***Answers to the reviewers' comments on* "Coupling of wave and circulation models in coastal-ocean predicting systems: a case study for the German Bight" *by* J. Staneva et al.**

**Reviewer #1**

We are grateful to Reviewer #1 who finds that the topic is interesting and worth pursuing to extend our understanding of wave-current interaction in the shallow coastal area. We are also grateful for his comments (below in italic) which we address point by point

*Rev. #1: I am also glad to see that this paper is kept short with regard to theoretical background and model development, as many previous papers already cover this part extensively. Instead, the authors focus on the validation of a coupled model system using measurements and the discussion of the effect of the implemented wave-current interactions in the study region.*

Authors: We are thankful for this positive comment and this structure is being kept in the revised version of the manuscript.

*Rev. #1: Please refer to Wahle et al.: "Response of the..." as "in preparation/under review", unless it is accepted for publication before you submit your final manuscript.*

Authors: We removed this reference from the text and explained in more detailed the coupling mechanisms.

*Rev. #1: The measurements clearly show that wave fields and sea surface elevation benefit from the implementation of wave-current interaction. In fact, Fig. 3e and Fig. 5 suggest that the effect of wave-current interactions may still be underestimated in this model system. Do you agree with this view? If so, do you have any suggestion why?*

Authors: We agree and this has been discussed in the revised version and also in the answers of rev'2 comments.

*Rev. #1: As wave-current interaction scheme, radiation stress formalism is chosen despite the fact that this scheme produces an unrealistic offshore transport, as the authors discuss in their introduction. Even though the produced errors may be small in the study region (small bottom slopes), the authors should discuss why the radiation stress formalism is chosen, and what the possible limitations for their conclusions are. I would not consider the choice of the radiation stress formalism critical for this paper because the measurements support the numeric results, but it would be good to discuss the consequences of this choice.*

Authors: Following the suggestion of the reviewer, we added a critical discussion in Section 2.3 on the use of radiation stress formalism and its applicability for our study area.

*Rev. #1: Would you recommend to continue using the radiation stress formalism for*

*coupling, or do you expect that the vortex force or generalized Lagrangian mean formulation for wave-current interaction may give better results in this, or other regions?*

Authors: We added comments on that in the conclusion (see also the comments on this issue below).

*Rev. #1: Fig. 2, caption: I don't fully understand what quantity is plotted here. Is this the difference between the control run and the coupled run?*

Authors: We rephrased this following the reviewer's comment.

*Rev. #1: p.4, line 3: Since the focus in this paper is not the parameterization, but the implication of wave-current interaction on the coastal predictions, it would be good to give some references to experiments in other regions. The introduction covers a lot of background on the parameterization & coupling techniques, but little on wave-current interaction experiments in other regions, i.e. Michaud et al. 2012, Zodiatis et al. 2015.*

Authors: Added in the revised version as suggested by the reviewer.

*Rev. #1: p10, line 21: The effect of wave-current interactions on Lagrangian particle transport has been investigated in Röhrs et al. (2012, 2014).*

Authors: Added in the revised version following the suggestion.

**Referee #2**

We are grateful to Reviewer #2 who finds that our manuscript "*Represents a consistent study of the wave-current interaction effects in the tidal dominated water, with focus on the North Sea and the Wadden Sea*" and that "*The model study is well designed and great efforts have been made to evaluate the coupling effects by model comparison with observations. The presented results are substantial and support the conclusion. The models seem to have been set-up correctly and the coupling mechanisms seem to have been implemented in the correct way.*"

We are very thankful for this comment that "*Adequate numbers of references have been provided to put a frame around the developments of the recent years. The methods are valid and clearly outlined.*" and that "*The amount of supplementary material is appropriate.*"

We are also grateful for his comments and suggestion what to improve (below in italic) which we address below point by point.

Rev. #2: *The authors should be more clear and specific about names and notations. Different names are used to describe similar terms. So are wave dependent stress, wave stress and radiation stress used to describe the same coupling parameter, and sometimes are even thrown together with the wave force, i.e. the divergence of the radiation stress. Parameters and concepts are rarely introduced, even when they are ambiguous (e.g. wave stress) or not commonly accepted (e.g. wave force). The whole paper should receive a work through to make its terminology explicit and consistent.*

Authors: We followed the reviewer suggestion and rephrase the terminology in the revised version.

Rev. #2: P-page, L-line P3170, L1: *WAM, which has been used in this study is not only a wind wave model, but it is also a model for swell prediction.*

Authors: We rephrased as suggested.

Rev. #2: P3170, L7: *Tidal currents in the North Sea might be one, but not the only effect that affects wind-wave generation and propagation. I assume that the authors refer to tidal variations of water level in general and consider its impact on depth dependent wave propagation in the shallow regions of the Wadden Sea. Furthermore, waves do not feedback onto tidal currents, but onto the mean currents. Waves also affect the water level (wave set-up), which again is affecting wave propagation.*

Authors: Thank you for this comment. We rephrased as suggested.

*Rev. #2: P3170, L10: produce instead of producing*

Authors: changes as suggested.

*Rev. #2: P3170, L11: maybe combined effect instead of collective role*

Authors: We agree and modified the sentence as suggested.

*Rev. #2: P3170, L14-17: Processes should be indicated more clearly and expected impacts should be presented. I assume that wave-dependent stress is actually the Radiation- stress. It is not clear if wave breaking is affecting the turbulent mixing. It is also unclear what the authors mean when they speak about different parameterizations of the wave effects on the ocean circulation. (On page 3173, L6-7 the authors write that the impact of different parameterizations are not subject of this paper.)*

Authors: We agree with the reviewer's comment and modified this part in the revised version. The comment means that in this manuscript we study the role of the wave forcing on the circulation model including the joint effects of ALL processes described in Section 2 and haven't performed any sensitivity experiments considering /excluding different wave-induced parameterizations separately.

*Rev. #2: P3171, L9: The processes that are listed here are affecting the interface between the ocean and the atmosphere, which is not subject of this paper. The authors should add the processes that are studied, i.e. momentum exchange between waves and mean currents and dissipation processes in the water column (turbulent mixing) and at the sea bed (bottom friction).*

Authors: We agree with the reviewer's comment and changed this accordingly.

*Rev. #2: P3171, L14 and in the entire document: The authors seem absolutely clear that the tidal impacts on the wave dynamic are mainly a consequence of the tidal currents, and not a result of the water level variation due to tides.*

Authors: We agreed and this has been modified in the revised version. We demonstrate also that depth induced wave breaking is much more important than refraction due to currents (as it can be seen from Fig. 2).

*Rev. #2 or by running a tidal driven model (no wind forcing) and only using the tidal currents, but not the tidal variation of water level to force the wave model WAM. The results of this run had to be compared with the fully coupled model, including the effects of varying water level (water depth), wave induced water level variations and surges.*

Authors: We agree with this comment. In the present manuscript, the effects of varying water level are included (described in Section 2.2). Additional experiments are performed and a manuscript that includes series of sensitivity studies, e.g. the fully coupled versus one-way coupled model, studding the individual effects of wave induced water level variations and wave breakings is to be submitted soon in Ocean dynamics. We will present all those studies in the follow-up paper and this is mentioned in the concluding remarks in the revised manuscript. Those are not included in this paper because: the Rev.#2 stated "The presented results are substantial and support the conclusion" and also Rev.#1 commented that our manuscript content sufficient information).

*Rev. #2: P3171, L13 to P3173, L2: This part of the document provides an overview of relevant publications and studies. Starting with a more general overview over coupling processes, the reader is confronted with a multitude of processes which could be organized a more structured. The literature review continues with a list of publications that are dealing with the model physics of coupled ocean-and-wave models (although this is not made clear). The comprehensive, but rather uncommented sweep through the publications makes it difficult to understand the authors view and motivation to select one alternative approach over the other. It remains unclear why Mellor 2008 (radiation stress divergence, i.e. wave force) was selected for this study and not one of the alternative approaches. The discussion between Mellor and Bennis & Ardhuin focused on the instantaneous and time integrated effect of topographical gradients, which are present in the Wadden Sea, although they might not be significant enough to influence the results significantly.*

Authors: We agree with the reviewer's comment. Similar comment was raised by the Reviewer #1 and in the revised version of the manuscript we added a discussion on this issue (see also the answer of Rev#1 comment).

*Rev. #2: Furthermore, the method of ocean circulation-to-wave model coupling should be explained in this paper as well.*

Authors: It is presented in chapter 2.3.

*Rev. #2: The link to the publication Wahle et al. (2015) is not available yet (see comment P3175,L26).*

Authors: We removed this reference from the revised version of the manuscript (see the answer of reviewer's #1 comment on that issue).

*Rev. #2: The general discussion in the introduction could cover additional points like*

*how much model coupling is needed for operational model applications. Are the selected processes the major ones? What would be the next level? Does operational model have to go to 200m resolution (GETM high resolution grid) to cover the scales needed for model coupling? Most basin scale, operational ocean models feature a coarser resolution.*

Authors: We added additional information and more detailed description on that in the introduction as well as in the other parts (Section 2 and conclusions). See also some of the answers of Rev#1 comments on similar issues.

*Rev. #2: P3174, L8: 200m*

Authors: Corrected.

*Rev. #2: P3174, L8: This is just a comment. Strong wave impacts on the ocean conditions are expectable at the North-Frisian islands, due to prevailing westerly winds. Why are the grids structured so as to better resolve the south-eastern North Sea?*

Authors: We agree with the author's comment. However in the present manuscript we provide an example of nesting toward the coastal areas only for the East Frisian Wadden Sea region.

