Authors response to the Reviewers' #1 comments

Revised manuscript "Wave-atmospheric modelling, satellite and in situ observations in the Southern North Sea: the impact of horizontal resolution and two-way coupling" by Kathrin Wahle et al. presents interesting results of how two-way atmosphere-wave coupling improves the coastal wave forecast. This is an important step in development of coupled models for short-term coastal forecasting with high-resolution, especially as Authors have been able to show that the very high- resolution coastal applications also benefit from the two-way coupling. The revision has improved the manuscript, making it more focused and easier to read. The Authors have also well taken into account the reviewers comments and suggestions.

Authors: Thank you for reviewing our manuscript again.

There are, however, still few places where further clarification is needed (please see my detailed comments below). Also, I suggest that some copy editing is done to the text before publication. Some sentences are quite long and therefore not easy to follow and there is also some repetition.

Authors: The revised manuscript has been crossed-checked again; additional copy editing has been also done. Following the reviewer's suggestion the long sentences have been split and we tried to avoid repetitions in the text.

Some detailed comments:

Section 1. Introduction: This section has improved a lot, and is now better structured and easier to follow. It is, however, quite long and has repetition. I think it would benefit of some copy-editing.

Authors: We agree and the suggested revision has been done; the section is shortened and repetitions are removed.

Section 1, lines 58-59: alternative to fully-coupled ocean-atmosphere model? Would this model include also waves? And why should we have alternatives, shouldn't we aim for the fully coupled models.

Authors: We agree and re-phrased the text in the introduction. Additionally we added in the discussion that: "Two-way coupling of wave and atmospheric models is an important component of a fully coupled ocean-atmosphere modelling system, as it resolves more adequately the interactions and exchanges in the atmospheric boundary layer."

Section 2.2, line 169: Should it be WAM4.5.4?

Authors: Yes, thank you. This has been corrected.

Section 3.1, line 260: the situ-data → the in-situ data?

Authors: We apologize for the mistake and corrected to "the *in-situ* data".

Section 3.2, first paragraph: The bias is calculated as measured minus modelled value and following this, in text it is said that altimeter data underestimates the modelled values. Shouldn't this be said the other way around? E.g. modelled values are overestimated compared to the satellite measurements. In most of the cases I'd assume the altimeter data to be more accurate than the modelled data and it is said to be the dataset against which the model is verified.

Authors: We agree and the suggested revision has been done.

Section 3.2, first paragraph: If the Authors do not trust the Cryosat-swh, why is it used for validation in the first place. Wouldn't two altimeter datasets be enough for validation? Anyhow, the explanation related to this in lines 287-297 is bit complicated to follow. Should the reader disregard the results from this comparison or interpret them with care?

Authors: We agree that the Cryosat-swh must be interpreted with care. This has been now better explained in the revised manuscript. The text in lines 287-287 has been re-phrased following the reviewer's suggestion.

Section 3.2, lines 285-287: Quite a long sentence, could be split to two parts

Authors: The sentence is split into two parts.

Section 3.3, second paragraph: The reason behind the better behaviour of the high-resolution model is probably mostly due to the better description of the bathymetry in the area, not the high-resolution *per se*. It is implicitly mentioned by the Authors, but it could be stated more clear.

Authors: We agree that the reason behind the better behaviour of the high-resolution model is probably mostly due to the better description of the bathymetry in the area, not the high-resolution per se and this is better stated in the revised manuscript. The suggested revision has been done.

Section 4, line 414: Why not simply say, that the fetch is too short for the waves to evolve.
Authors: We re-phrased the sentences just explaining that "the fetch is too short for the waves to evolve".

Section 5, lines 446-449: Quite a long sentence, could be split to two parts.

Authors: The sentence has been split to two parts.

Section 5, lines 473-474: What is meant by potential uncertainties of shallow water in the wave model? Is this related to the description of bathymetry or to the wave model source terms related to shallow water physics?

Authors: The potential uncertainties of shallow water in the wave model are due to both: inaccurate description in the bathymetry as well as to the wave model source terms related to shallow water physics. This has been now clearer explained in the revised manuscript.

Tables 1-3: Table captions should explain what the red and green colouring means.

Authors: The suggested revision has been done.

Figure 3: Please explain the marked overflight also in the Figure caption.

Authors: The suggested revision has been done.

In the Figure and table captions there is a mixture of terms “wave height” and “significant wave height”. Preferably “significant wave height” should be used in all of them.

Authors: The suggested revisions have been done.

Authors response to the Reviewers’ #2 comments

The manuscript has certainly improved, but there is still work left.

Authors:

Thank you for reviewing our manuscript again. The manuscript has been again carefully checked and the suggested revisions have been done.

Title

I liked the old title better than the new one. The title should convey the essence of the paper, and for me that is the effect of a two-way coupling of an atmosphere and wave model on the representation of atmospheric and wave parameters in a shallow and complex coastal area. Explicitly mentioning both in-situ and satellite observations draws to much attention away from that. And, moreover, the title is now too much a collection of loose terms without really connecting them.

Authors: In the revised manuscript the tile has been changed to the initial one.

1. Introduction

line 112: *then* should be *than*.

Authors: The suggested revision has been made.

line 124: I would use *in the German Bight* (more places in the manuscript).

Authors: We agree and changed the text accordingly.

2.2 The wave model WAM

line 169: The first of the paragraph line speaks of version 4.5.4, but here it is 5.4.5 (and with a hyphen).

Authors: We apologize for this incorrectness, which we now correct.

2.4 Study period and data availability

line 210: Figures 2 and 3 are not (hardly) on storm Xaver, and certainly do not show the minimum pressure.

Authors: We modified the text accordingly.

line 210, 211: Use singular *high tide*: even though it occurs at different locations on the German Bight at different times, it is still the top of one tidal wave.

Authors: The change has been made.

line 214: *at low tide* instead of *at low water time*? Or do you mean really something different?

Authors: The change has been made.

line 215ff: something is wrong there.

Authors: This sentence has been re-phrased.

3.1 Altimeter data

line 253ff: Bad sentence. The time series are of wave heights and wind speeds during storm Xaver.

Authors: The paragraph in this section was re-phrased.

line 268: *wave heights of 2 meter respectively*: something is missing there.

Authors: We apologize for the unclear statement; the sentence has been modified.

line 268: Note the inconsistency between *in-situ* here and *in situ* elsewhere.

Authors: The inconsistency has been corrected. We use now everywhere “*in-situ*”.

line 271ff: Do not use the abbreviation *std* without at least one time explaining it in full.

Authors: The suggested revision has been made. We explained it in the text before using the abbreviation *STD*.

3.2 Altimeter-model comparison

You compare the output of *wave models* to remotely sensed data. It would help if you tell here whether you mean 1-way versus 2-way coupled or also already North Sea versus German Bight.

Authors: This was discussed in the introduction and then explained in details in Section 2.3.

line 287: In Section 3.1 you found that the altimeters underestimate the wind speed compared to the in-situ measurements. Then, to conclude that a better agreement of the models with the satellite data means a *skill improvement* seems a step too far. They are closer, but might suffer from the same bias.

Authors: We agree and modified this text accordingly. We also removed the statements about *"skill improvement…"* .

line 297: *waves smaller than one metre*: Why 1 m? Notice also the inconsistent spelling of *metre*, in other places I see *meter*. I do not understand the context smaller than one

Authors: We are sorry for the misspelling and changed "metre" to "meter". The sentence has been also changed. Explanation, including references has been added.

line 307: Something is wrong there

Authors: We removed the redundant part.

line 314ff: The modeled wave height is much smoother than the observations because the model does not resolve the small scales which you see in the observations. That has little to do with post processing.

Authors: We agree with this comment and the discussion on the comparisons (Fig. 5a,b in the revised manuscript) has been re-phrased accordingly.

line 319: You can not conclude that the peak is shifted northward: you are at the end of the satellite track (Why? The satellite should have data more North as well). The valid conclusion would be that you miss the observed peak just above 58°N, but that the field data suggest this might be outside the model area. But you can not rule out either that there is another peak there which you miss because of the broken satellite track.

Authors: We agree with the remark and this has been changed in the revised version, accordingly.

line 324ff: this disagreement between model and observation does **not** indicate anything about the satellite algorithm. You might just remark that it confirms conclusions of Fenoglio-Marc or something like that.

Authors: We agree with the comment and the discussion about the disagreement between model and observation has been modified.

3.3 Validation against in situ measurements

line 342ff: *The comparison ... are exemplified* is grammatically incorrect, and you should probably formulate it completely different. Figure 7 gives the results and you are now going to compare them.

Authors: The discussion on the comparisons (the results in Fig. 5a,b in the revised manuscript) has been re-phrased accordingly.

line 352: *due to the time shift in the wind data*: suggests that you explained this time shift somewhere earlier. But I can not find that.

Authors: In the revised manuscript the variability in the wind data and the shift of the simulated wind peak has been demonstrated and the time-shift explained before discussing the measured and modeled significant wave height comparisons.

line 382: *behaviour* is always singular

Authors: The suggested revision has been made.

line 396: *reduced by 5%*: I read an *increase* of 2.5% in Table 3.

Authors: We agree and apologize for the mistake. This has been corrected in the revised manuscript.

4. Impact of the two-way coupling

I am still not happy with the use itself of *bias* in this case. Bias indicates a deviation from a reference, but here you are just comparing two different model configuration of which neither should be considered as reference a-priori. The phrasing *average difference in wave height* is correct, but you should not call it *bias*.

Authors: The suggested revisions have been made: instead of “bias” we used “average difference”

Something similar applies to the use of *RMSE*. This stands for Root Mean Squared Error, but for that you also need a reference. In the original manuscript it was correctly called *root mean squared difference*.

Authors: Now instead of “Root Mean Squared Error “we used “root mean squared difference”

5. Summary and Outlook

line 342: the use of *perform* is incorrect here.

Authors: This sentence has been re-phrased.

line 343: I do not think that the coupling software *analyses* anything. It just couples two models.

Authors: This sentence has been re-phrased.

line 470: *than from* ? Probably *from* should go away.

Authors: We apologize for the redundancy and removed “from” from the text.

line 471: *This study* is confusing: do you mean the current paper or Staneva et al.?

Authors: This sentence has been re-phrased. We meant the paper of Staneva et al.

line 475ff: The way this is formulated suggests more than what is dealt with in this paper. The use of *largely* is probably not appropriate here, as is *nevertheless*.

Authors: The suggested revision has been made.

Figures

Figure 1b

The name *Westerland* is still unreadable.

Authors: We agree and Figure 1b has been re-plotted, making the text readable.

Figure 2

What exactly is the radial variable?

Authors: The wind rose diagram is described in the Figure 2 caption.

Figure 3

The first subfigure is quite different from the other two. Especially when the colours used are not the same: red for Saral/Altika in the map and blue in the time series. I would make a separate Figure 4 for the time series.

Authors: We split now the sub-plots in different figures (Figure 3 and 4 in the revised manuscript).

The caption of the new Figure 4 should more clearly indicate that it is the observations in station FINO-1 together with the Saral/Altika observation. The blue vertical lines in the time series should be removed: the square is the satellite observation.

Authors: We modified the capture of the new Figure 4 accordingly. Also the suggested revisions in the figures have been done.

Figure 4 (old)

No tick marks on the left axis of the right plot; the Y axis text is far too close to the left plot; the caption is a mess; *pattern* should be *panel*.

Authors: The suggested revisions in the figures have been done. The quality of the figure has been improved.

Figure 6

Figure 6a lacks the x-axis title *latitude*.

Authors: The suggested revisions in the figures have been done.

Figure 7

The yellow lines are still hardly visible. I actually meant in my earlier comments, that you should not use yellow for such lines at all.

Authors: In the revised manuscript we changed the colours of the lines.

References

I only looked up 3 or so in the references list, but of those 2 had incorrect years in the text. So, all references should be carefully checked.

Authors: The references in the revised manuscript have been cross-checked.

