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.

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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 wavesWaves-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 processesUnderstanding 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 tidalthe 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 mone 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.

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2 Model Description

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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-ε turbulence closure to solve for the turbulent kinetic energy k and its dissipation rate ε. Horizontal discretization was done on a spherical grid. The coarse resolution North Sea–Baltic Sea (3 nautical miles and 21 σ-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 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: ~~$\Delta\varphi x \Delta\lambda$ = 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 ($\Delta\varphi x \Delta\lambda$ = 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.

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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 ~~eastward~~eastwards 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 ~~circulation~~hydrodynamics 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~~

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~~*Hs* goes up to 30%, mainly due to the changes in water depth. The STD 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 STD of *tm1* reaches values 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. A detailed analysis of the large SDT in the entrance of the Jade Bay (8.25^{0}E, 53.5^{0}N water depth 6 m ±1 m) reveals that *Hs* and *tm1* increase substantially during southerly wind (local wave growth, longer effective fetch) and opposing currents (wave blocking and Doppler shift).~~

~~3.2~~3.1 Model validation

At the buoy 'Elbe', which is located in the open sea (water depth about 21 m, see the middle panel of Fig. 1), two different wind regimes occurred between 1. July and 10. July, 2011 (Fig. ~~3~~2). From July 1st to 5th the dominating north-western wind did not change its direction (see the red line in Fig. ~~3b~~2b). However wind speed increased from 7.7 m/s on 1st July to a maximum of 15 m/s on 3. July (Fig.~~3c~~2c). The decrease of wind speed to moderate values after 5 of July, 2011 (less than 5 m/s) was accompanied by changing wind direction. The variations of water depth and currents are tidally dominated (Fig. ~~3a~~2a) and not much influenced by the wind during the whole period. The observed significant wave height (Fig. ~~3d~~2d) and the wave direction (Fig. ~~3f~~2f) are generally in a good agreement with ~~any of~~ the ~~two~~measurements for both the wave model ~~simulations. It is noteworthy that a~~only and the coupled wave-circulation one. A clear tidal signal can be seen in the wave periods in the coupled model simulations, which accounted for the varying currents. It is noteworthy that in addition to current refraction, the tidal water level variations and depth refraction play a strong role in tidal-dominated seas like the North Sea. This well replicates the available measurements (blue dots on Fig. ~~3e~~2e). Consequently ~~the STD between the measured and simulated~~difference of the SD of tm1 period decreases form 0.439s in the non-coupled run to 0.397s in the coupled one and the bias (model-measurement) decreases from 0.245s to 0.174s, respectively (see Table 1). The bias and ~~STD~~SD of the significant wave height (*Hs*) are small in both runs demonstrating that the wave models fit well with the observations.

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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 8.25^0E, 53.5^0N and water depth 6 m ±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).

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4 Impact of waves on hydrodynamics

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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-T4~~ST1-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 ~~hydrodynamical~~hydrodynamic 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 ~~root~~Root Mean Square Errors (RMSE) between observations and coupled model have been significantly reduced compared with the RMSE differences between the ~~observation~~observations 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 stress~~wave-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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The results shown here are indicative that the uncertainties in most of the presently used non-coupled operational models result from the missing nonlinear feedback between strong tidal currents and wind-waves. This can no longer be ignored in the operational oceanography, in particular in the coastal zone where the wave-circulation interplay seems to be dominant. The statistical analyses of simulated seal level elevation (SLE amplitude) versus tide gauge data over the German Bight (Table 2) show that the coupling improves significantly improves the ocean predictions for the whole German coastal area. The RMSEs during the calm conditions are small in both coupled and circulation model only. However during the extreme events the RMSE of sea surface elevation are significantly reduced when considering ocean-waves interactions.

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

Predictions of both zonal and meridional velocity have been also improved due to the coupling between the waves and circulation during Storm Britta (see Fig. 8). The zonal velocity has been under-estimated in the circulation only model only (green line) and got closer to the ADCP data for the coupled wave-circulation model (red line). There is also a very good correlation between the differences of the predicted velocity and significant wave height (Fig. 8, bottom patterns). During the Britta storm when the significant wave height reached almost 8m in the coastal station the difference of the zonal velocity between the coupled run and the hydrodynamicalhydrodynamic model was more than 40 cm/s. The transport along the coastal area has been also increased in the coupled runs (the differences of the zonal velocity between both runs being above 35 cm/s). These results are indicative that coupled hydrodynamics and wave models could be of significant importance for further Lagrangian drift applications e.g. for search and rescue operations as well as oil-spill 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 hindcasts~~hydrodynamic hindcast and ~~forecasts~~forecast 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 analyze~~analyse 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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enhancements of the both forecast applications at operational services and long-term hindcasts and climate analyses for the North Sea and the German Bight.