*Rev. #2: P3174, L25, and following: There is no figure indicating the coverage of the WAM grid. Ideally one figure should represent both set-ups, i.e. the coupled WAM-GETM set-up. For operational applications it would also be helpful to learn more about the spectral discretization and the time steps for source integration that have been used. The definition of the grid resolution is presented with rather high resolution. It should be done in the same way as with GETM. The terms delta phi and delta lambda are strictly speaking undefined.*

Authors: For the coupled model system both WAM and GETM grid are absolutely identical and this is now better explained in the revised version of the manuscript.

*Rev. #2: P3175, L12, L14: The term "wave force" is not generally accepted and unambiguous. It is used and defined in the WAM manual as the divergence of the radiation stress.*

Authors: We agree and this has been rephrased in the revised manuscript.

*Rev. #2: P3175, L13-14: I don't quite understand this sentence. What do you get when you subtract the Stokes drift (a velocity) from the wave force (a force)? I understand that the wave force was added to the momentum equation to calculate the dynamic of the mean currents, the sum of the Stokes drift and the Eulerian drift (Mellor, 2008, eqn. 11a).*

Authors: We modified it giving more explanations and providing additional references.

*Rev. #2: P3175, L24: The coupling processes described above, take only wave effects on the ocean circulation into consideration. The description is therefore incomplete. Circulation model feedback mechanisms of varying depths, currents and*

*ice concentrations are not described.*

Authors: We agree and this is now described in the revised manuscript in Section 2.

*Rev. #2: P3175, L26: I could not find the link to Wahle et al. (2015). The paper must be still in print. The paper is used as a reference for the in-detail description of the coupling technique. I could only find a link to a presentation at the GODAE workshop 2014. The coupling technique: circulation-to-wave-model is not described either.*

Authors: Removed from the text (see the answer of the same of Rev.#1 comment)

*Rev. #2: P3177, L1: "both runs", the two runs are not defined yet. Furthermore, figure2 does not show results for both runs. Instead it shows the ratio of the standard deviation of the coupled run to the mean value of the uncoupled run (which works because Hs and tm1 are strictly positive).*

Authors: The two runs are defined on P6 L22-27 and the description of Fig.2 was reformulated.

*Rev. #2: P3177, L3: Why did the authors analyze the coupling effects only for calm wind periods, and not for storm scenarios as well? Wave induced sea level variation, i.e. the wave setup is noticeable only during storm scenarios, and coupling effects are more pronounced.*

Authors: We analyzed the influence of waves on hydrodynamic under two strong storms.

*Rev. #2: P3177, L7: One "coastal areas" to many*

Authors: We are sorry for the typo and removed this in the revised version.

*Rev. #2: P3177, L11-17: Comment: The connection between the further analysis of a station at the entrance to the Jade Bay and the high SD value of tm1 should be made clearer. I had to read the paragraph twice to understand this.*

Authors: Rephrase to make it clearer.

*Rev. #2: P3177, L14: SDT or SD*

Authors: Rephrase to SD.

*Rev. #2: P3177, L16: Southerly winds means winds from the south (meteorological convention) or winds in southerly direction (mathematical convention)? The reason for this question is, that I don't understand why waves that have been generated inside the Jade Bay could have longer effective fetch than waves coming from the North, i.e. waves that have crossed some distance of North Sea.*

Authors: This sentence has been rephrased.

*Rev. #2: P3177, Chapter 3.2: The model validation chapter could be presented before the analysis chapter 3.1 and 4.*

Authors: Done.

*Rev. #2: P3177, L28: which two model simulations.*

Authors: Rephrased according to suggestion.

*Rev. #2: P3178, L2: Please see my comment to P3171, L14. I don't argue that current refraction does not play a role, but it is not the only player. Tidal water level variations and depth refraction plays a strong role tidal dominated seas like the North Sea.*

Authors: We agree with the reviewer's comment and modified the paragraph accordingly.

*Rev. #2: P3178, L3: I think the authors mean the difference of the SD and not the SD between measured and simulated values, which is the RMS error?*

Authors: Rephrased according to the suggestion.

*Rev. #2: P3178, L22: I can't find the locations for the buoys T1-T4 in figure1. Throughout the paper, figure1 is references when it comes to indicate individual locations and transections, but none of these locations is presented in the figure.*

Authors: The locations of the stations were included in the first submission of the paper (the MS Word document). Unfortunately by the processing of the manuscript paper and its publishing as a discussion paper they were omitted from the figure 1. We will make sure that the locations appear at the final version of the manuscript.

*Rev. #2: P3178, L20 to P3179, L12 It is interesting that the additional wave force during storms does not lead to exaggerated sea level predictions, as it usually does, when the wave force (divergence of the radiation stress) is directly applied to the momentum equation, without additional penance due to mixing or reduced wind stress. This would be interesting point to elaborate on.*

Authors: We agree and it is discussed in the revised version. See also the previous answers.

*Rev. #2: P3179, L21 (see also previous point): Increased water levels of 10 to 15 cm during calm situations are rather significant. Operational circulation models and set-ups are highly tuned. The annual miss rate, i.e. the percentage of time with water level forecasts that are exceeding a range of 20cm is about 3% to 5%. High water events have a tendency to be slightly over-predicted. Additional 10 to 15cm, or even 30cm during storms, would lead to exaggerated water levels. My assumption would be that the authors used a somewhat lower drag coefficient than operationally is used, to avoid water level over-prediction.*

Authors: We haven't adjusted the drag coefficient in GETM and the model and current set-up is not tuned to the tidal conditions in the area.

*Rev. #2: P3179, L18: Clear use of terminology: This is the first time that term radiation stress is used. The radiation stress is also not increasing the water level,*

*but the wave force (divergence of the radiation stress tensor) is, when applied to the momentum equation.*

Authors: Rephrased, according to the suggestion.

*Rev. #2: P3180, L2: What is the SLE amplitude?*

Authors: We are sorry for the improper use of the terminology; it has been changed in the revised version.

*Rev. #2: P3180, L7-16: What is the reason for the TKE increase? Figure7 indicates that depth induced wave breaking under normal meteorological conditions leads to an increase of TKE in the surf zone (where the waves break). Under storm conditions and high water levels the zone where waves break extends entirely over the shallows regions. The manuscript remains unclear about the reasons for this increase. Is it because of enhanced wave propagation, refraction, stronger wave growth under strong wind conditions or maybe other reasons?*

Authors: We explained this in Section 4.2 of the revised manuscript.

Rev. #2: P3180, L18 and the following: Figure8, lower right panel (zonal velocity difference). Why is there a shift in time between the maximum of the significant wave height and the maximum of the current velocity difference? It seems that while the waves are still growing, the difference between the zonal currents is already reducing.

Authors: We explained this in Section 4.2 of the revised manuscript and agree with the reviewer.

*Rev. #2: P3181, L2: The positions are not plotted in figure1*

See the comment above about the positions in Figure 1.

# Coupling of wave and circulation models in coastal-ocean predicting systems: A case study for the German Bight

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## Abstract

This study addresses the impact of coupling between ~~wind~~ wave and circulation models on the quality of coastal ocean predicting systems. This is exemplified for the German Bight and its coastal area known as the Wadden Sea. The latter is the area between the barrier islands and the coast. This topic reflects the increased interest in operational oceanography to reduce prediction errors of state estimates at coastal scales, which in many cases are due to unresolved nonlinear feedback between strong ~~tidal~~ currents and wind-waves. In this study we present analysis of wave and hydrographic observations, as well as results of numerical simulations. A nested-grid modelling system is used to ~~producing~~produce reliable nowcasts and short-term forecasts of ocean state variables, including ~~wind~~ waves and hydrodynamics. The data base includes ADCP observations (taken from the BSH) and continuous measurements from data stations. The individual and ~~collective role~~combine effects of wind, waves and tidal forcing are quantified. The performance of the forecast system is illustrated for the cases of several extreme events. ~~Effects~~The combined role of ~~ocean waves~~wave effects on coastal circulation and sea level are investigated by considering the wave-dependent stress and wave breaking parameterization. Also the ~~effects~~response, which the circulation exerts on the ~~wind~~ waves are tested for the coastal areas ~~using different parameterizations~~. The improved skill of the coupled forecasts compared to the non-coupled ones, in particular during extreme events, justifies the further enhancements of coastal operational systems by including ~~wind~~wave effects into circulation models.

# 1    Introduction

In the last decade the north European coasts were affected by severe storms which caused serious damages in the North Sea coastal zones. Additionally, different human activities, e.g. offshore wind power industry, oil industry and coastal recreation necessitate information about the sea state in the coastal ocean with high resolution in space and time. There seems to be a consensus that high-quality predictions of extreme events like storm surges and flooding caused by storms could substantially contribute to avoid or minimize human and material damages and losses. Therefore reliable wave forecasts and long term statistics of extreme wave conditions are of utmost importance for the coastal areas. In many coastal areas the need for reliable risk assessments increases the demand of precise coastal predictions. This cannot be achieved by further neglecting the ~~wind~~ wave-current interaction in coastal ocean operational forecasting.

~~Wind waves~~Waves-current interaction is recently an important issue in the field of coastal ocean forecasting (Roland and Ardhuin, 2014, Bolaños et al., 2014). ~~Ocean waves control the exchange of energy, momentum, heat, moisture, gas, etc. between the ocean and atmosphere. Understanding these processes~~Understanding this process is of utmost importance on the road of fully integrating the atmospheric, wave and ocean models and their further coupling with biological, morphological, and hydrographical forecasting systems.

The uncertainties in most of the presently used models results from the nonlinear feedback between ~~strong tidal~~the currents, water level variations and wind-waves, which can no longer be ignored, in particular in the coastal zone. The joint impact of surges, currents and waves is strongly inter-related (Wolf et al., 2011, Brown et al., 2011) and those cannot be considered separately for coastal ocean predictions.