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

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Abstract

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, especially in dynamically complicated coastal ocean areas, such as the southern part of the North Sea – the German Bight. Here, we study the effects of coupling ~~between~~of an atmospheric model (COSMO) and a wind wave model (WAM), which is enabled through ~~an introduction of~~implementing wave induced drag in the 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~~simultaneously 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~~as the German Bight is a very shallow and dynamically complex coastal area exposed to storm floods. The two-way coupling leads to a reduction of both surface wind speeds and simulated wave heights. In this study, the sensitivity of atmospheric parameters, such as wind speed and atmospheric pressure to the wave-induced drag, in particular under storm conditions and the impact of two-way coupling on the wave model performance is quantified. Comparisons between data from *in-situ* and satellite altimeter observations indicate that two-way coupling improves the simulation of wind and wave parameters of the model and justifies its implementation for both operational and 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 however, the wind waves extract energy and momentum from the atmosphere as they grow under the influence of wind. This effect is greater for young sea states and high wind speed~~,~~ in comparison to decaying sea and calm atmospheric conditions. Under such conditions, the drag coefficient cannot be considered as independent from the sea-state and as uniform in time and space. This dependence needs to be accounted for in coupled atmosphere-wave models. Jenkins *et al.* (2012) demonstrated that the wave field alters the ocean's aerodynamic roughness and the air–sea momentum flux~~,~~ depending on the relationship between the surface wind speed and the propagation speed of~~ 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~~speed, and modulate ~~the~~ heat and moisture transports between the atmosphere and ocean~~; and concluded that~~ . As a result of this boundary layer modification~~,~~ Doyle (1995) concluded that the mesoscale structures associated with ~~the cyclone~~cyclones are perturbed. The impact of sea surface roughness ~~has been~~was investigated in studies by Bao *et al.* (2002) and ~~Desjardings~~Desjardins *et al.* (~~2001~~2000). As shown by Lionello *et al.* (1998), the two-way wave-atmosphere coupling attenuates the depth of the pressure minimum. In particular, non-linearities increase under extreme conditions, ~~non-linearities increase and~~which can modify the intensity of storms ~~can be modified~~ due to feedbacks between waves and the atmosphere. This feedback ~~must~~needs to be accounted for in coupled models ~~because~~as strong winds cause the drag coefficient of the sea surface to increase~~, which leads~~ leading to ~~wind speed~~a reduction of wind speeds and modification of ~~the~~ wind ~~direction~~directions (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~~(2010) showed that the ~~surface drag was overestimated in the~~ used atmospheric ~~weather prediction~~ model overestimates the surface drag for high wind speeds~~, and~~ . At the same, the simulations underestimated the intensity of hurricane winds~~ was underestimated in the simulations; they~~. Zweers *et al.* (2010) proposed an approach of calibrating the boundary layer parameterization using ~~the~~a one-way coupled model. They tested a new parameterization that decreased the surface drag for two hurricanes in the Caribbean~~ and demonstrated that the~~. This 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.

The coupling between atmospheric and wind wave models was first introduced operationally in 1998 by the European Centre for Medium-Range Weather Forecasts (ECMWF). The method, which 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. Waves have beenwere recently considered in operational coupled model systems, such as forthat of Meteo-France (Voldoire *et al.* 2012., 2013). Breivik *et al.* (2015) incorporated the effects of surface waves onto ocean dynamics via ocean side stress, turbulent kinetic energy due to wave breaking, and the Stokes–Coriolis force in the ECMWF system.

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

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~~Analyses of the differences between altimeter and *in-situ* measurements over longer time intervals ~~provides~~provide an ~~estimation~~estimate of the accuracy of altimeter data relative to *in-situ*-data assumed as ground-truth. Significant wave ~~height~~heights derived from satellite altimetry ~~has~~have been compared to wave height ~~measured by~~measurements from several wave-riders in Passaro *et al.* (2015). Fenoglio-Marc *et al.* (2015) ~~considers~~consider 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~~ In this study, we aim at a quantification of the effects of coupling ~~between~~of the ~~waves~~wave and ~~atmosphere~~atmospheric model, ~~especially~~also during extreme storm events. We ~~present intercomparisons~~compare simulations from between coupled and stand-alone models ~~and~~that we 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 the computed sea-surface roughness back to the atmospheric model. Then, we statistically assess the impact of the two-way coupling and validate the two setups against available *in-situ* and remote sensing data. Our novel contribution here is that we simultaneously ~~running~~run (via a coupler) a regional North Sea coupled wave-atmosphere model together with a nested-grid high resolution in the German Bight wave model (one atmospheric model and two wind wave models). Using this configuration allows us to study the individual and combined effects of (1) model coupling and (2) grid resolution, especially under severe storm conditions, which is a challenging aspect for wave modelling at the German Bight because it is a very shallow and dynamically complex coastal area.

The paper is structured ~~by describing~~as follows. First, we describe the models used, the coupling and specification of different model setups, period of model integration, and available data for validation in section 2. ~~Validation of~~Afterwards, we validate the models against satellite and *in-situ* measurements ~~are described~~ in section 3. ~~A discussion on~~Section 4 discusses the impact of two-way coupling ~~is provided in Section 4.~~. The ~~paper ends with a summary~~final section summarizes our findings and also provides an outlook for future research.

2. Model description and set-up

2.1 The atmospheric model COSMO

The atmospheric model used in the study is the non-hydrostatic regional climate model COSMO-CLM (CCLM) version 4.8 (Rockel *et al*~~.~~., 2008, Baldauf *et al*~~.~~., 2011). The model is developed and applied by a number of national weather services affiliated in the Consortium for Small-Scale Modeling (COSMO, see also http://www2.cosmo-model.org/). Its climate model COSMO-CLM (CCLM) is used by the Climate Limited-area Modelling Community (http://www.clm-community.eu/). CCLM is based on the primitive thermo-hydrodynamical equations that describe compressible flow in a moist atmosphere. The model equations are formulated in rotated geographical coordinates ~~and a~~with generalized terrain following vertical coordinates. The model uses the primitive momentum equations ~~for momentum~~. The continuity equation is replaced by a prognostic equation for perturbation pressure (i.e., pressure deviation from a reference state representing a time-independent dry atmosphere at rest, which is prescribed as horizontally homogeneous, vertically stratified and in hydrostatic balance).

In our setup, we use a spatial resolution of ~10 km and 40 vertical levels to discretize the area around the North Sea and Baltic Sea (Fig. 1a). Forcing and boundary condition data are taken from the coastDat-2 hindcast database for the North Sea (Geyer, 2014) covering the period 1948-2013 with a spatial resolution of ~24 km (0.22°) and a temporal resolution of six hours.

2.2 The wave model WAM

WAM Cycle 4.5.4 is an update of the third generation WAM Cycle4 wave model (Komen *et al*~~.~~., 1994). The basic physics and numeric are maintained in the new release. The source function integration scheme of Hersbach and Janssen (1999) and the reformulated wave model dissipation source function ~~(Bidlot *et al*., 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 ~5 km (Fig. 1a), and a finer wave model for the German Bight with a resolution of ~900 m (Fig. 1b). These models~~, which are~~ (described ~~by~~in Staneva *et al*~~. (2016),~~., 2015) use a directional resolution of ~~15^0~~15° and 30 frequencies~~,~~ with an equidistant relative resolution ~~between~~ranging from 0.04 ~~and~~to 0.66. The boundary values for the North Sea model are taken from the regional model EWAM (European WAM) of the German Weather Service (DWD). The forcing wind data are provided by CCLM (see Section 2.1). The German Bight wave model uses boundary values of the outer North Sea model and accounts additionally for depth induced wave breaking and depth refraction. The sea state dependent roughness length, according to Janssen (1991), has already been implemented into ~~the~~ WAM-4.5.4.~~5,~~ Thus for the present study, the model only needed to be adapted for the usage with the OASIS3-MCT coupler (see Section 2.3).

2.3 Coupling of Models

~~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) from the European Centre for Research and Advanced Training in Scientific Computation (CERFACS) and MCT (the Model Coupling Toolkit) that was developed by Argonne National Laboratory in the USA. Details of properties and usage of the coupler OASIS3 can be found in Valcke (2013). Exchanged fields between the atmospheric and wave models in this study are wind and sea surface roughness length. For the coupling with OASIS3 the modifications in the atmospheric model are as in Ho-Hagemann *et al.* (2013), and in the wave model WAM as in Staneva *et al*~~.,~~. (2016).

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

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 CCLM 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, while it is not in the ~~second~~first experiment.~~ This study is novel,~~ Compared to previous atmosphere-wave coupling research, ~~because with the OASIS coupler~~our study is novel as we are able to simultaneously run a high resolution coastal model (the German Bight one) that uses winds and lateral forcing provided by the coupled regional atmosphere (COSMO-2wc) and wave (WAM-NS-2wc) models.

2.4 Study Period and Data Availability

The coupled wave-atmosphere model system described in the previous section was used to simulate a three-month period from October to December 2013. This period was chosen because it includes the time when the storm Xaver passed over the study area on the 6th of December, 2013. This was one of the most severe storms of the last decade, which originated south of Greenland and rapidly deepened as it moved eastwards from Iceland over the Norwegian Sea to South-Sweden and further to the Baltic Sea and Russia. ~~It reached its lowest sea level pressure on the 5th of December at 18 UTC over Norway (~970 hPa, Figs. 2 and 3). At~~At the German Bight, the arrival of Xaver coincided in time with a high ~~tides~~tide. Because of the high ~~tides~~tide and wind gusts of greater than 130 km/h, an extreme weather warning was given to the coastal areas of north-western Germany (Deutschländer *et al.*, 2013). This storm event was also exceptional because of its long duration of nearly two days. The surge height reached ~2.5 m, with its maximum at low ~~water time~~tide. 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. They found that the surge derived from the tide gauge records at Aberdeen and Lowestoft stations, had only one maximum, reaching the eastern North Sea coastal areas (anticlockwise propagation) approximately ten hours later than at Lowestoft (easternmost UK coast). This caused the second storm surge maximum, which was detected by the measurements ~~on~~in the German Bight. As demonstrated by Staneva *et al.* (2016), the wave-induced ~~processes~~mechanisms contributed to a persistent increase of the surge after the first maximum (with slight overestimation after the second peak).

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

To validate our experiments, we use wind speed and significant wave height data measured by satellite altimeters SARAL/AltiKa, Jason-2 and CryoSat-2 over the North Sea (see Fig. 3 with the tracks of the different satellites over the three-month study period). The first two carry ~~on board a~~ classical pulse-limited ~~altimeter~~altimeters that ~~operates~~operate in a low resolution mode (LRM), while the CryoSat-2 ~~instrument operates~~instruments operate in an LRM or in Delay Doppler Altimetry (DDA) mode. The CryoSat-2 data used here were extracted from the RADS database (Scharroo *et al*~~.~~., 2013), where CryoSat-2 data acquired in DD mode in our region was processed to generate pseudo-LRM data (PLRM). Accuracy and precision of PLRM data are slightly lower than LRM and SAR data (Smith and Scharroo, 2015). The altimeter satellites observe along their ground-track offshore up to a few kilometres from the coast (Fig. 3). Their ground track pattern and repeat period are different for each of the three missions, as the same location is revisited by each mission every 27, 10, and 350 days (Chelton *et al.*, 2001). The SARAL/AltiKa data are of special interest in our study because this satellite passed over German Bight during the storm Xaver when the surge was at its maximum (Fenoglio-Marc *et al*~~.~~., 2015). The *in-situ* wave data from four directional waveriders at German Bight are provided by the Federal Maritime and Hydrographic Agency (BSH) (see Fig. 1b for the buoy locations). The wind speed measurements close to the shore of the Island of Sylt, near the Westerland buoy location, and on the island of Helgoland are provided by the DWD. At station FINO-1 (see Fig. 1b for its location), there were also wind speed measurements available at 50 and 100 m above sea level for the selected period.

3. Validation of the results

3.1 Altimeter data

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

The differences between the altimeter and *in-situ* measurements over longer time intervals provide an ~~estimation~~estimate of the accuracy of the altimeter data relative to the in-situ-data assumed as ground-truth. Fenoglio-Marc *et al.* (2015) considered both wave height and wind speed derived from DDA, (also called SAR altimetry) located at a distance to coast ~~larger~~greater than 10 kilometres and showed that comparison to *in-situ* observations from the same *in-situ* stations network in the German Bight gave standard deviations between 30 and 15 cm for wave height~~,~~; 1.6 m/s and 1.8 m/s for wind speed. They also found a good consistency between pseudo-conventional (PLRM) and ~~DDA~~SAR in the open ocean, with ~~rms~~root mean square*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~~SAR compared to PLRM. As a demonstration, ~~Figure 4~~Fig. 5 shows the scatterplots for FINO-1 and CryoSat-2 ~~DDA~~SAR and PLRM measurements. For the wind speed the accuracy of ~~CryoSat-2 DDA~~SAR and PLRM is similar ~~(std~~and the standard deviation (*STD*) between the two data sets is 1.9 m/s~~)~~.. For the significant wave height~~,~~ (Fig. 5a), we observe a higher accuracy in ~~DDA~~SAR than in the standard PLRM retracking (*STD* ~~are~~is 18 and 30 cm, respectively). The accuracy in the significant wave height from PLRM increases (*STD* is 19 cm) when a dedicated retracking procedure is applied (Fenoglio-Marc *et al.*, 2015). Figure ~~4b~~5b shows an underestimation of wind speed of altimetry relative to the *in-situ* data (slope is below 0.8 in all cases).

3.2 Altimeter-model comparisons

In this section, we quantify the performance of one-way *versus* two-way coupling by comparing the output of the atmospheric and wave models against remotely sensed data. Table 1 gives the statistics of the differences (bias and standard deviations) between the model and altimeter-derived values of wave height and wind speed over the selected three-month period. The numbers of matched pairs (approximately 7000) of observations and simulations are also given in Table 1 for the different satellites. For all three satellites, the standard deviation in the two-way coupled model is smaller than in the one-way coupled model. ~~Similarly~~ For Jason-2 and SARAL/Altika, the bias in the two-way coupled model is nearly halved compared to the bias in the one-way model~~, 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 lower than the modelled values in the one-way and two-way experiments.

