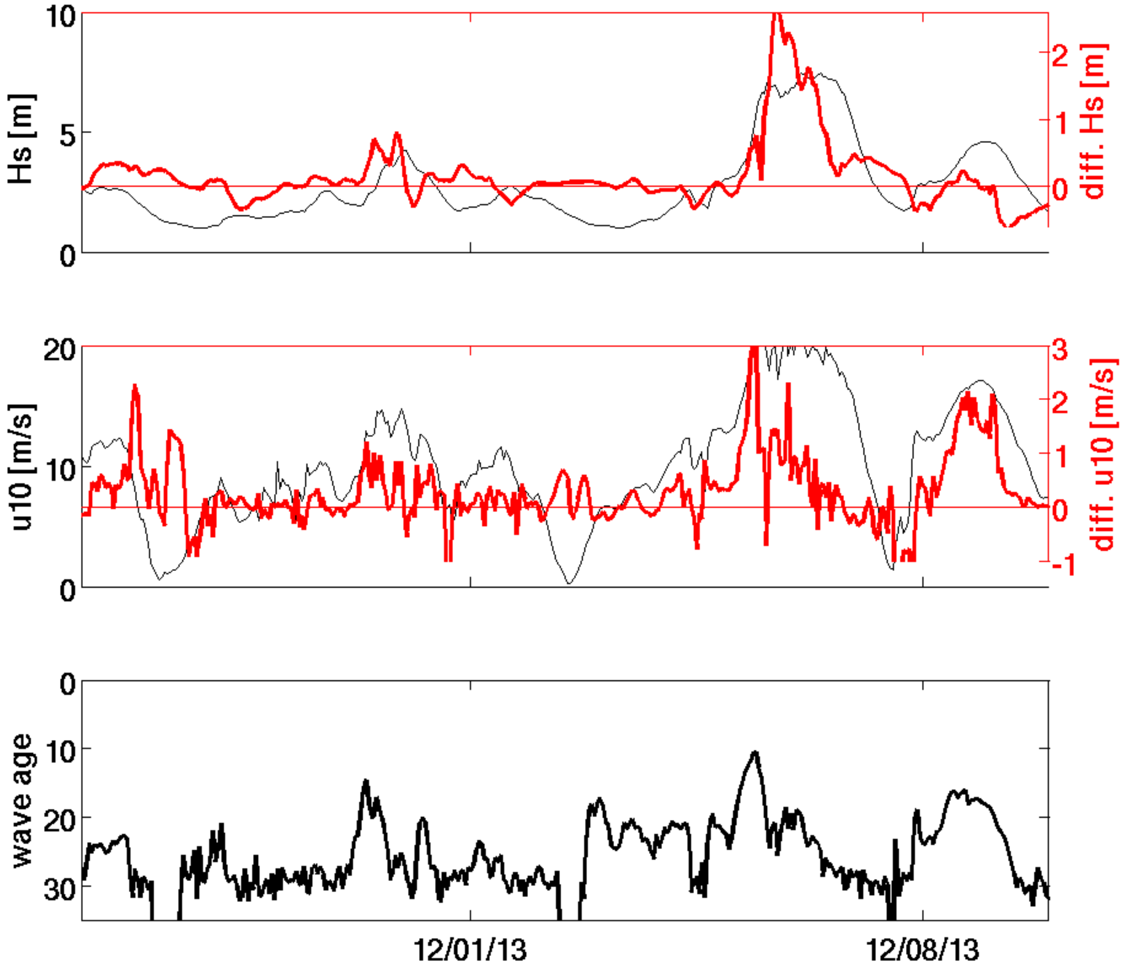


Figure 12: As Figure 8 but during the storm 'Xaver'