The ocean waves affect not only the sea level but also the currents and mixing, the latter being of utmost importance for the sediment dynamics (Lettmann et al, 2009). Prandle et al. (2000) demonstrated the need of accounting for surface waves with a significant wave height larger than ~~1 m~~one meter in the sediment modelling. This is of big importance for sediment dynamic and other ecosystem processes (Wolf and Prandle, 1999). These authors showed also that the effects of waves add to the ones due to surges and tides; on the other side the waves' characteristics are affected by the changes of sea level height due to tides and wind.

The main effects of waves that are commonly considered in the coupled modelling are due to radiation stress and Stoke drift. Babanin et al. (2010) showed that interaction of turbulence and bottom stress is also very important.

Wave-current interaction has been a topic of many studies recently (Ardhuin et al., 2008, Mellor, 2003; 2008; 2011; Kumar et al., 2012; ~~Michaudetal., 2012).~~Michaud et al. 2012, Zodiatis et al. 2015).). Mellor (2003, 2005, 2008) extended the radiation stress formulation based on the linear wave theory of Longuet-Higgins and Stewart (1964). Bennis and Ardhuin (2011) questioned the method of Mellor and suggested the use of ~~lagrangian~~Lagrangian mean framework leading to the so called vortex force. Vortex force method has been implemented in ROMS-SWAN (Kumar et al., 2012; Lane et al., 2007; McWilliams et al., 2004; Uchiyama et al., 2010). Moghimi et al. (2013) compared critically the two approaches claiming that the radiation stress formulation showed unrealistic offshore directed transport in the wave shoaling regions; on the other hand the results of longshore circulations performed similarly for both methods. Aiki and Greatbatch (2013, 2014) proved that the radiation stress formulation of Mellor is applicable for small bottom slopes. Bolaños et al. (2011, 2014) demonstrated the importance of wave-current interactions in a tidally dominated estuary and showed that the inclusion of wave effects through 3D radiation stress improves the velocity in the study area. They also compared the different radiation stress methods and concluded that for the tidally dominated area the 3D version of radiation stress produces better results than the 2D version. Polton et al~~. (~~. (2005) found that accounting for the Stokes-Coriolis forcing results in encouraging agreement between model and measurements of the mixed layer~~;~~. Janssen (2012) showed positive impact of wave breaking to the daily cycle of sea surface temperature~~, later~~. Later Breivik et al. (2015) demonstrated reduced bias between modelled and measured water temperature by incorporating the Stoke-Coriolis forcing, turbulence induced by breaking waves and ocean side stress in the NEMO model at global ocean scale. Weber et al. (2006) estimated that the wave induced stress is about 50% of the total atmospheric stress for moderate to strong wind. Wolff et al. (2011) studied the effects of waves on hydrodynamics; Brown et al. (2013) considered the wave effects on the storm surges; Roland et al. (2009) studies wave effects on water level for the Adriatic Sea. The importance of ocean depth and velocity variations for the simulated waves in the estuaries is analysed by Pleskachevsky et al~~. (~~. (2011) and Lin and Pierre (2003). However, within the framework of practical coastal ocean forecasting, the interactions between ~~wind~~ waves and currents are still not yet enough considered.

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In this study we will address the coupling between ~~wind~~ wave and circulation models for coastal ocean ~~predicting~~prediction systems on the example of the German Bight. We do not plan to analyse the role of different ~~parameterization processes between wind-waves and current.~~parameterizations used. Rather we will demonstrate the areas of improvements of coastal ocean predictions due to coupling between wave and hydrodynamic models.

The structure of the paper is as follows. The wave and hydrodynamic models and the processes of their interaction are described in Section 2. Section 3 addresses the effects of hydrodynamics on wave model performance, while in Section 4 we discuss the effects of waves on hydrodynamics and improvement of short-term forecast; followed finally by concluding remarks.

## 2 Model Description

### 2.1 Hydrodynamical Model

The General Estuarine Transport Model (GETM, Burchard and Bolding, 2002) was used in this study to simulate the circulation. This model solves the primitive equations for momentum, temperature, salinity, and water level. The model set up described here uses the k-$\varepsilon$ turbulence closure to solve for the turbulent kinetic energy k and its dissipation rate $\varepsilon$. Horizontal discretization was done on a spherical grid. The coarse resolution North Sea–Baltic Sea (3 nautical miles and 21 $\sigma$-layers) outer model was described in more detail by Staneva et al. (2009); see also Fig. 1 of for the maps of model domains. The sea surface elevation at the open boundary was generated using 13 tidal constituents obtained from the satellite altimetry via the OSU Tidal Inversion Software (Egbert and Erofeeva, 2002). The model was forced by atmospheric fluxes computed from bulk aerodynamic formulas. These formulas used model-simulated sea surface temperature, 2-m air temperature, and relative humidity together with 10-m winds from atmospheric analysis data. This information was derived from the regional model COSMO-EU operated by the German Weather Service (DWD; Deutscher Wetter Dienst) with a horizontal resolution of 7 km. River runoff data were provided by the German Federal Maritime and Hydrographic Agency (BSH; Bundesamt für Seeschifffahrt und Hydrographie). A set up for the German Bight based on the same model with about 1-km horizontal resolution was nested in the coarser domain model as explained by Staneva et al. (2009). Further downscaling to the scales of the Wadden Sea coastal areas

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was implemented in nested area in the German Bight resolved with 200 m horizontal resolution. All model configurations account for flooding and drying, which ~~are~~is a fundamental dynamic ~~processes~~process in the Wadden Sea.

## 2.2 Wave Model

WAM is a third generation wave model which solves the wave transport equation explicitly without any presumptions on the shape of the wave spectrum. The basic physics and numerics of the WAM Cycle 4 wave model, which is described in Komen et al. (1994) and Guenther et al. (1992) are kept in the new release WAM 4.5.3. ~~However~~In the coupled model system , 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~~Additionally, depth induced wave breaking (Battjes and Janssen, 1978) has been included as ~~an additional~~ source function. Depth and/or current fields can be non-stationary. ~~Grid~~It is crucial for strongly tidally forced shallow areas, like the German Bight one, that model grid points can fall dry and refraction due to spatially varying current and depth is accounted for. These modifications are of utmost importance for the improvement of wave modelling results in the coastal areas such as the Wadden Sea~~, which is strongly influenced by tides..~~. The wave model code is freely available under http://mywave.github.io/WAM/.

~~The computational system includes a~~ Similar to the circulation model, the open boundary conditions for the German Bight WAM are taken from the regional WAM set-up for the North Sea ~~(area (with a~~ spatial resolution: ~~ΔφxΔλ = 0.05°x0.08333°~~ of ca. 5 km~~) and a nested grid finer~~). The German Bight wave model has the same horizontal resolution ~~model for the German Bight (ΔφxΔλ = 0.00928°x0.015534° 900 m).~~and uses the same topography as the circulation model GETM. The driving wind fields are the same as the ~~areas~~ones used in

the hydrodynamical model. The required boundary information at the open boundaries of the North Sea model is derived from the regional wave model EWAM for Europe that is running twice a day in the operational wave forecast routine of the DWD. Within the framework of Coastal Observing System for Northern and Arctic Seas (COSYNA), a pre-operational wave and ~~hydrodynamical~~hydrodynamic forecast system has successfully been implemented and is running continuously since December 2009 providing ~~hindcasts~~hindcast and ~~forecasts~~forecast data freely available on COSYNA web site under http://www.coastlab.org.

## 2.3 Coupled model implementation and periods of analyses

The original version of GETM was modified to account for the depth dependent radiation stress and Stokes drift. The terms were calculated from the integrated wave parameters according to Mellor (2008, 2011) and Kumar et al. (2011). The gradients of the radiation stresses serve as additional explicit wave forcing in the momentum equations for the horizontal velocity components. Here the Stokes drift components have been subtracted from the wave ~~force in order to transfer it to the Eulerian framework.~~processes in order to transfer it to the Eulerian framework. Moghimi et al. (2013) studied the effects of the two different approaches utilising the radiation stress (Mellor 2011) and vortex force (Ardhuin et al. 2008) using GETM –SWAM coupled models and showed that the results for the longshore-directed transport are similar for both formulations. Recently Aiki and Greatbatch (2013) showed that the radiation stress parameterization is applicable for small bottom slopes and Grashorn et al. (2015) showed that radiation stress formalism is applicable for shallow area like the German coastal ones. They also demonstrated that the criterion proposed by Mellor (2013) to test the applicability of the radiation stress method gives reasonable results in this region. This gives us a confidence that despite the know limitations of the radiation stress formalism it is well applicable for our study area. Additionally, the bottom friction modifications as dependent upon bottom roughness and wave properties (Styles and Glenn, 2000) have been implemented. Turbulent kinetic energy due to wave friction (wave breaking/white capping and bottom dissipation) that is wave enhanced turbulence has also been taken into consideration (Pleskachevsky et al., 2011).

In order to demonstrate the impact of wave-current interaction on coastal model simulations we performed two different experiments. In the first one the wave model WAM and the circulation model GETM have been run separately (we will further refer to it as non-coupled run). The results have been compared with the GETM-WAM coupled model system, in which all wave-hydrodynamic processes described above are considered. We will further refer to it as the coupled model run). ~~Details about the coupling technique can be found in Wahle et al. (2015).~~

Three case studies have been analysed here, which we consider interesting in terms of both atmospheric conditions/extreme events and observational data availability.

The first analyses period is in July 2011, which was a calm weather period. Two different wind regimes were dominating the atmospheric state in July, 2011, which will be addressed separately.

The next two analyses periods are chosen such as to address the effects of two of the most severe storm surges affecting our study region in the last hundred years. The first storm surge is the Britta storm of 31 October–1 November 2006 causing serious damages for the off-shore infrastructures and shipping in the North Sea region. Britta storm was characterized by a deep low-pressure centre that moved on a trajectory from north of Scotland to western Norway and then eastwardeastwards through the Baltic Sea. Severe storm surge damages occurred in the East Frisian Wadden Sea. Extreme sea level during this storm-surge is considered as a 100-year event (Madsen et al., 2007). In addition to the storm surge, unusually high waves have been measured in the southern North Sea developing on northern North Sea and propagated southward under the influence of strong north winds with a long fetch. The Britta storm has been given particular attention in our analyses for the types of changes that may occur during single event (Bartholomä et al., 2009; Lettmann et al., 2009; Stanev et al., 2009; Grashorn et al., 2015).