~~In contrast,~~ For Cryosat-2, ~~the opposite is true. In other words~~on the contrary, the measured values are higher than the modelled 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 between the CryoSat-2 data and the one-way model runs. Fenoglio-Marc *et al.* (2015) also found that the CryoSat-2 derived wave height data overestimate the wave model data from the DWD. However, they found the opposite for the wind speed. i.e. the CryoSat-2 derived wind speed underestimates the COSMO winds from the DWD data. This disagreement is due to the different data that have been used to force the atmospheric models by DWD and this study. ~~This demonstrates again that a determination of wave height from satellite altimetry is particularly challenging for waves smaller than one metre (Passaro *et al.*, 2014).~~ Particularly challenging for the significant wave height (*SWH*) detection are coastal data, due to land and calm water interference in the altimeter footprint, and low sea states, due to an extremely sharp leading edge in the waveform that is consequently poorly sampled (Passaro et al., 2015). The wind speed instead is derived from the backscatter coefficient, which is related to the amplitude of the waveform.

To perform a spatial comparison between model simulations and the satellite data, we analysed individual tracks over the North Sea, and two of these are shown in Figures ~~5~~6 and ~~6~~7. The satellite altimetry observations along the ground-track at the time of the overflight at the German Bight last ~38 sec. The selected SARAL/AltiKa passes are very diverse, as one was taken under calm conditions (Fig. ~~5~~6) and the other ~~pass occurred~~ during the storm Xaver (Fig. ~~6). Therefore,~~7), which therefore provided an opportunity ~~was provided~~ to compare measured and modelled wave heights and wind speeds along the satellite tracks under different atmospheric and wave conditions~~. Here, we provide a demonstration only for two tracks, but these tracks offer illustrative comparisons for calm conditions and an extreme storm event.~~ illustrated in Figures 6 and 7. Under calm conditions, differences between the results of the one-and two-way coupling are very small (Fig. ~~5a~~6a). Both models (WAM-NS-1wc and WAM-NS-~~1wc~~ 2wc) overestimate the measured wave height (red line) over a large part of the track. However, the ~~increased~~increase of modelled wave height with increasing latitude appears to be consistent with the northward wind speed increase observed by the satellite data and simulated in the two simulations (Fig. ~~5b~~6b). During the storm Xaver, the difference between the wave height in the WAM-NS-1wc and WAM-NS-2wc simulations (Fig. ~~6a~~7a) increases up to 1 m in the southern North Sea. The altimeter-derived quantities fluctuate greatly. However, the two-way coupled-model results are closer to the satellite data, in comparison to the ones in WAM-NS-1wc, except for the latitude ~~~56 deg.~~of ~56° 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~~), which can be explained by the ~~different post-processing of the significant wave height~~fact that the model is not capable to resolve the small scales seen in the satellite ~~data and by the statistical nature of the wave spectral model.~~observations. The corresponding wind speed does not grow at this latitude, neither for the measured nor the modelled wind speeds. It is noteworthy that ~~the measured peak of the storm is underestimated in~~ both model experiments ~~and also shifted northwards by ~2 degrees~~missed the peak in measured SWH above 58° N (Fig. ~~6a~~7a). The modelled wind speed well fits ~~well with~~ the altimeter-derived ~~wind speed in the~~data during calm ~~situation for~~ conditions in both experiments (COSMO-1wc/2wc, Fig. ~~5b~~6b). Northwards of ~~55 degrees~~55° N, the wind speed is higher than 10 m/s, ~~and~~while the wind speed in the two-way coupled experiment (COSMO-2wc, full line) is ~~reduced~~slightly lower than in COSMO-1wc. During the storm Xaver, the measured wind data fluctuate ~18 m/s, whereas the modelled data show much higher values of ~20 m/s, ~~which reached~~reaching ~22 m/s at ~~latitudes~~ ~57° N and 59 ~~degrees~~° N (Fig. ~~6b~~7b). This ~~finding indicates that~~confirms the ~~algorithm for retrieving wind speeds is saturated under these extreme conditions.~~findings of Fenoglio-Marc *et al.* (2015), who had compared the same altimeter data ~~to~~with ERA-Interim, NOAA/GFC and COSMO/EU winds~~, have~~. They suggested that the low wind speeds derived from the altimeter are caused by an overestimation of the atmospheric attenuation of the radar power in the Ka-band. ~~Indeed,~~In fact a larger attenuation correction would result in a too large backscatter coefficient and hence a reduced wind speed~~.~~ (Fenoglio-Marc *et al.*,2015) The correction in the SARAL/AltiKa products is larger than the correction based on surface pressure, near-surface temperature, and water vapour content (Lillibridge *et al.*, ~~2014). The wind speed simulated by COSMO-2wc is lowered up to 1 m/s compared to that of the COSMO-1wc.~~2014). Similar analyses along all tracks over the study period agree with the two examples demonstrated in Figs. ~~5~~6 and ~~6~~7. In general, the measured wind speeds were in slightly better agreement with the two-way coupled model results, which was also demonstrated by statistics presented in Table 1. The track during the time of storm Xaver was the only track taken under such extreme conditions.

3.3 Validation against in-situ measurements

Analyses of the temporal variability of the significant wave heights ~~at~~in the German Bight under stormy conditions allow us to investigate not only the impact of two-way coupling but also the role of the horizontal resolution. ~~The comparison between data from two waverider buoys~~Figure 8 illustrates the time variability of the significant wave height (top) and the wind speed (bottom) at the Helgoland and Westerland stations (see for locations Fig. 1b) ~~and~~ from observations (black line) and the ~~coarse North Sea wave~~different model ~~(WAM-NS-1wc/2wc) and fine German Bight model (WAM-GB-1wc/2wc) are exemplified in Fig. 7~~runs during the storm Xaver.

The wind fields in both locations are very similar in the COSMO-1wc/2wc model runs; the peak of the storm is reduced from 26 to 22 m/s. By comparing the model and measured wind speed, it is noticeable that the modelled wind speeds grow too early and too high at all locations at the beginning of the storm (see the bottom patterns in Fig. 8a,b for the Helgoland and Westerland examples). The storm characteristics are matched well at Helgoland but are slightly underestimated at Westerland. Still, the overall model performance at Westerland is satisfactory, considering the strongly fluctuating wind measurements. Similar behaviour is observed for the Elbe and Fino-1 (not shown here) wave buoy stations.

Throughout this period, the highest values of significant wave ~~height~~heights are simulated by the WAM-NS-1wc experiment. The lowest values, and closest to the observations, are from the WAM-GB-2wc simulations (Fig. ~~7~~8). At the beginning of December, during the calm atmospheric conditions, all model results are similar and fit relatively well with the *in-situ* measurements. The differences in the wave growth between the different model simulations become ~~significant~~notable after the storm onset. During the peak of the storm, ~~as estimated by~~ the WAM-NS-1wc simulation~~, overshoots~~ overestimates the measured wave heights by ~3 m at the Helgoland station (water depth 30 m, Fig. ~~7a~~8a) and by ~4 m at the shallow water of the Westerland station (water depth 13 m, Fig. ~~7b).~~ 8b). Compared to the in-situ measurements, this peak occurs earlier in all simulations ~~in comparison to the *in situ* measurements,~~ due to the time~~-shift in the~~ discrepancy between wind data~~.~~ and model time steps. The wave heights predicted by the WAM-GB-2wc are ~~in better agreement~~agree with the observations best, especially for the Westerland station (Fig ~~7b~~8b, 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 (Fig. 1b),~~, for which ~~explains why~~ the differences ~~of~~between simulated wave ~~height~~heights during the storm Xaver reach ~1 to 1.5 m in the corresponding North Sea and German Bight simulations (Fig. ~~7a~~8a). This

~~finding identifies~~buoy is located in an area of large gradients in water depth (Fig. 1b), where the ~~importance of increasing the horizontal~~high resolution ~~of the models in the~~model uses a finer bathymetry at coastal areas with a rather complex ~~bathymetry.~~shore (such as at Helgoland) leading to a better simulation of wave heights.

At the shallow Westerland buoy station (Fig. ~~7b~~8b) the differences are additionally enhanced by the depth-induced wave breaking in the German Bight model. This can also be seen in the snapshots of wave height in the North Sea and German Bight models at the peak of the storm (Fig. ~~8~~9 a, b). Shoreward of the 15 m isobaths, the wave heights drop from 6 to 4 m in the German Bight model. In contrast, for the North Sea model, the 6 m high waves reach the south-eastern coast. The WAM-NS-1wc model run underperforms in comparison to the WAM-NS-2wc simulation at Westerland. This ~~shows convincingly~~underperformance further proves the importance of two-way coupling for the coastal German Bight areas, where the model wind speed is even higher (by ~2 m/s) than at Helgoland. We admit that it is difficult to differentiate between the effects ~~coming from~~due to wave breaking and ~~from~~ two-way coupling because both contribute to reducing the wave height ~~by~~under extreme weather conditions. Wave breaking plays a dominant role in very shallow water, especially during storm events, by preventing unrealistically high waves near the coast. For~~ the~~ deep waters, the sea surface roughness feedback due to the two-way coupling plays a very important role (Fig. ~~7a~~8a). The importance of the two-way coupling is clearly demonstrated by comparing the WAM-GB-2wc (the blue line) and WAM-GB-1wc (the red line) in Fig. ~~7~~8. For all stations, the simulated SWH in WAM-GB-2wc is reduced, especially during the Xaver peak, and is closer to the measurements~~. The wind fields in both locations are very similar in the COSMO-1wc/2wc model runs; the peak of the storm is reduced from 26 to 22 m/s. By comparing the model and measured wind speed, it is noticeable that the modelled wind speeds grow too early and too high at all locations at the beginning of the storm (see the bottom patterns in Fig. 7 a,b for the Helgoland and Westerland examples). The storm characteristics are matched well at Helgoland but are slightly underestimated at Westerland. Still, the overall model performance at Westerland is satisfactory, considering the strongly fluctuating wind measurements. Similar behaviours are observed for the Elbe and Fino-1 wave buoy stations~~.

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

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

4 Impact of the two-way coupling

In the following discussion, the impact of coupling is analysed for the North Sea focusing on the spatial patterns under different physical conditions. The three-month ~~averaged~~average of the significant wave height and wind speed ~~is~~are reduced significantly (Fig. ~~9) due to~~10) for the two-way coupling~~, which~~ compared to the one-way coupling. This reduction results from an extraction of energy and momentum ~~by waves~~ from the atmosphere by waves. The average difference ~~(bias)~~ in wave height (Fig. ~~9a~~10a) is ~20 cm, which is a reduction of ~8% of the three-month mean value (~2.3 m). The ~~RMSE~~*RMS* difference between the two simulations (Fig. ~~9b~~10b) is ~40 cm in the central North Sea. For the wind speeds, the ~~bias~~averaged difference (Fig. ~~9c~~10c) is ~30 cm/s when averaged over the model area, corresponding to a reduction in wind speed of ~3% of the three-month mean value (~10 m/s). The ~~RMSE~~*RMS* difference (Fig. ~~9d~~10d) between the two-way and one-way coupled simulations over the whole North Sea area is ~80 cm/s. The spatial patterns in the ~~bias~~averaged differences in Fig. ~~9~~10 can be explained by the dominant westerly winds (Fig. 2). As the wind comes from land (Great Britain) and strikes the North Sea, the differences in the wind speed between the two models are larger closer to the coast because of differences in sea surface roughness. Moving further east, the atmospheric boundary layer adapts in both cases to the winds over sea, and there is less difference between the one- and two-way coupled models. For the wave height, the averaged differences ~~in bias~~ close to the western coasts and in the English Channel are small because ~~some~~the fetch is ~~needed~~too short for the waves to evolve ~~and the fetch is too short there.~~.

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

Another illustration of the influence of the coupling is given by the two time series at the FINO-1 station, each ~~of ~~about two weeks long and taken under very different conditions. One period is in November, which was rather calm~~,~~ and contained young and developing wind seas (Fig. ~~11~~12). The other period was in December with several storms coming from the North Sea (including Xaver) with higher wave ages (Fig. ~~12~~13). The differences in significant wave height and wind speed between the one- and two-way coupled models are mostly positive, i.e~~.,~~. both parameters are reduced in the two-way coupled model. The largest differences can be observed when the wave age (the ratio of phase velocity at the peak of the wave spectrum with friction velocity) is well below 20 and occurs before the maximum wave height has been reached (this can be well seen for Xaver, Fig. ~~12~~13). Thus, the waves grow slower in the two-way coupled model. Negative differences seldom occur~~,~~; only ~~occurring ~~when the wave age increases rapidly (when the wind speeds ~~go to~~approaches zero, the wave age ~~goes to infinity~~diverges infinitely).

5. Summary and Outlook

We developed a two-way coupled wave-atmosphere model for the North Sea~~, which includes~~ including the possibility of nesting a coastal, high-resolution wave model~~;~~, where the two models ~~perform~~run simultaneously. ~~This analysis was done by using ~~The coupling software OASIS3-MCT~~, which~~ that we used, allows for 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 in the German Bight wave model (one atmospheric model and two wind wave models) were performed. This ~~allowed~~enabled 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 better agreement with the *in-situ* and remotely sensed data of significant wave height and wind speed, in comparison to the one-way coupled model (COSMO drives WAM). New in this paper is the use of satellite altimetry, which provides complementary information to *in-situ* data for the validation of models. We show that comparisons between the model results and satellite-derived parameters are satisfactory, except for a known degradation of wind speed in storm conditions, which is under investigation. The two-way coupling improved the modelled significant wave heights in the German Bight, which was demonstrated by the validation against *in-situ* observations from four different buoys.