The second extreme event that we consider here is the winter storm Xavier on the 5th and 6th of December, 2013 causing severe flooding and devastation along the German North Sea coast. Besides of extreme high water levels along the coasts extreme sea state conditions have been observed causing serious erosion of dunes and sand-displacements on the barrier islands.

## 3  Impact of circulationhydrodynamics on waves

### 3.1  Spatial patterns

To quantify the impact of currents, including water depth hydrodynamics on the results of wave model, the standard deviation (STD) of significant wave height ($Hs$) and the mean period ($tm1$), simulated in both runs normalized by the mean values of the non-coupled wave model are shown in Fig. 2. The horizontal patterns are given as one month average for July, 2011. In the open North Sea area there are no significant differences between the coupled and non-coupled wave modes for both $Hs$ and $tm1$. However, along the coastal areas, where currents and water level change rapidly under the influence of tides, the impact of coupling seems to be significant. Within the coastal areas of the German Bight coastal areas the STD of

7

1  *Hs* goes up to 30%, mainly due to the changes in water depth. The STD of *tm1* is about 10-

2  15% in the coastal area. In particular, in the South-East of the German Bight, where the rivers

3  Elbe and Weser are entering, the impact of coupling on *tm1* period spreads much further off-

4  shore.

5  Interesting to notice are several relatively small areas, mainly located on the tidal inlets where

6  the STD of *tm1* reaches values up to 30%. These areas are characterized by strong currents,

7  up to 1.5 m/s, see Staneva et al. (2009), often parallel to the waves inducing a large Doppler

8  shift. A detailed analysis of the large SDT in the entrance of the Jade Bay (8.25$^0$E, 53.5$^0$N

9  water depth 6 m ±1 m) reveals that *Hs* and *tm1* increase substantially during southerly wind

10  (local wave growth, longer effective fetch) and opposing currents (wave blocking and

11  Doppler shift).

12  ### 3.2~~3.1~~  Model validation

13  At the buoy 'Elbe', which is located in the open sea (water depth about 21 m, see the middle

14  panel of Fig. 1), two different wind regimes occurred between 1. July and 10. July, 2011 (Fig.

15  ~~3~~2). From July 1st to 5th the dominating north-western wind did not change its direction (see

16  the red line in Fig. ~~3b~~2b). However wind speed increased from 7.7 m/s on 1st July to a

17  maximum of 15 m/s on 3. July (Fig.~~3c~~2c). The decrease of wind speed to moderate values

18  after 5 of July, 2011 (less than 5 m/s) was accompanied by changing wind direction. The

19  variations of water depth and currents are tidally dominated (Fig. ~~3a~~2a) and not much

20  influenced by the wind during the whole period. The observed significant wave height (Fig.

21  ~~3d~~2d) and the wave direction (Fig. ~~3f~~2f) are generally in a good agreement with ~~any of~~ the

22  ~~two~~measurements for both the wave model ~~simulations. It is noteworthy that a~~only and the

23  coupled wave-circulation one. A clear tidal signal can be seen in the wave periods in the

24  coupled model simulations, which accounted for the varying currents. It is noteworthy that in

25  addition to current refraction, the tidal water level variations and depth refraction play a

26  strong role in tidal-dominated seas like the North Sea. This well replicates the available

27  measurements (blue dots on Fig. ~~3e~~2e). Consequently ~~the STD between the measured and~~

28  ~~simulated~~difference of the SD of tm1 period decreases form 0.439s in the non-coupled run to

29  0.397s in the coupled one and the bias (model-measurement) decreases from 0.245s to 0.174s,

30  respectively (see Table 1). The bias and ~~STD~~SD of the significant wave height (*Hs*) are small

31  in both runs demonstrating that the wave models fit well with the observations.

The frequency wave spectra from the Elbe buoy and the two runs are shown in Fig. 4~~3~~ for the first 5 days in July during the strong wind event. ~~Similar~~Similarly to Fig. 3~~2~~, the patterns of wave spectra from the measurements and those of the coupled model run are in a very good agreement (compare the top and bottom panel of Fig. 4~~3~~). This is not the case for the non-coupled wave model (the middle panel in Fig. 4~~3~~). The tidal currents are mainly affecting the tail of the spectra, whereas the energy around the peak is not much different in all three panels.

The statistical analysis of the observations and simulations (see Table 1) clearly demonstrates the improvement of the quality of coupled wave-circulation model forecasts for the German Bight in ~~comparisons~~comparison to the non-coupled one.

### 3.2   Spatial patterns

To quantify the impact of currents, including water depth hydrodynamics on the results of wave model, the standard deviation (SD) of $Hs$ and the mean period ($tm1$), of the coupled run normalized by the mean values of the non-coupled wave model are shown in Fig. 4. The horizontal patterns are given as one month average for July, 2011. In the open North Sea area there are no significant differences between the coupled and non-coupled wave modes for both $Hs$ and $tm1$. However, along the coastal areas, where currents and water level change rapidly under the influence of tides, the impact of coupling seems to be significant. Within the German Bight coastal areas the SD of $Hs$ goes up to 30%, mainly due to the changes in water depth. The SD of $tm1$ is about 10-15% in the coastal area. In particular, in the South-East of the German Bight, where the rivers Elbe and Weser are entering, the impact of coupling on $tm1$ period spreads much further off-shore.

Interesting to notice are several relatively small areas, mainly located on the tidal inlets where the SD of $tm1$ reaches values of up to 30%. These areas are characterized by strong currents, up to 1.5 m/s (see Staneva et al., 2009), often parallel to the waves inducing a large Doppler shift. The large SD in the entrance of the Jade Bay (located in the east Frisian Wadden Sea which is the southern German Bight area with coordinates 8.25$^0$E, 53.5$^0$N and water depth 6 m $\pm$1 m) reveals that the wave variables $Hs$ and $tm1$ increase substantially during northerly wind periods (inducing local wave growth, longer effective fetch) and opposing currents (responsible for wave blocking and Doppler shift).

9

## 4 Impact of waves on hydrodynamics

### 4.1. Analyses for the periods of extreme events

In this section we demonstrate the role of coupling by analysing the impact of waves on hydrodynamics during several extreme events. Sea level variability in four locations (T1-T4ST1-ST4, see Fig.1 for their geographical locations) are analysed along the German coast for the period including the extreme event Xavier on 06.12.2013 (see description in Section 2). The observations and simulations are shown in Fig. 5 for the tide gauge observations (black line), coupled wave-circulation model simulations (coupled run- red line) and the non-coupled run (circulation model only, blue line). During normal meteorological conditions, the coupled and non-coupled models fit well with the tide gauge data. However, during the storm Xavier, the sea level predicted by the hydrodynamicalhydrodynamic model only is underestimated with more than 40 cm. It appears that the sea level predictions of the coupled model are closer to the measurements (compare the red and black lines). This demonstrates the importance of wave-current interactions also for the hydrodynamics. The rootRoot Mean Square Errors (RMSE) between observations and coupled model have been significantly reduced compared with the RMSE differences between the observationobservations and circulation only model only for all coastal locations (Table 2). Predictions of storm events with coupled models could be of utmost importance for many coastal applications dealing with risk analyses (e.g. off-shore wind industry, oil platform operations, etc.) where higher accuracy is needed. This justifies the consideration of waves in operational forecasting.

### 4.2 Spatial patterns

In order to give an idea of the spatial distribution of the effects resulting from  coupling we show in Figure 6  the differences of sea surface elevation between the coupled and circulation only model for 3.12.2013 at 01:00  UTC (normal meteorological situation, left panel) and 06.12.2013- 01:00 UTC (extreme event, right panel). The radiation stresswave-induced parameterization increases the average water level, which is more pronounced in the coastal area. In the open North Sea the effects of coupling are almost negligible. During normal conditions the difference of the sea level due to the coupling of circulation and wave models reaches a maximum of 10-15 cm in the area of Elbe Estuary. However, during the storm Xavier, the differences of simulated sea level when considering waves are more than 30 cm along the whole German coast. In some of the Wadden Sea areas the increase of water level in the simulations taking into consideration the wave-current interactions was above half meter.

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1    The results shown here are indicative that the uncertainties in most of the presently used non-
2    coupled operational models result from the missing nonlinear feedback between strong tidal
3    currents and wind-waves. This can no longer be ignored in the operational oceanography, in
4    particular in the coastal zone where the wave-circulation interplay seems to be dominant. The
5    statistical analyses of simulated seal level elevation (SLE amplitude) versus tide gauge data
6    over the German Bight (Table 2) show that the coupling improves significantly improves the
7    ocean predictions for the whole German coastal area. The RMSEs during the calm conditions
8    are small in both coupled and circulation model only. However during the extreme events the
9    RMSE of sea surface elevation are significantly reduced when considering ocean-waves
10   interactions.

11   In the following we will demonstrate the effect of coupling on the storm Britta on 1$^{st}$ of
12   November, 2011. During this storm event (see Fig. 7a), significant wave height over 10 m has
13   been simulated in the open North Sea (close to the north-western boundary). The East Frisian
14   Wadden Sea area was exposed to waves with a magnitude of about 6-7 m. Only 2 days later
15   significant wave height dropped to 4 m within the German Bight (Fig. 7b). As an example of
16   the impact of wave forcingeffects we show the dissipation of surface turbulent kinetic energy
17   in the German Bight area at the peak of the storm at 03:00 UTC on 1$^{st}$ of November (Fig. 7c)
18   and under calm meteorological conditions (Fig. 7d). Along the coast dissipation rates exceed
19   0.06 m$^2$/s$^2$, which is about 100 times larger than under normal meteorological conditions.

20   Predictions of both zonal and meridional velocity have been also improved due to the
21   coupling between the waves and circulation during Storm Britta (see Fig. 8). The zonal
22   velocity has been under-estimated in the circulation only model only (green line) and got
23   closer to the ADCP data for the coupled wave-circulation model (red line). There is also a
24   very good correlation between the differences of the predicted velocity and significant wave
25   height (Fig. 8, bottom patterns).  During the Britta storm when the significant wave height
26   reached almost 8m in the coastal station the difference of the zonal velocity between the
27   coupled run and the hydrodynamicalhydrodynamic model was more than 40 cm/s.  The
28   transport along the coastal area has been also increased in the coupled runs (the differences of
29   the zonal velocity between both runs being above 35 cm/s). These results are indicative that
30   coupled hydrodynamics and wave models could be of significant importance for further
31   Lagrangian drift applications e.g. for search and rescue operations as well as oil-spill

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analyses. The effect of wave-current interactions on Lagrangian particle transport has been investigated in Röhrs et al. (2012, 2014).

Vertical section of the intensification of the longshore currents during the Britta storm is shown on Fig. 9 (the location of the section is plotted in Fig. 1). Not only does the longshore velocity increases but also its vertical structure has been changed through the effects of coupling. Similar behaviour has been also observed by Grashorn et al. (2015).

## 5   Conclusions

Wave and hydrodanamic hindcastshydrodynamic hindcast and forecastsforecast for the North Sea and German Bight are of great importance for the management of coastal zones, ship navigation, off-shore wind energy, naval operations etc. Storms and wind waves which they generate have direct impact on the coastal and marine environment. The population living in the coastal areas is recently concerned with the impacts of erosion and flooding, and actions aiming at better predictions, impact assessments of minimization of damages are of greatest importance. Some driving forces that cause serous damages on coastal environment are due to the wave conditions. Their absolute and relative impact can be estimated by using coastal models. In this paper we demonstrated the improvements of coastal ocean predictions due to consideration of wind waves-current interaction for the North Sea and German Bight regions.

The state-of the art wave (WAM) and hydrodynamic (GETM) models coupled interactively demonstrate here one step on the road to improving the ocean state estimates and predictions in the coastal areas. Improved forecast statistics once considering coupling is being demonstrated for both wave and circulation models.

The coupled system presented here enables to provide reliable predictions as well as to analyzeanalyse long term changes of wave and circulation conditions, including extreme events. The performance of the forecasting system was illustrated for the cases of several extreme events along with the effects of ocean waves on coastal circulation. For our study area it can be coincided that the use of radiation stress parameterization produced physically reasonable results However, the different wave-induced formalisms lead to different limitations and no general recommendation should be performed. The improved skill resulting from the recent coupled model developments, in particular during storms, justifies further

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1    enhancements of the both forecast applications at operational services and long-term

2    hindcasts and climate analyses for the North Sea and the German Bight.

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4    **Acknowledgements:**

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# References

Aiki H., Greatbatch R.J.: The vertical structure of the surface wave radiation stress for circulation over a sloping bottom as given by thickness-weighted-mean theory, J Phys Oceanogr, 43(1):149– 164, 2013.

Aiki H., Greatbatch R.J.: A new expression for the form stress term in the vertically Lagrangian mean framework for the effect of surface waves on the upper-ocean circulation, J Phys Oceanogr. 44(1):3–23, 2014.

Ardhuin, F., Rascle, N., Belibassakis, K.: Explicit wave-averaged primitive equations using a generalized Lagrangian mean, Ocean Modell., 20 (1), 35–60, 2008.

Babanin, A. V., Chalikov, D., Young, I. R., and  Savelyev, I.: Numerical and laboratory investigation of breaking of steep two- dimensional waves in deep water, J. Fluid Mech., 644, 433–463, 2010.

Bartholomä A., Kubicki A., Badewien T., Flemming B.W.:Suspended sediment transport in the German Wadden Sea-seasonal variations and extreme events, Ocean Dyn., 59(2):213– 225, 2009.

Battjes, J.A., Janssen, P., 1978: Energy loss and setup due to breaking of random waves. International Conference on Coastal Engineering, ASCE, pp. 569–587, 1978.

Bennis, A., and Ardhuin, F.: Comments on the depth-dependent current and wave interaction equations: a revision, J. Phys. Oceanogr., 41, 2008–2012, 2011.

Bidlot, J., Janssen P., and Abdalla S.: A revised formulation for ocean wave dissipation in CY29R1. MEMORANDUM RESEARCH DEPARTMENT of ECMWF, April 7, 2005 File: R60.9/JB/0516, 2005.

Bidlot, J.-R., Janssen P., Abdalla S., and Hersbach H.:, A revised formulation of ocean wave dissipation and its model impact, ECMWF Tech. Memo. 509 , Eur. Cent. for Medium-Range Weather Forecasting, Reading, UK, 2007.

Bolaños, R., Osuna, P., Wolf, J., Monabiu, J., Sanchez-Arcilla, A.: Development of the POLCOMS–WAM current–wave model, Ocean Model., 36, 102–115, 2011.

Bolaños, R.; Brown, J.M.; Souza, A.J.: Wave-current interactions in a tide dominated estuary. Continental Shelf Research, 87. 109-123. 10.1016/j.csr.2014.05.009, 2014.

14

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

Brown J.M., Bolaños R., and Wolf J,: Impact assessment of advanced coupling features in a tide-surge-wave model, POLCOMS-WAM, in a shallow water application, J Mar Syst 87(1), 13–24, 2011.

Brown J.M., Bolaños R., and Wolf J.: The depth-varying response of coastal circulation and water levels to 2D radiation stress when applied in a coupled wave-tide-surge modelling system during an extreme storm, Coast Eng., 82:102–113, 2013.

Burchard, H. and Bolding K.: GETM - a General Estuarine Transport Model, No EUR 20253 EN, printed in Italy, European Comission, 2002.

Egbert and Erofeeva: Efficient inverse modeling of barotropic ocean tides, J. Atmos. Ocean. Technol. 19: 183–204, doi: 10.1175/1520-0426, 2002.

Günther, H., S. Hasselmann, P.A.E.M. Janssen,: The WAM Model Cycle 4.0. User Manual. Technical Report No. 4, Deutsches Klimarechenzentrum, Hamburg, Germany, 102 pages, 1992.

Grashorn, S., Lettmann, K.A., Wolff, J.-O., Badewien, T.H., Stanev, E.V.: East Frisian Wadden Wea hydrodynamics and wave effects in an unstructured-grid model, Ocean Dynamics 65 (3), 419–434, 2015.

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

Jansen P: Ocean wave effects on the daily cycle in SST, J. Geophys. Res., 117,C00J32, doi:10.1029/2012JC007943, 2012.

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

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

Lane, E.M., Restrepo, J.M., and McWilliams, J.C.: Wave–current interaction: a comparison of radiation-stress and vortex-force representations, J. Phys. Oceanogr. 37 (5), 1122–1141, 2007.

Lettmann K., Wolff J-O, and Badewien T.: Modeling the impact of wind and waves on suspended particulate matter fluxes in the East Frisian Wadden Sea (southern North Sea), Ocean Dyn., 59(2), 239–262, 2009.

Lin, R.Q., and Perrie, W.: Wave–current interactions in an idealized tidal estuary, J. Geophys.Res., 108, 1–18, http://dx.doi.org/10.1029/2001JC001006., 2003.

Longuet-Higgins M.S., and Stewart R.W.: Radiation stresses in water waves: a physical discussion with applications, Deep-Sea Res., 11, 529–562, 1964.

Madsen, K. S., Hoyer, J. L., and Tschering, C. C.: Near-coastal satellite altimetry: sea surface 15 height variability in the North Sea–Baltic Sea area, Geophys. Res. Lett., 34, L14601, doi:10.1029/2007GL029965, 2007.

McWilliams, J., Restrepo, J., and Lane, E.: An asymptotic theory for the interaction of waves and currents in coastal waters, J. Fluid Mech., 511, 135–178, 2004.

Mellor G.: The three-dimensional current and surface wave equations, J Phys. Oceanogr., 33(9), 1978–1989, 2003.

Mellor G.: Some consequences of the three-dimensional current and surface equations. J. Phys. Oceanogr., 35(11), 2291–2298, 2005.

Mellor G.: The depth-dependent current and wave interaction equations: a revision, J. Phy.s Oceanogr. 38(11), 2587–2596, 2008.

Mellor G.: Wave radiation stress. Ocean Dyn. 61(5), 563–568, 2011.

Mellor G.: Waves, circulation and vertical dependance. Ocean Dyn 63(4), 447–457, 2013.

Michaud, H., Marsaleix, P., Leredde, Y., Estournel, C., Bourrin, F., Lyard, F., Mayet, C., and Ardhuin, F., 2012.: Three-dimensional modelling of wave-induced current from surf zone to the inner shelf, Ocean Sci., 8, 657–681, 2012.

Moghimi S., Klingbeil K., Gräwe U., Burchard H.,.: A direct comparison of a depth-dependent radiation stress formulation and a vortex force formulation within a three-dimensional coastal ocean model, Ocean Model., 70, 132–144, (2013).

Pleskachevsky, A., Dobrynin, M.; Babanin, A. V.; Günther, H., and Stanev, E.: Turbulent mixing due to surface waves indicated by remote sensing of suspended particulate matter and its implementation into coupled modeling of waves, turbulence and circulation. Journal of Phys. Oceanogr. 41 (4), S. 708-724. doi: 10.1175/2010JPO4328.1, 2011.