For the storm event Xaver, the impact of the two-way coupling was of highest significance. Wave heights decreased from ~8 m to ~5 m due to the coupling, which matched buoy measurements very well. The corresponding wind speeds were lowered from ~22 to ~20 m/s. In addition to this extreme event, such large differences between one- and two-way coupled model results were only observed for young seas (wave age well below 20). We also found a slight spatial shift in the minimum of the cyclone mean sea level pressure together with a slight increase of the pressure field from the two-way coupled model runs. These results may also have been caused by the wave-mean flow interactions in the atmosphere. This will be the subject of subsequent work, where we will study in more depth the consequences of coupling with other atmospheric parameters at sea level and the vertical structure of the planetary boundary layer.

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

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Table 1: Bias and standard deviation of validation of wind speed (m/s) and significant wave height (m) of the one- and the two-way coupled models against the available satellite data over the whole period (measured minus modelled). The green shaded colouring means an improvement of the two-way coupled model skills; red shading colouring means that the one-way coupled model skill are better than the ones of the two-way coupled model.

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

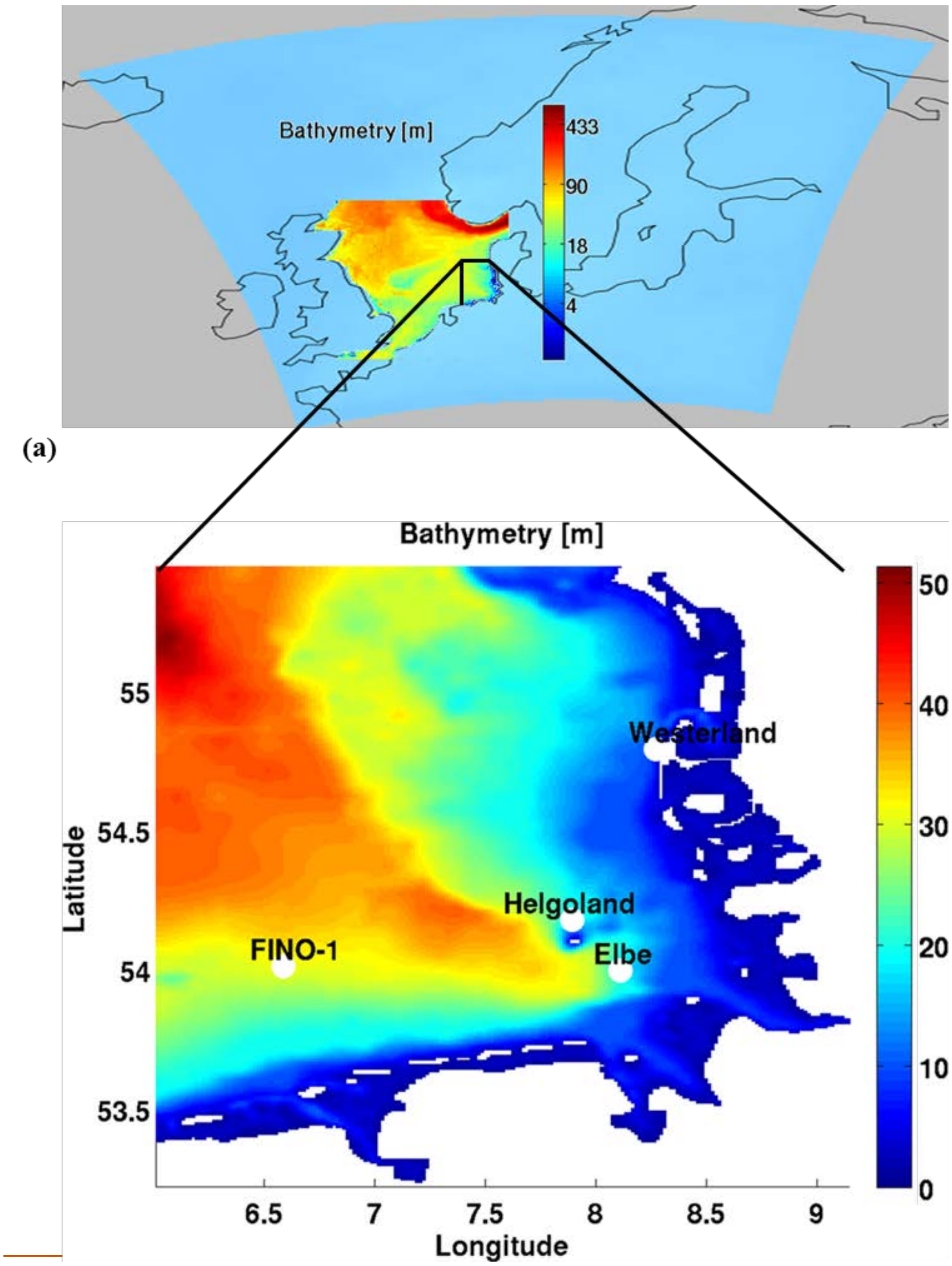
Table 2: Wind speed (m/) bias and standard deviation of the one- and the two-way coupled COSMO model data against the FINO-1 data over the whole period (measured minus modelled). The green shaded colouring means an improvement of the two-way coupled model skills; red shading colouring means that the one-way coupled model skill are better than the ones of the two-way coupled model.

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

Table 3: Significant wave height (m) bias and standard deviation of the one- and two-way coupled WAM German Bight model data against the available buoy data over the whole period (measured minus modelled). The green shaded colouring means an improvement of the two-way coupled model skills; red shading colouring means that the one-way coupled model skill are better than the ones of the two-way coupled model.

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

965 **Figures**



Bathymetry [m]
433
90
18
4
(a)
Bathymetry [m]
55
54.5
54
53.5
Latitude
6.5
7
7.5
8
8.5
9
Longitude
50
40
30
20
10
0
Westerland
Helgoland
FINO-1
Elbe

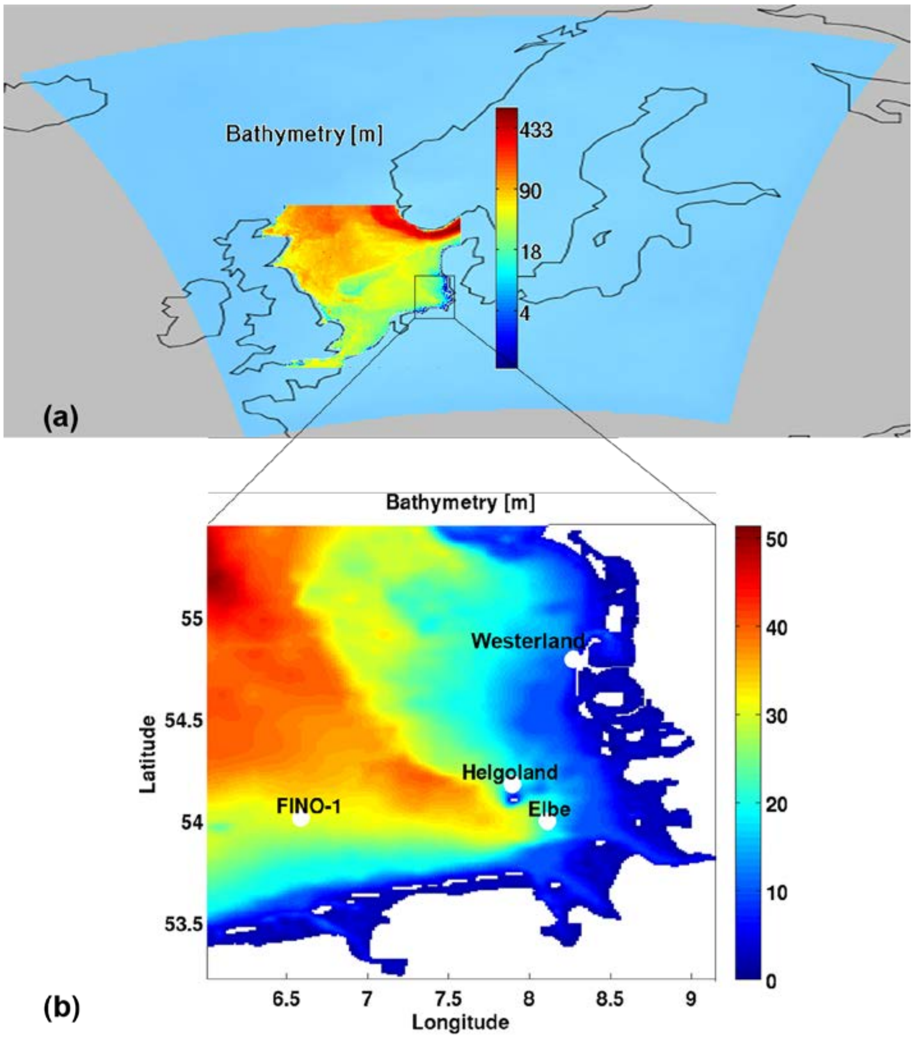


Figure 1: (a) Bathymetry (m) of the North Sea embedded in the COSMO model area (using a logarithmic scale) and (b) bathymetry (m) of German Bight as used in the WAM model. The positions of four

970 *waverider buoys used for the validation is indicated, too.*

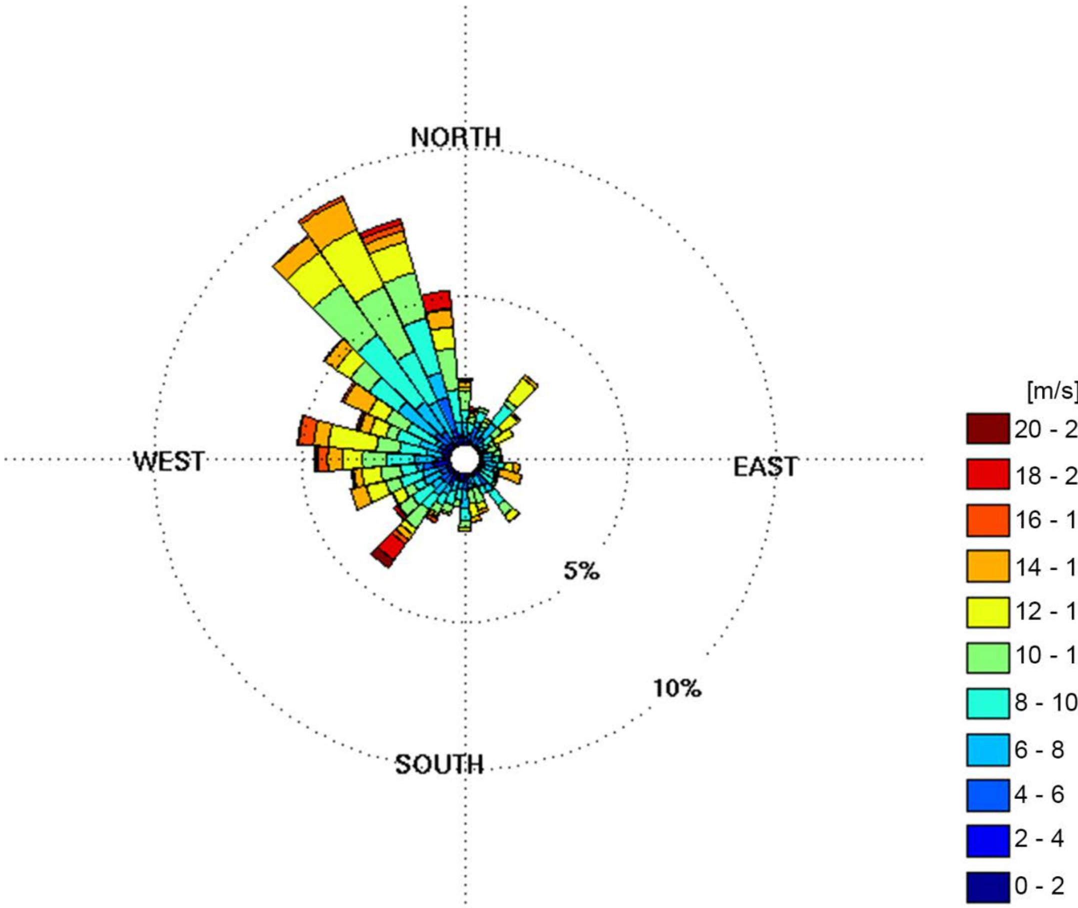
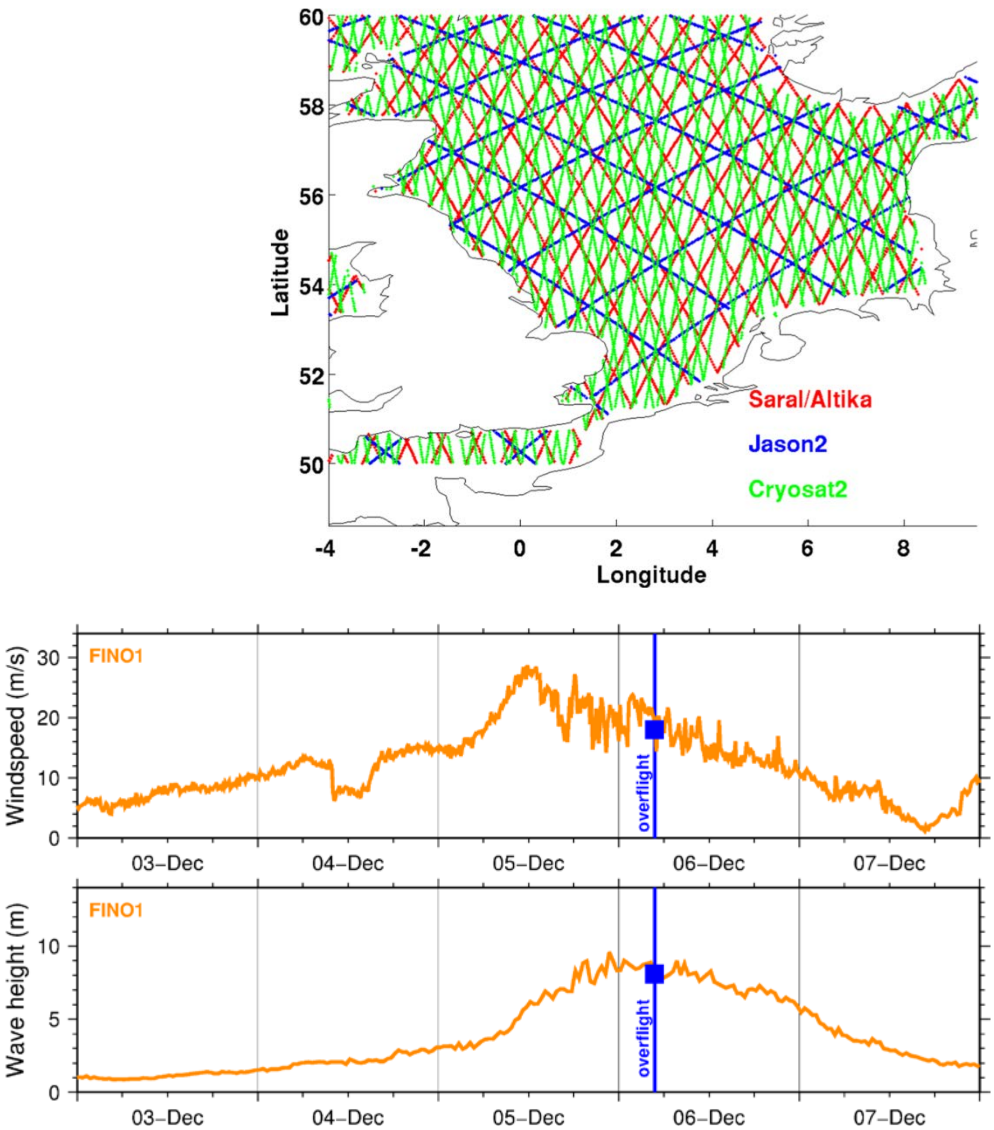