Polton, J.A., Lewis, D.M., and Belcher, S.E.: The Role of Wave- Induced  Coriolis-Stokes Forcing on the Wind-Driven Mixed Layer, J. Phys. Oceanogr., 35, 444–457, doi: 10.1175/JPO2701.1, 2005.

Prandle et al.: Tide, wave and suspended sediment modelling on an open coast: Coastal Engineering, 4, 1-3, 237-267, 2000.

Röhrs, J.; Christensen, K. H.; Hole, L. R.; Broström, G.; Drivdal, M. & Sundby, S.: Observation-based evaluation of surface wave effects on currents and trajectory fore- casts. Ocean Dynam., 62, 1519-1533, 2012.

Röhrs, J.; Christensen, K. H.; B., V. F.; Sundby, S.; Saetra, &O. & Broström, G.: Wave-induced transport and vertical mixing of pelagic eggs and larvae. Limnol. Oceanogr., 59(4), 1213-1227, 2014.

Roland A., and Ardhuin F.: On the developments of spectral wave models: numerics and parameterizations for the coastal ocean. Ocean Dyn 64, 6, 833–846, 2014.

Roland, A., Cucco, A., Ferrarin ,C., Hsu,T. ,Liau,J. ,Ou,S., Umgiesser, G., Zanke ,U.: On the development and verification of a 2-D coupled wave–current model on unstructured meshes. J. Mar. Syst. 78, 244–254, 2009.

Stanev,  E. V., Schulz-Stellenfleth, J., Staneva, J., Grayek, S., Seemann, J., and Petersen, W: Coastal observing and forecasting system for the German Bight–estimates of hydrophysical states, Ocean Sci., 7, 569-583, 2011.

Staneva, J., Stanev, Wolff, J-O., Badewien, T., Reuter, R., Flemming, B., Bartholomae A., and Bolding, K.: Hydrodynamics and sediment dynamics in the German Bight. A focus on observations and numerical modeling in the East Frisian Wadden Sea, Cont. Shelf Res., 29, pp. 302-319, 2009.

Styles, R., and Glenn, S.: Modeling stratified wave and current bottom boundary layers on the continental shelf, J. Geophys. Res. 105, C10, 24119–24124, 2000.

17

1   Uchiyama, Y., McWilliams, J., and Shchepetkin, A.: Wave-current interaction in an oceanic

2   circulation model with a vortex-force formalism: application to the surf zone, Ocean Modell.

3   34, 16–35, 2010.

4   Wahle K., Staneva J., Koch W. and Stanev E.: Response of the German Bight hydro and

5   sediment dynamics to wave, tidal and atmospheric forcing. Ocean Dyn., 2015.

6   Weber, J.E.H., Brostrom, G., Saetra, O.: Eulerian versus Lagrangian approaches to the wave-

7   induced transport in the upper ocean. J. Phys. Oceanogr., 31, 2106–2118, 2006

8   Wolf, J., Brown, J.M., Bolaños, R., and Hedges, T.: Waves in coastal and estuarine waters. In:

9   Eric, Wolanski, Donald, McLusky (Eds.),Treatise on Estuarine and Coastal Science,Vol.2.

10  Elsevier, 171–212, 2011.

11  Wolf, J., and Prandle, D.: Some observations of wave-current interaction, Coast. Eng. 37,

12  471–485, 1999.

13  Zodiatis, G.; Galanis, G.; Kallos, G.; Nikolaidis, A. Kalogeri C, Liakatas, S. S.: The impact of

14  sea surface currents in wave power potential modeling. Ocean Dynam, 65, 1547-1565, 2015.

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Table 1: Statistics of the validation. Additionally to mean and standard deviation the coefficients of a linear regression are given.

| | 'Elbe' | | | | 'Hoernum Tief' | | | |
|---|---|---|---|---|---|---|---|---|
| | hs [m] | | tm1 [s] | | hs [m] | | tm1 [s] | |
| mean meas. | 1.10 | | 4.36 | | 0.33 | | 2.43 | |
| | WAM | WAM-GETMl | WAM | WAM-GETM | WAM | WAM-GETM | WAM | WAM-GETM |
| bias | 0.004 | -0.025 | 0.245 | 0.174 | -0.073 | -0.120 | 0.326 | 0.150 |
| ~~std~~SD | 0.164 | 0.171 | 0.439 | 0.397 | 0.117 | 0.136 | 0.350 | 0.293 |
| slope | 1.051 | 1.085 | 0.982 | 1.026 | 0.779 | 0.835 | 0.322 | 0.574 |
| intercept | -0.061 | -0.068 | -0.169 | -0.285 | 0.146 | 0.174 | 1.323 | 0.886 |

2

3  Table 2: Elevation amplitude (cm) Root-Mean Square Errors (RMSE) and mean errors

4  (model-observations) for the coupled wave-circulation model and GETM model only for the

5  tide gauge data from British Oceanographic Data Centre (BODC) over the German Bight area

6

| | RMSE | | MEAN Error | |
|---|---|---|---|---|
| | WAM-GETM | GETM | WAM-GETM | GETM |
| Period1 (01.12.2013-12.12.2013) | 12.4 | 19.4 | -7.6 | -11.5 |
| Period2 (01.12.2013-05.12.2013) | 11.8 | 15.2 | -6.6 | -10.4 |
| Period3 (06.12.2013-07.12.2013) | 13.6 | 22.7 | -8.5 | -18.5 |

7

1

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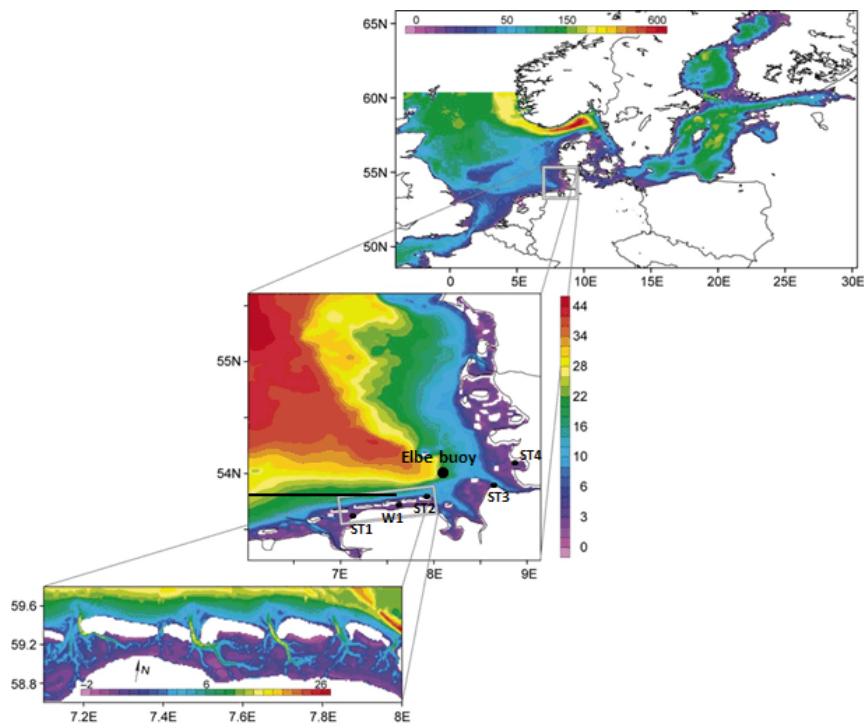
Figure 1. Nested grid model domains for the North Sea (top pattern), German Bight (middle pattern) and East-Frisian Wadden Sea (bottom pattern). The spatial resolution is: 3 nm, 1 km and 200 m, respectively. The geographical location of stations and sections analysed later are shown as well.

7

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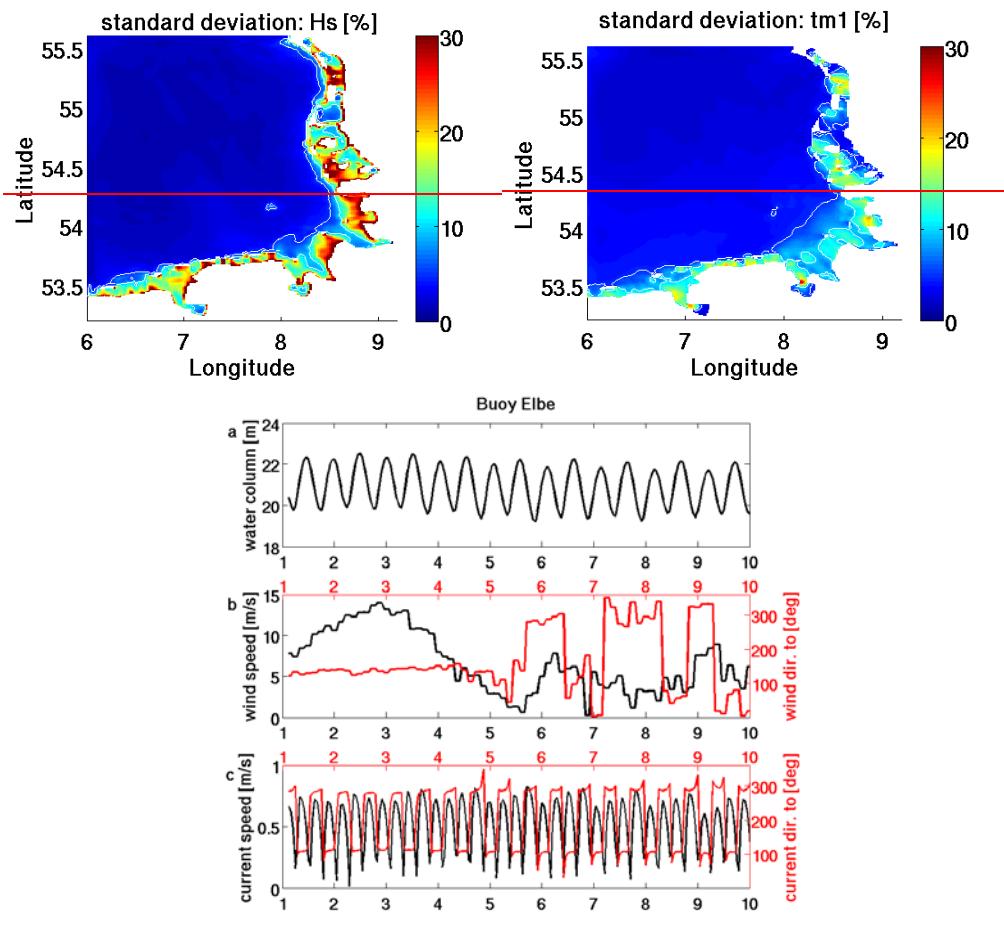
Figure. 2. Impact of hydrodynamics on the wind waves: Normalized standard deviation of significant wave height (*Hs*, left) and mean period (*tm1*, right) between coupled wave-circulation model and wave model only. Averaging is for one month (July 2011). The 5% and 10% isolines are plotted with white lines.