Figure 2: Distribution of frequency and wind speeds in m/s (see color bar) and ~~directions~~wind direction at the FINO-1 waverider buoy for the period of 01. October~~–~~, 2014 until 31 December 2013.


Saral/Altika
Jason2
Cryosat2
Latitude
Longitude
FINO1
Windspeed (m/s)
overflight
03–Dec
04–Dec
05–Dec
06–Dec
07–Dec
FINO1
Wave height (m)
overflight
03–Dec
04–Dec
05–Dec
06–Dec
07–Dec

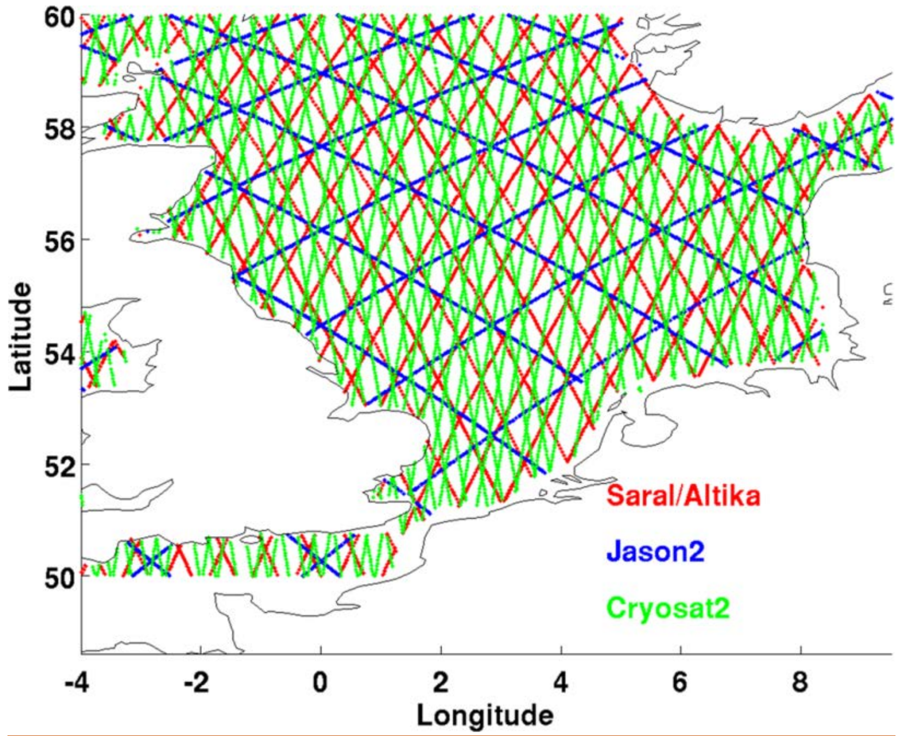


Figure 3: ~~(top pattern)~~ Tracks of all satellites during the study period (01. October, 2013 until 31 December 2013).

985

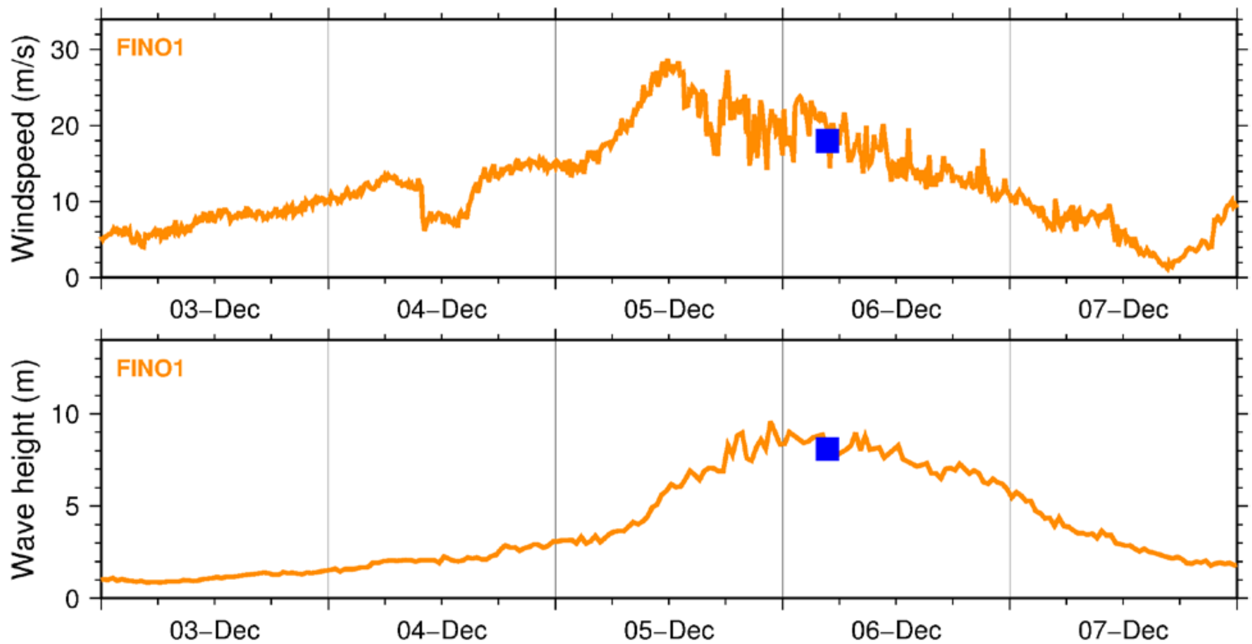
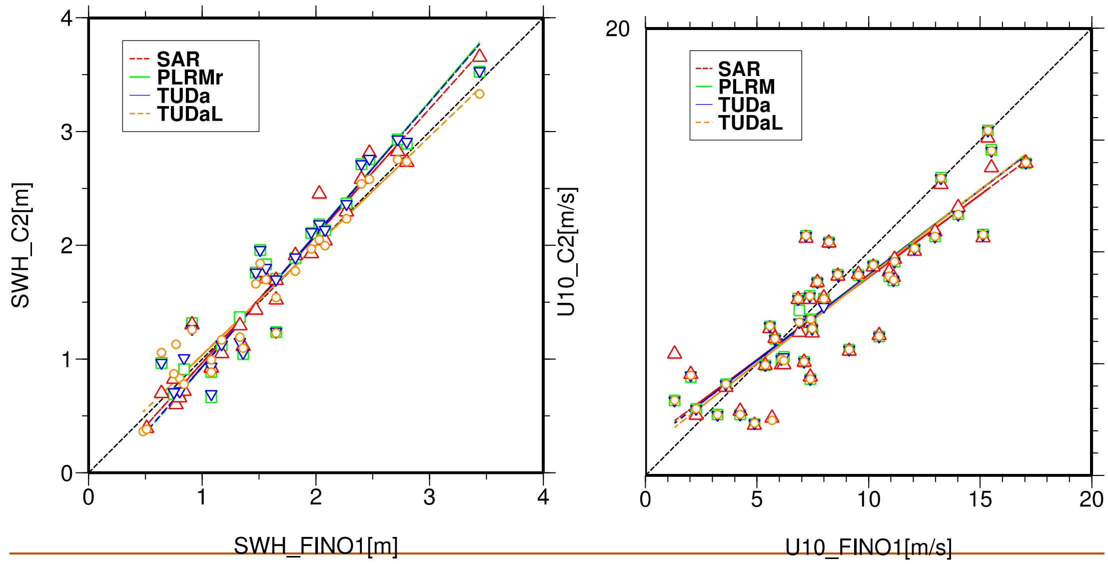
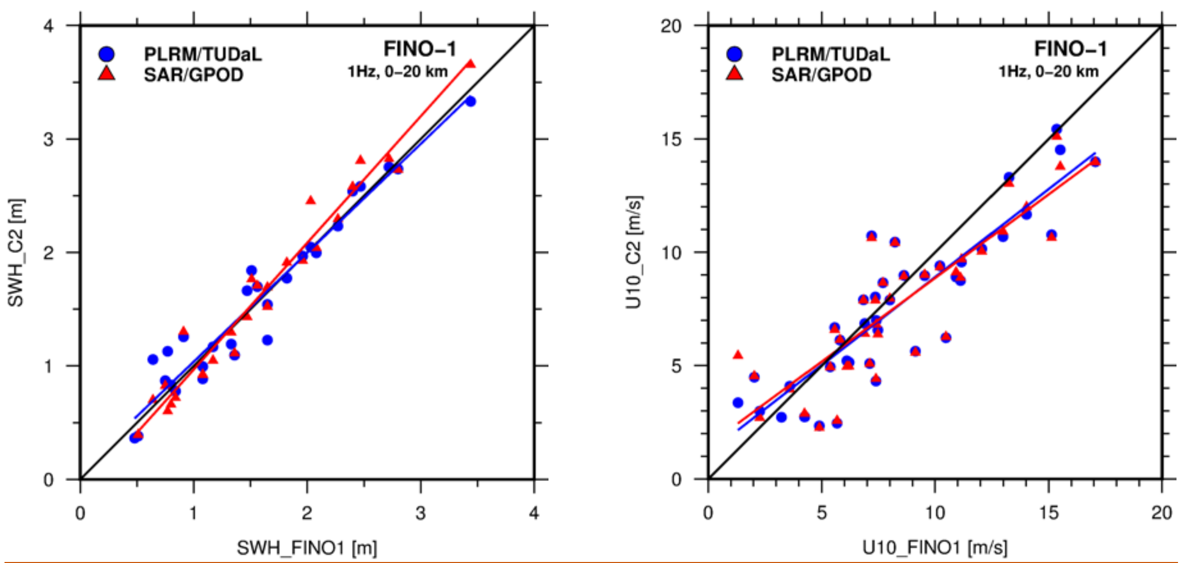


Figure 4~~; (middle and bottom pattern) Wind speed *(middile) and wave height (bottom)*~~: Time series during five days , which include the storm Xaver ~~*storm at*~~of the observations in station FINO-1~~.~~ (orange line) together with the Saral/Altika observation (blue full square): (top) wind speed (m/s) and bottom: significant wave height (m) The SARAL/AltiKa passed over the German Bight during the storm Xaver when the surge was at its maximum (the data during the overflight are ploted with a full blue mark).

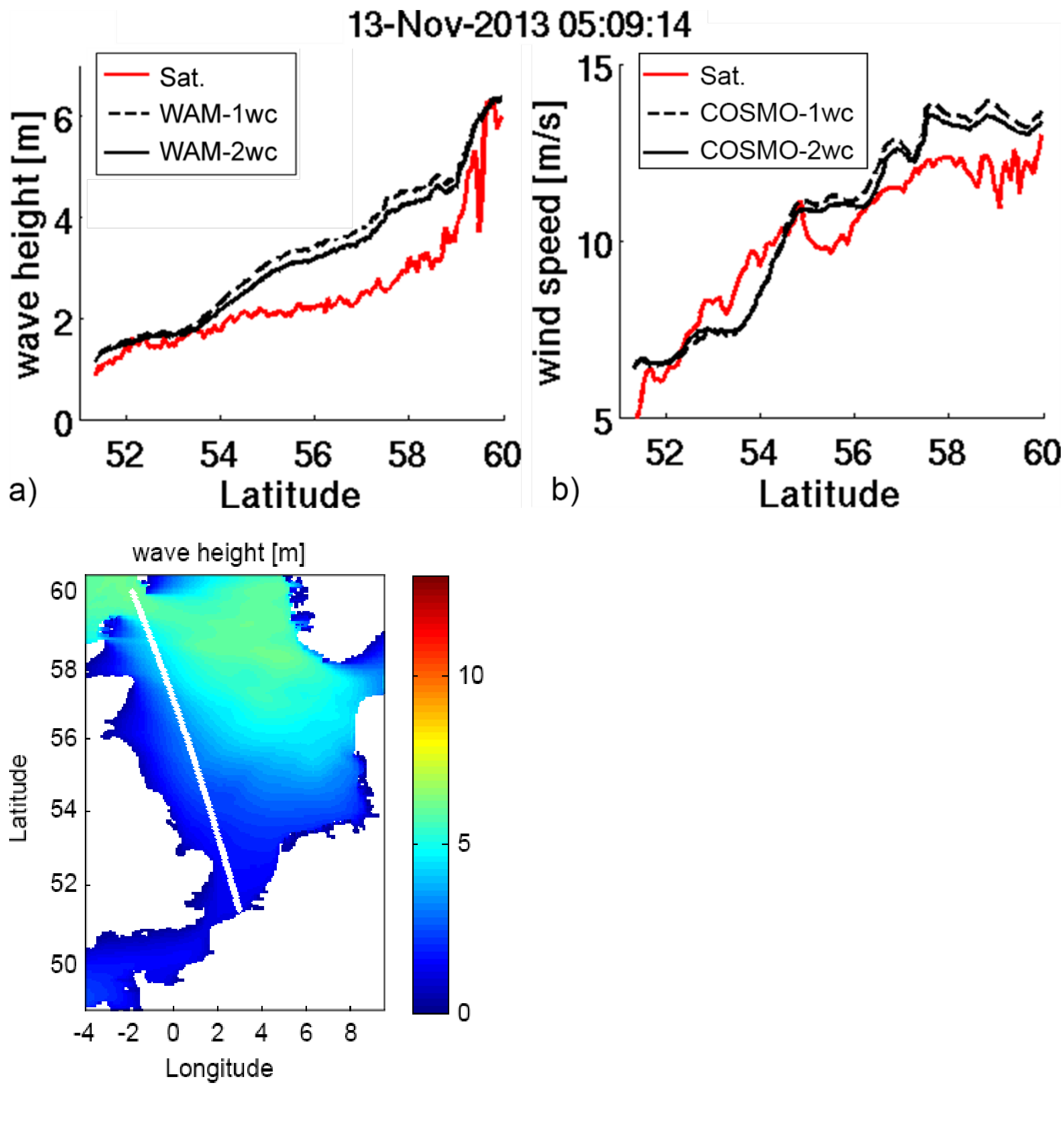


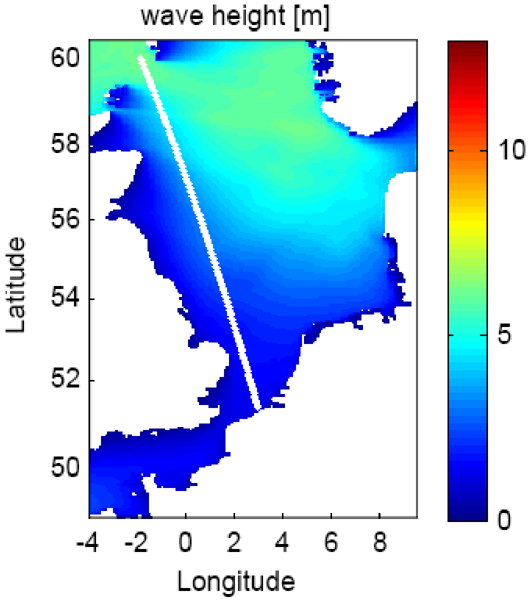


(a) (b)

Figure 5. Comparison

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. of in-situ and altimeter-derived (a) significant wave height and (b) wind speed of in-situ and co-located altimeter measurements at the FINO-1 station. Altimeter data *used* are *DDA*SAR altimetry *(SAR,* (triangle*), standard*) and PLRM (*PLRMr and TUDA, square and inverse triangle) and improved PLRM (TUDaL,* circle).

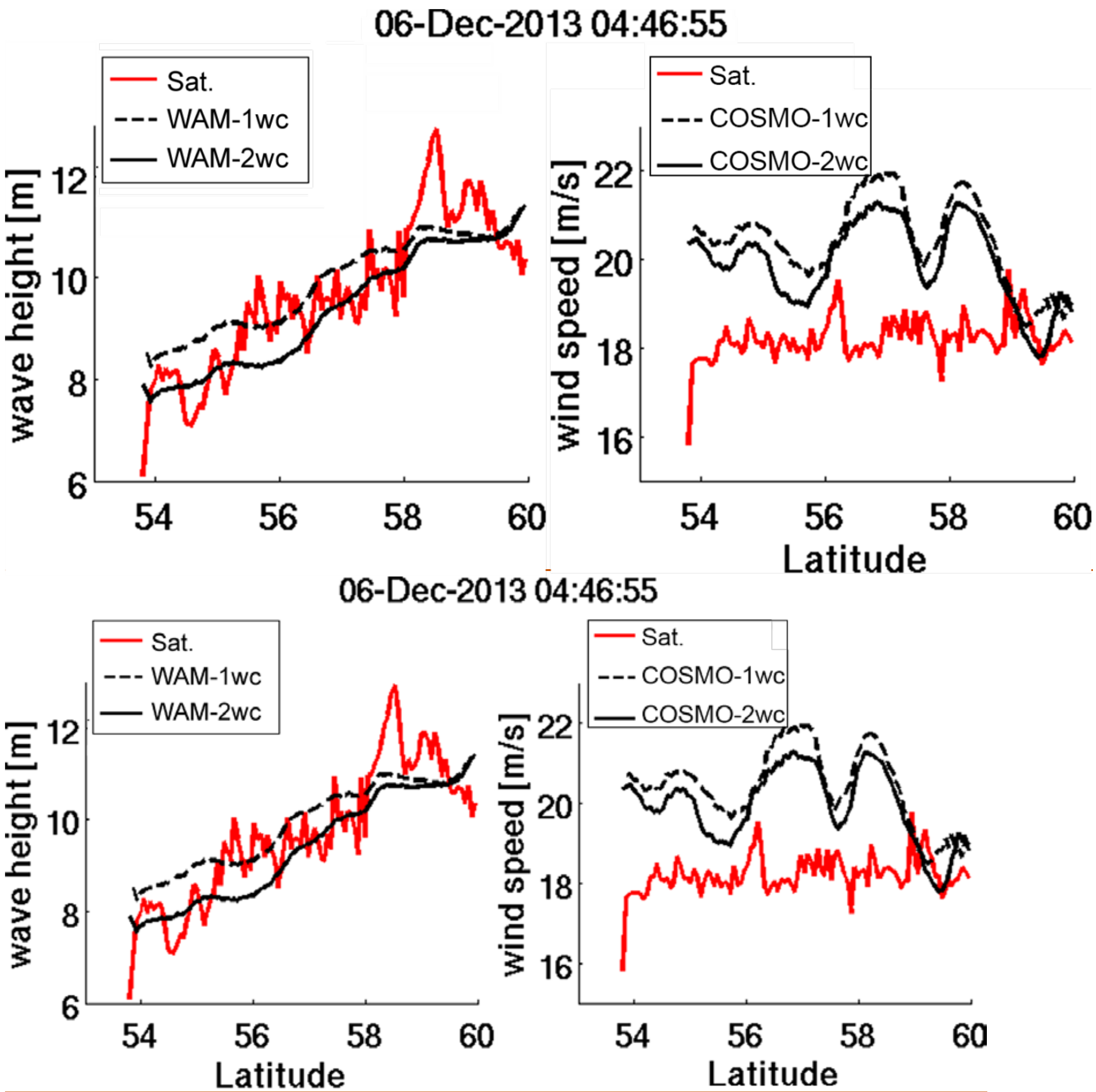

13-Nov-2013 05:09:14
Sat.
WAM-1wc
WAM-2wc
wave height [m]
Latitude
a)
Sat.
COSMO-1wc
COSMO-2wc
wind speed [m/s]
Latitude
b)
wave height [m]
Latitude
Longitude



c)

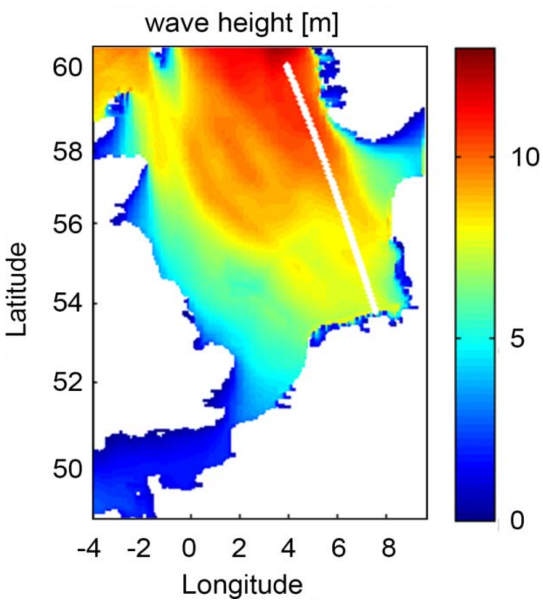
Figure ~~5~~6: Time series wave height (m) and wind speed (m/s) from the Saral/AltiKa data and as modelled

1025 *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).*



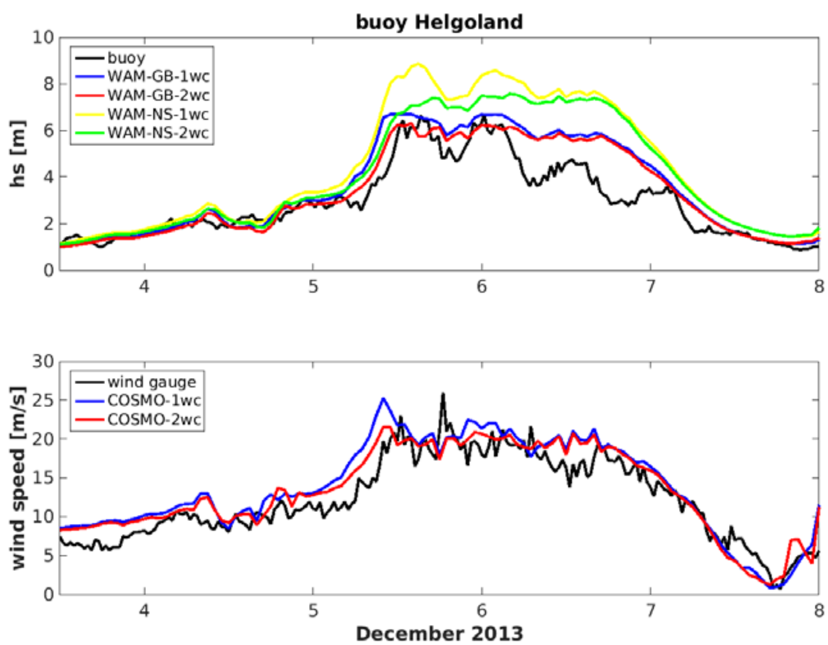
06-Dec-2013 04:46:55
Sat.
WAM-1wc
WAM-2wc
wave height [m]
Sat.
COSMO-1wc
COSMO-2wc
wind speed [m/s]
Latitude
06-Dec-2013 04:46:55
Sat.
WAM-1wc
WAM-2wc
wave height [m]
Latitude
Sat.
COSMO-1wc
COSMO-2wc
wind speed [m/s]
Latitude

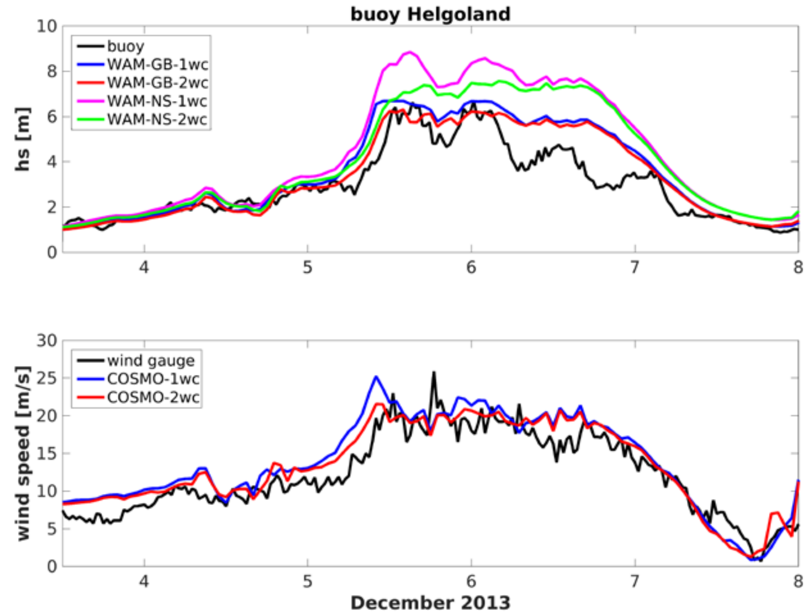
a) b)