1



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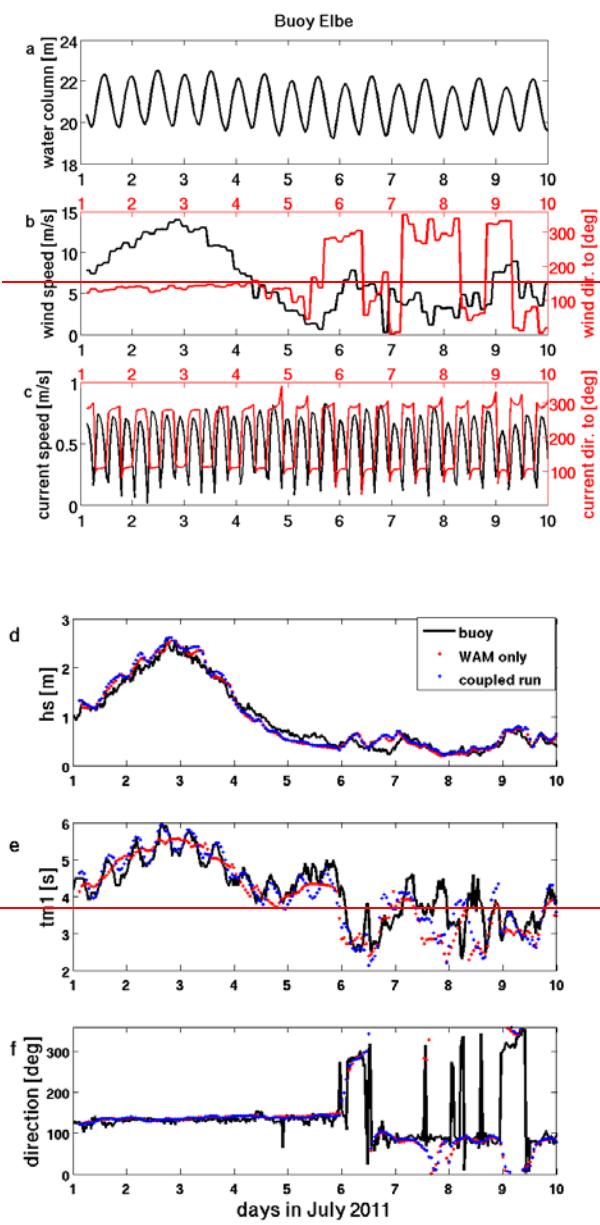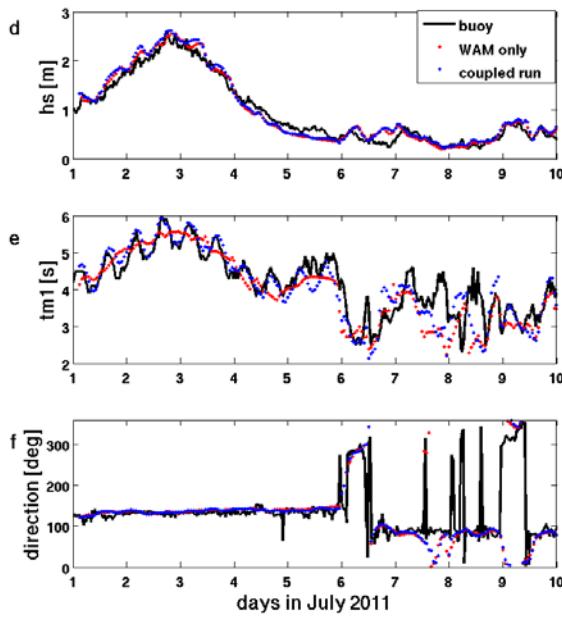
1     ~~Figure 3~~

2     Figure 2: Time series at the buoy Elbe station (see Fig. 1 for its location) from 01.07.2011 to

3     10.07.2011) of: (a): water column [m], (b) wind speed [m/s ] (black line-left axis) and wind

4     direction [deg.]  (red line, left axis; (c) surface current  magnitude  (black line-left axis) and

5     current  direction (red line, left axis) (d) significant  wave height [m]; (e) mean period-tm1 [s];

6     and (f) wave direction  [%]. For the patterns (d-f) black line corresponds to the buoy

7     measurements, red  dots– coupled model simulations, blue – wave model only.

23
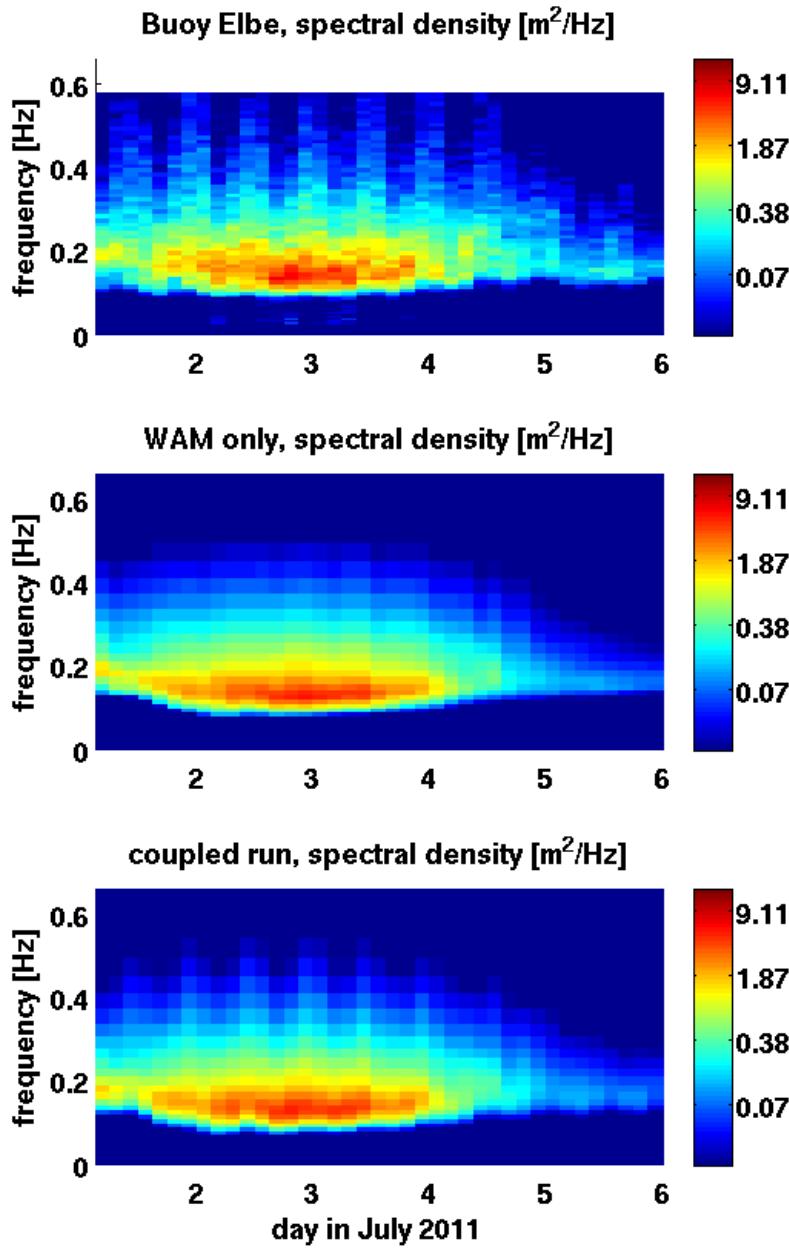
Figure 43. Comparison of measured (top) and computed values of the spectral energy density at the buoy 'Elbe', (see Fig. 1 for its location)).

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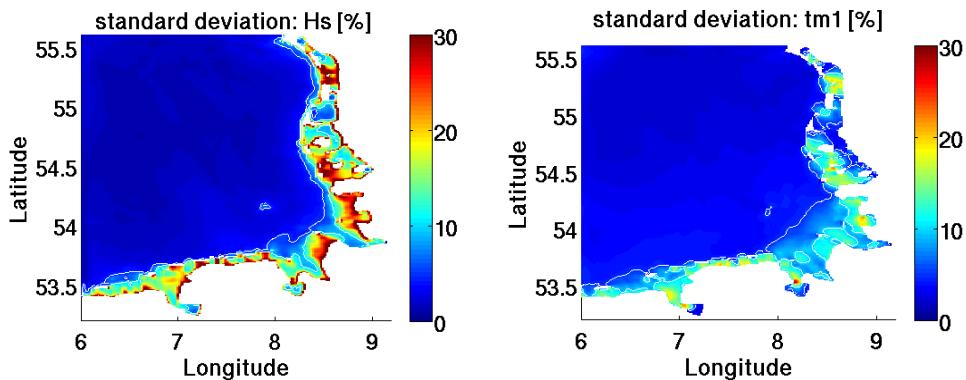
Figure. 4. Impact of hydrodynamics on waves: Normalized standard deviation (estimated as the difference between the control run and the coupled run relative to the control run values) of significant wave height (*Hs*, left) and mean period (*tm1*, right) between coupled wave-circulation model and wave model only. Averaging is for one month (July 2011). The 5% and 10% isolines are plotted with white lines.

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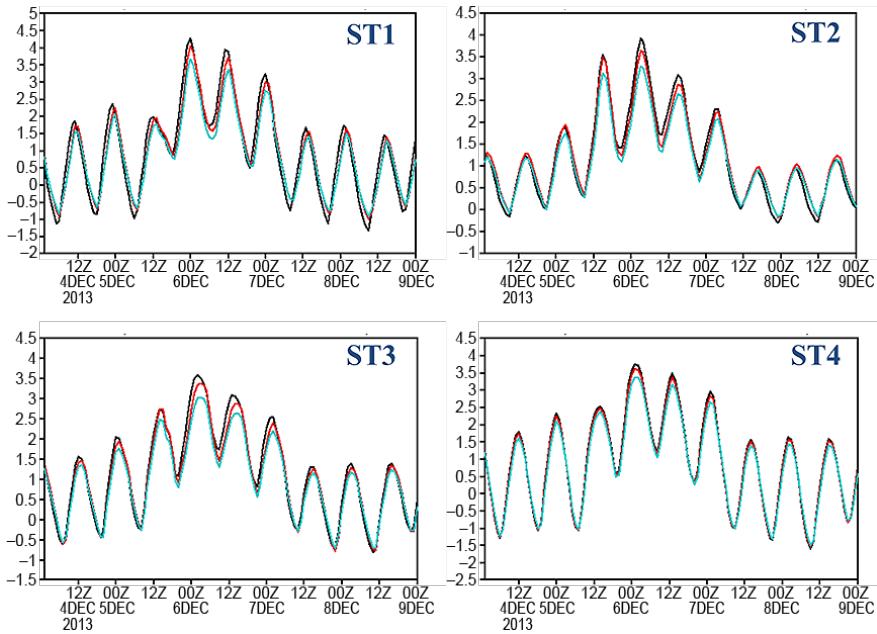


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5  Figure 5: Time series of Sea Level Elevation (SLE) in [m] at four coastal stations of the
6  German Bight (ST1-ST4, see Fig. 1 for the locations). Black line: tide gauge observations, red
7  line: coupled wave-circulation model (WAM-GETM) and green line only circulation model
8  (GETM).
9

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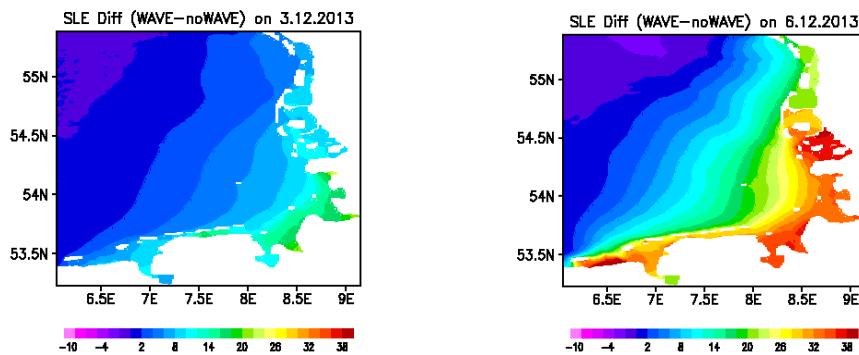
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4 Figure 6: Sea level elevation (SLE) difference [cm] between coupled wave-circulation model
5 (WAM-GETM) and ~~only~~ circulation only model (GETM)~~-~~ for the German Bight on
6 03.12.2013 01:00 UTC (left) and during the storm Xavier on 06.12.2013, 01:00 UTC.
7

27

1    (a)                                                  (b)



2
3    (c)                                                  (d)
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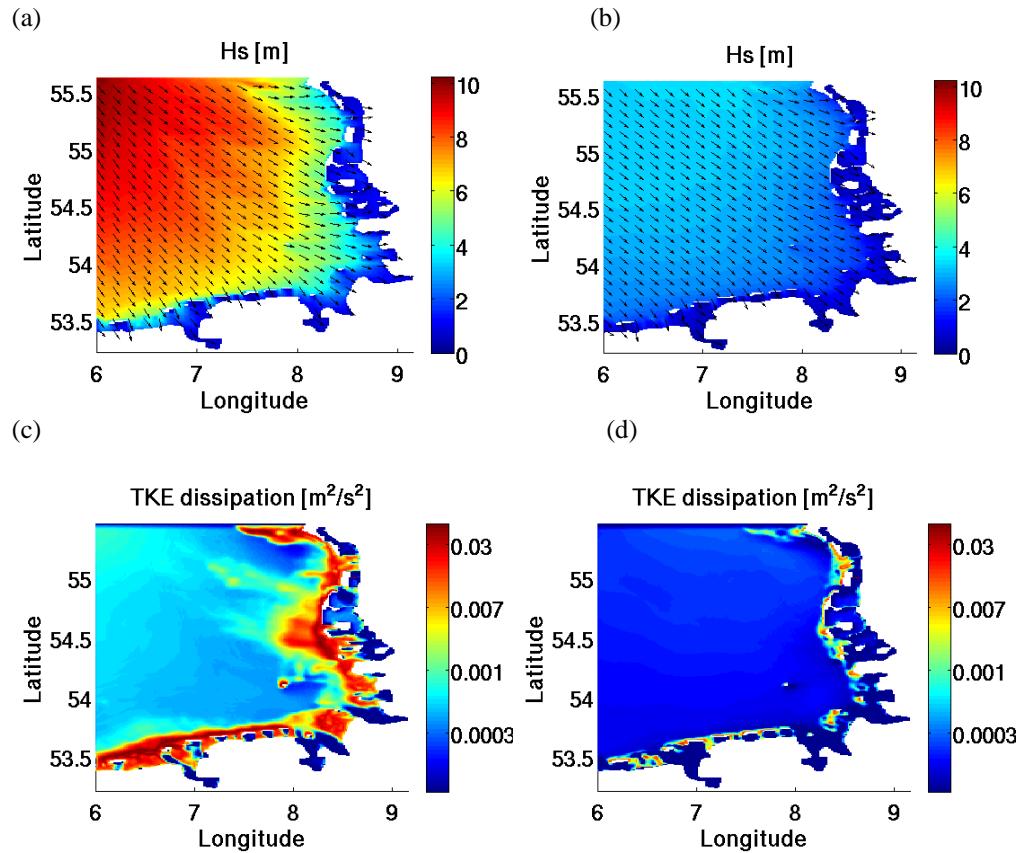
7    Figure7. (a) Significant wave height [m] in the German Bight during the peak
8    of storm Britta on 01.11.2006 03:00 UTC (b) (a) Significant wave height [m] in
9    the German Bight during normal meteorological conditions on 03.11.2006
10   03:00 UTC (c) TKE distribution in the German Bight during storm  Britta on
11   01.11.2006 03:00 UTC (d) TKE distribution in the German Bight during
12   normal meteorological conditions on 03.11.2006 03:00 UTC.

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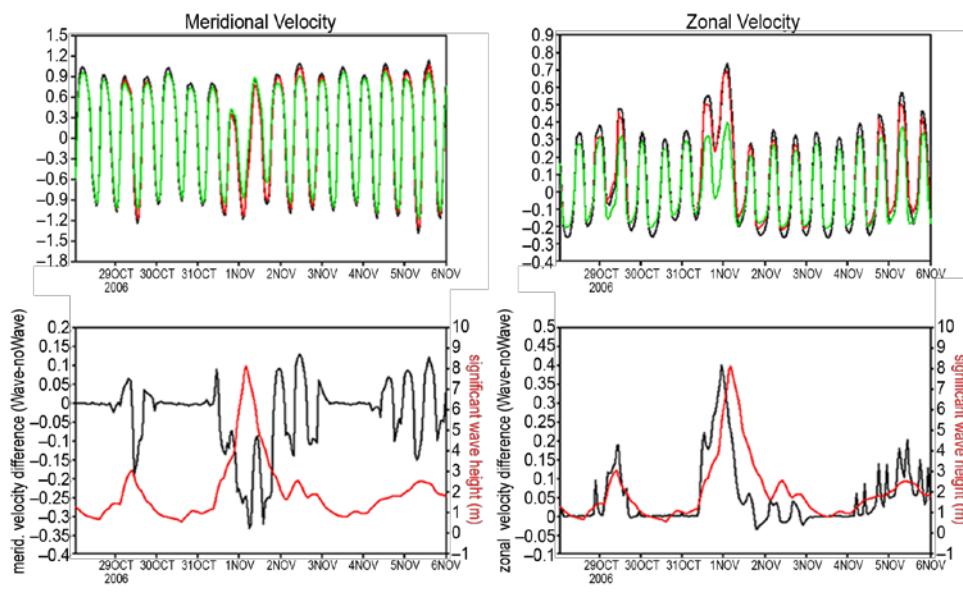
Figure 8: Top: Meridional (left) and zonal (right) velocity time series [m/s] on station W1 (see Fig. 1 for its location) from measurements (black line), coupled wave-circulation model (red line) and hydrodynamical hydrodynamic only model only (green line) during storm Britta. Bottom: Differences between the coupled and non-coupled model simulations of meridional (left) and zonal (right) velocity [m/s]-black line and significant wave height [m]-red line.

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Figure 9: Zonal velocity vertical section [m/s] during Britta on 01.11.2006 03:00 UTC (the location of the section is shown on Fig. 1) from the hydrodynamic only model (left) and coupled model (right).

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