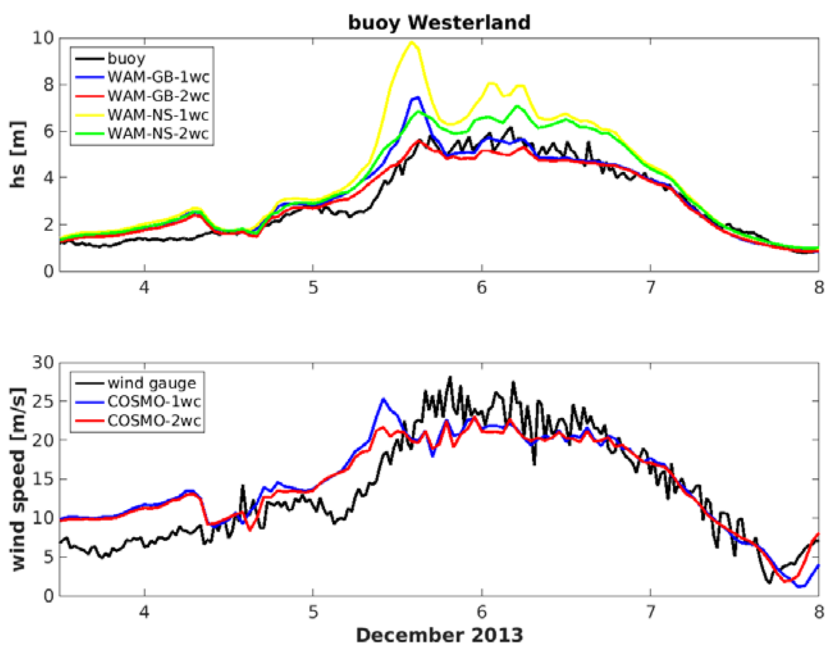
c)

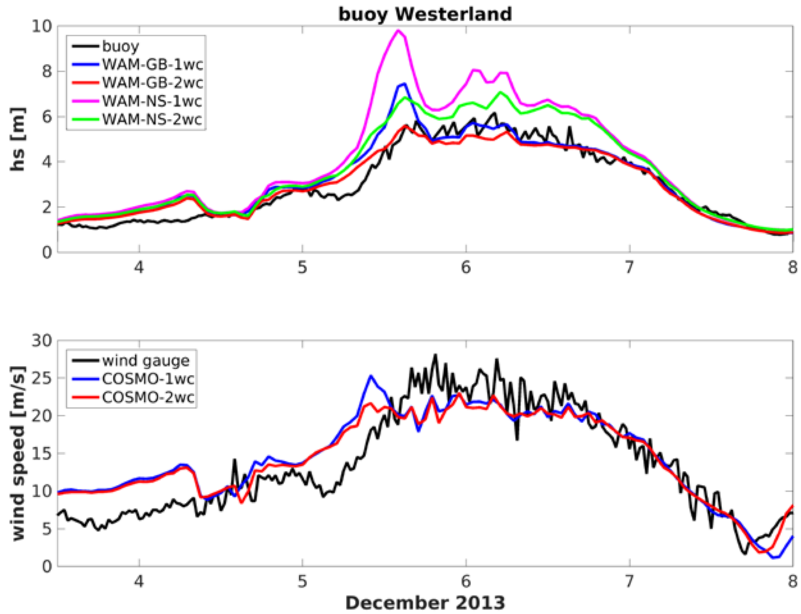
Figure ~~6~~7: As Figure ~~5~~6 but for the storm ‘Xaver’ on 06 December 2013~~.~~.




buoy Helgoland
hs [m]
buoy
WAM-GB-1wc
WAM-GB-2wc
WAM-NS-1wc
WAM-NS-2wc
wind speed [m/s]
wind gauge
COSMO-1wc
COSMO-2wc
December 2013

(a)


buoy Westerland
hs [m]
buoy
WAM-GB-1wc
WAM-GB-2wc
WAM-NS-1wc
WAM-NS-2wc
wind speed [m/s]
wind gauge
COSMO-1wc
COSMO-2wc
December 2013



(b)

Figure ~~7~~8: (a,b) Significant wave height (m, top) and wind speed (m/s, bottom) during the storm 'Xaver' at the buoys Helgoland (a) and Westerland/Sylt (b).

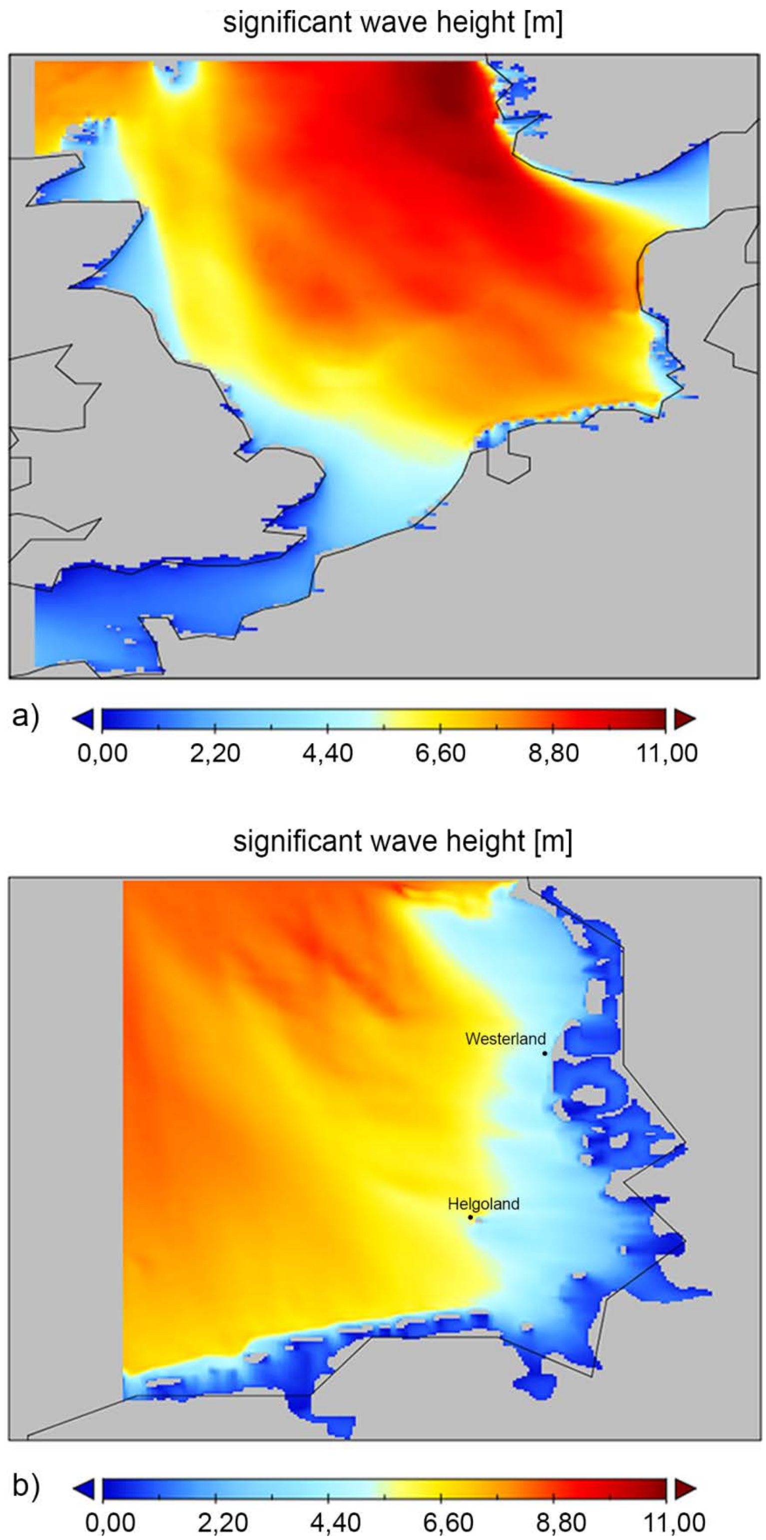
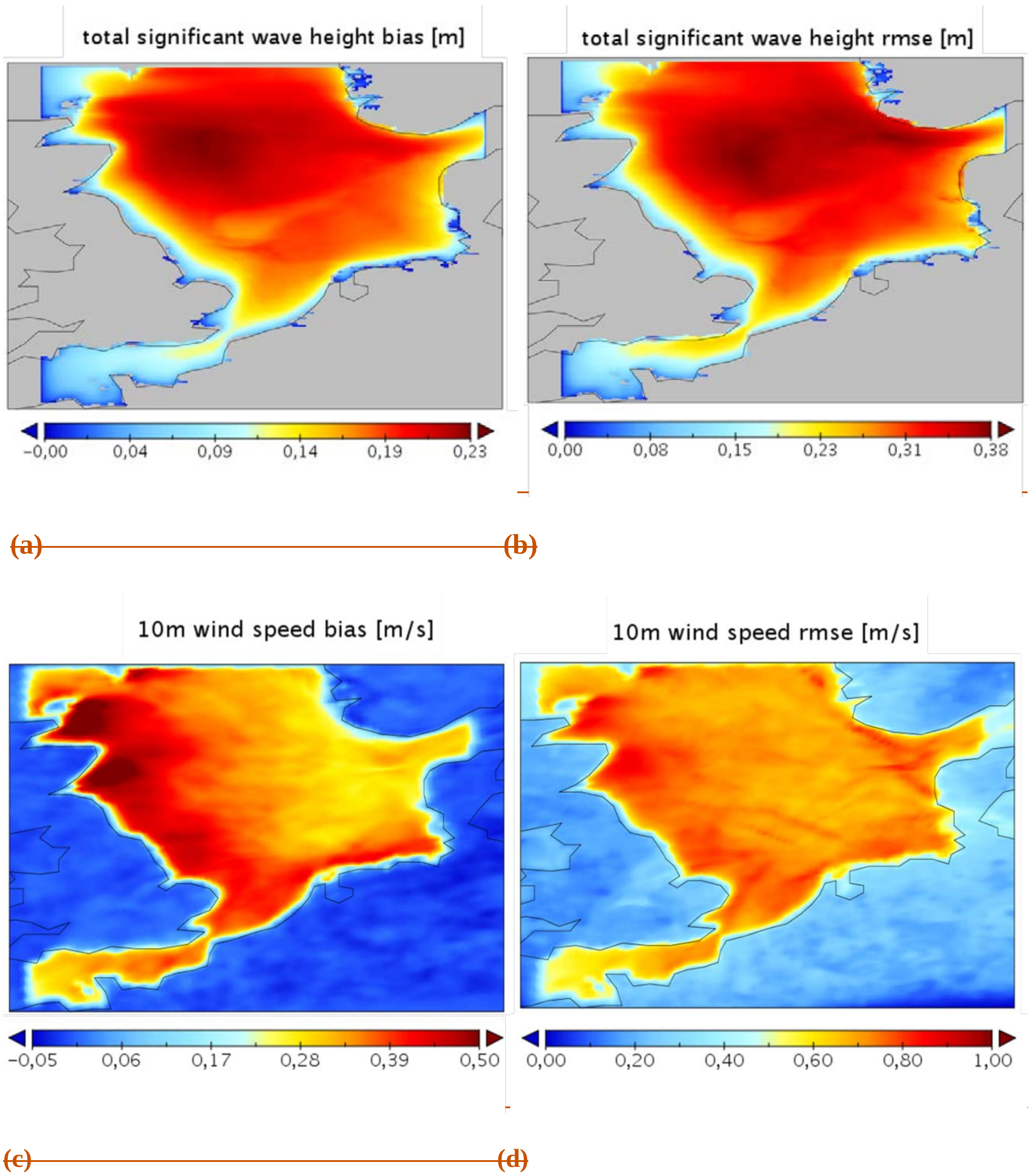


Figure ~~8~~9: (a,b) Significant wave height (m) in the North Sea (a) and the German Bight (b) at the peak of the storm 'Xaver' (2013/12/6 9UTC) calculated by WAM-NS/GB-2wc.


total significant wave height bias [m]
-0,00 0,04 0,09 0,14 0,19 0,23
total significant wave height rmse [m]
0,00 0,08 0,15 0,23 0,31 0,38
(a)
(b)
10m wind speed bias [m/s]
-0,05 0,06 0,17 0,28 0,39 0,50
10m wind speed rmse [m/s]
0,00 0,20 0,40 0,60 0,80 1,00
(c)
(d)

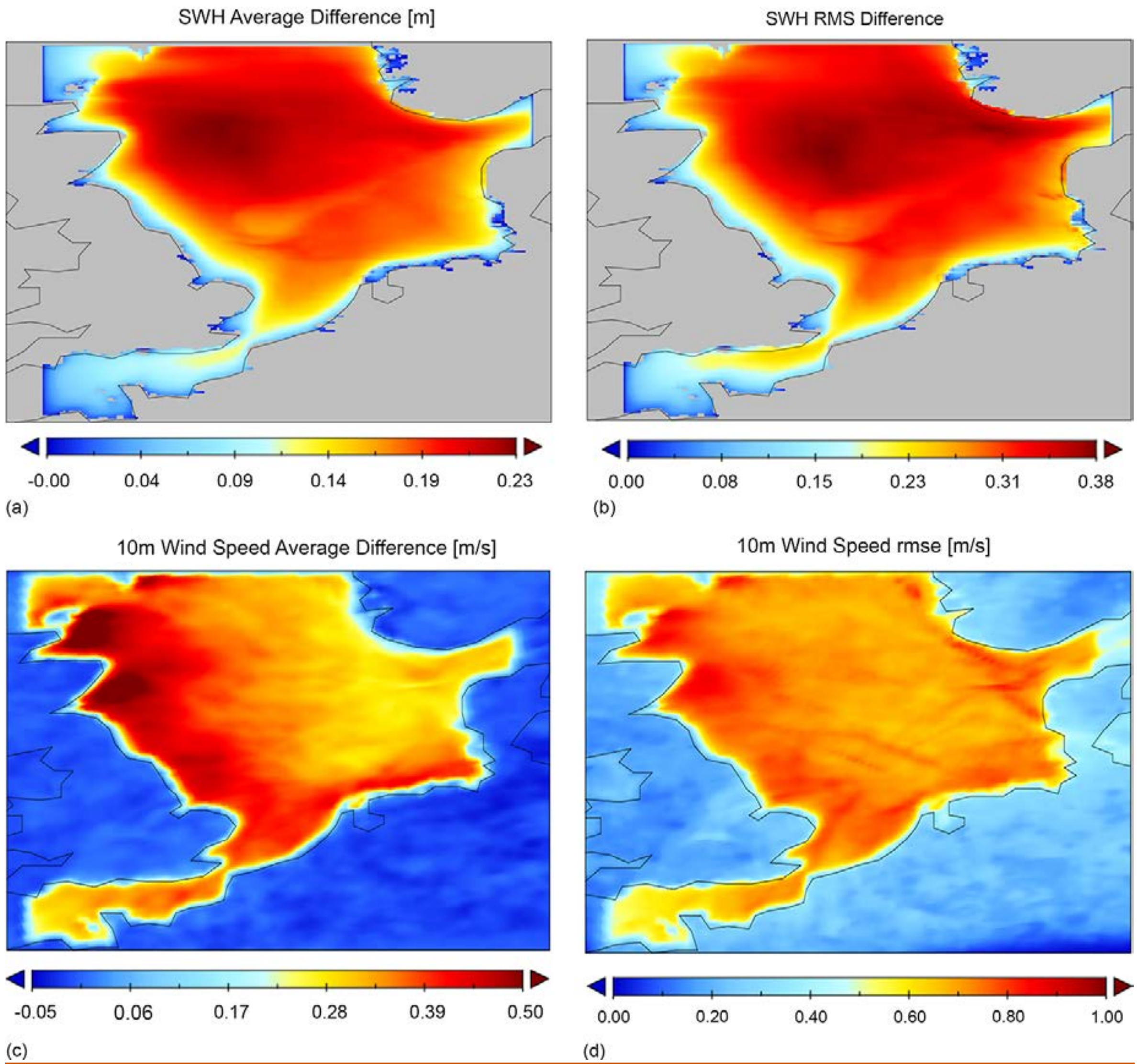
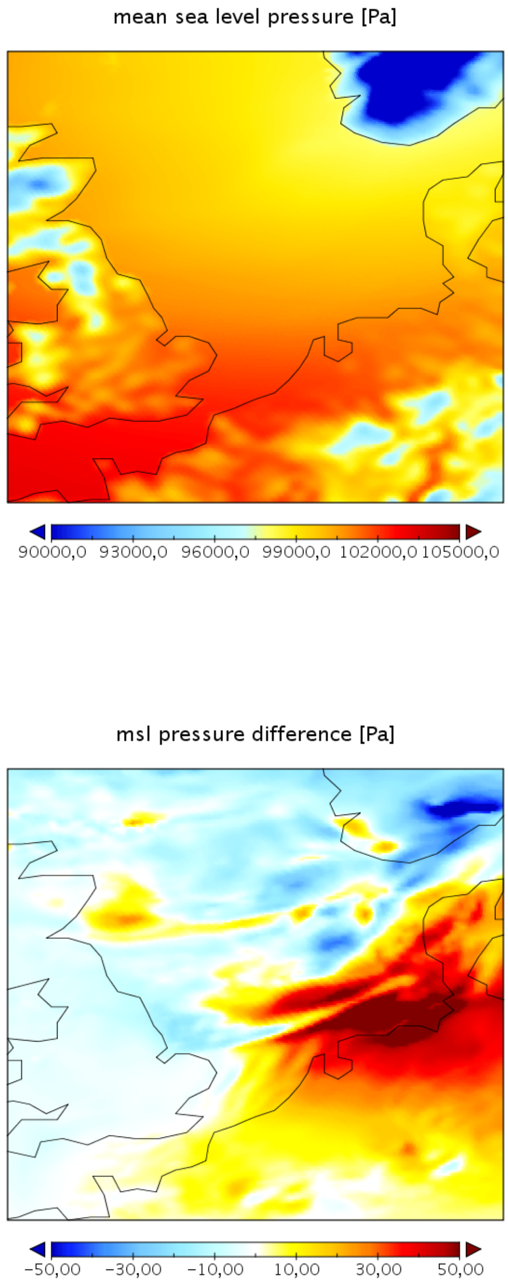


Figure ~~9~~10: (a,c) Average difference ~~(bias)~~ and (b,d) rms difference (~~rmse)~~ rms difference) of WAM modeled significant wave height (m, top panel) and COSMO modeled wind speed (m/s, bottom panel) when comparing one-way minus two-way coupled modeling results. The differences are calculated as ~~averaged~~averages over the whole three month period.



(a)

(b)

Figure ~~10~~11: (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).

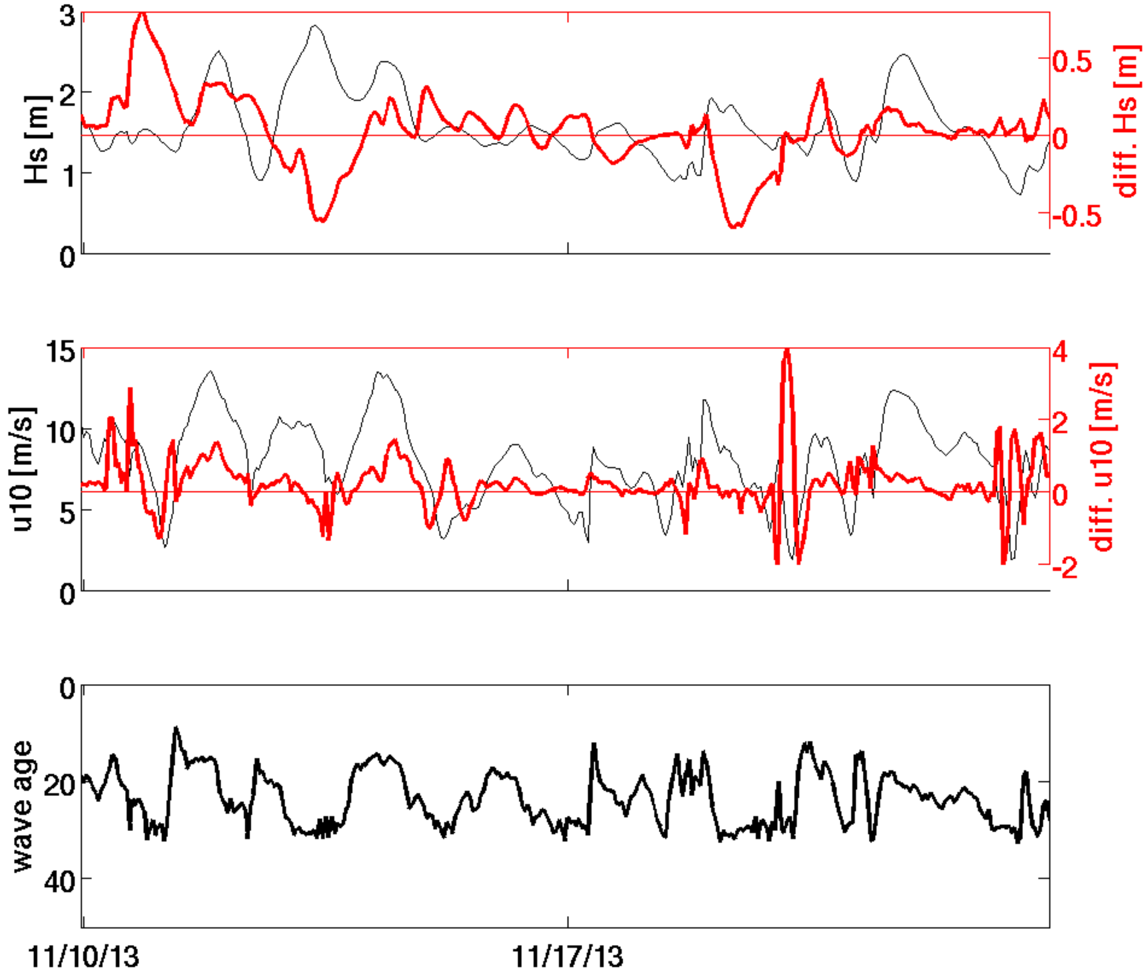


Figure ~~11~~12: Time series of significant wave height (m, top), wind speed (m/s, middle) and wave age (bottom) from the two-way coupled German Bight setup at FINO-1 for (a) a rather calm period with young wind sea and (b) during the storm 'Xaver'). Red lines in the top and middle panel show the differences between the one-way and the two-way coupled models.

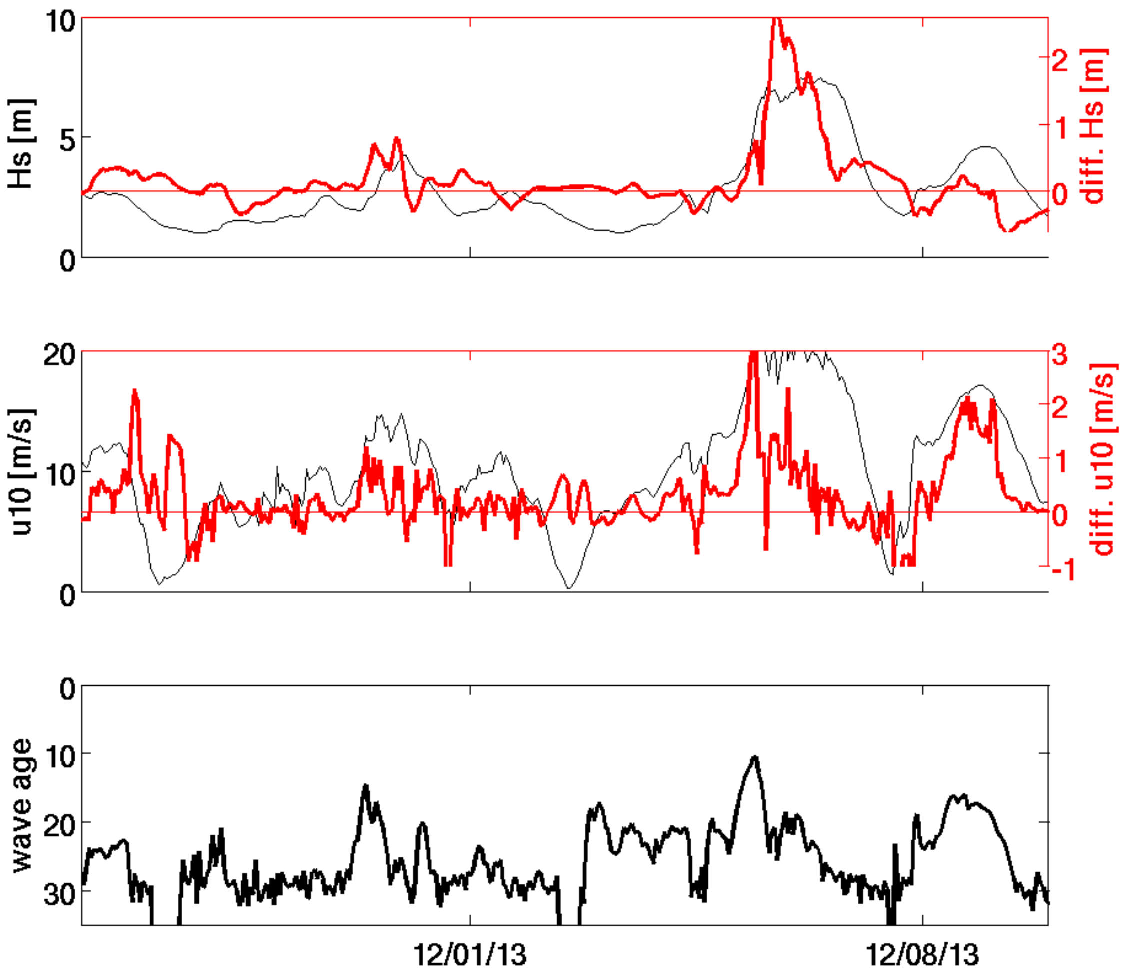


Figure ~~12~~13: As Figure ~~8~~12 but during the storm 'Xaver'