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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

Table 2: Elevation amplitude (cm) Root-Mean Square Errors (RMSE) and mean errors (model-observations) for the coupled wave-circulation model and GETM model only for the tide gauge data from British Oceanographic Data Centre (BODC) over the German Bight area

	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

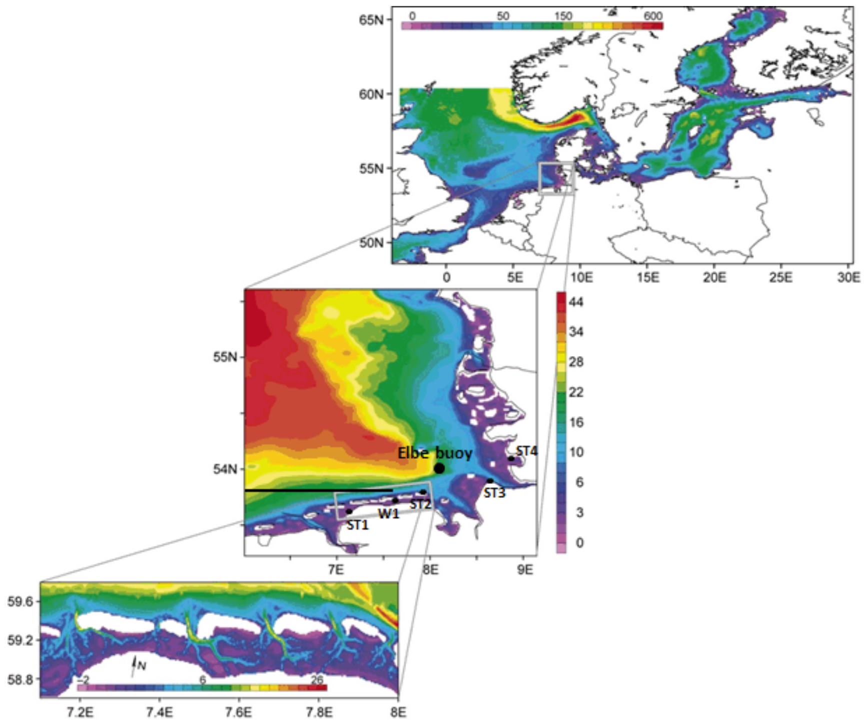

Figure 1. Nested grid model domains for the North Sea (top pattern), German Bight (middle pattern) and East-Frisian Wadden Sea (bottom pattern). The spatial resolution is: 3 nm, 1 km and 200 m, respectively. The geographical location of stations and sections analysed later are shown as well.

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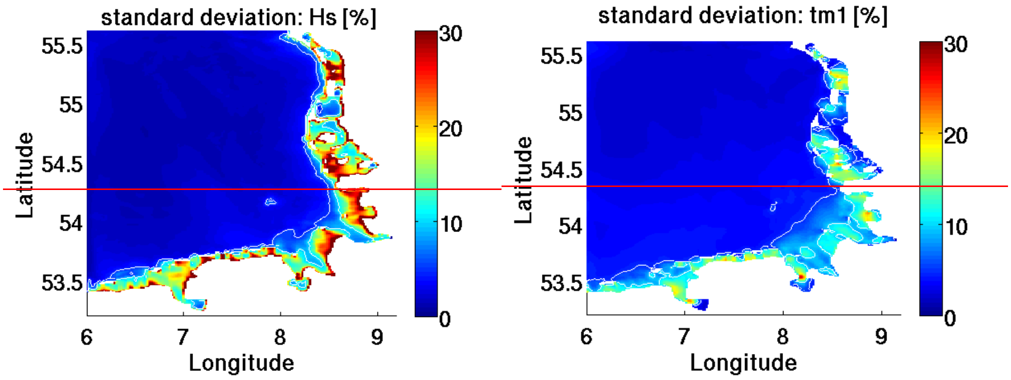

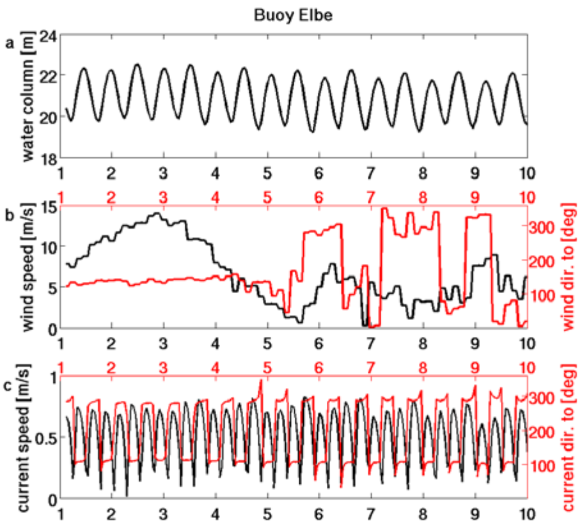

~~Figure. 2. Impact of hydrodynamics on the wind waves: Normalized standard deviation of significant wave height (*Hs*, left) and mean period (*tm1*, right) between coupled wave-circulation model and wave model only. Averaging is for one month (July 2011). The 5% and 10% isolines are plotted with white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

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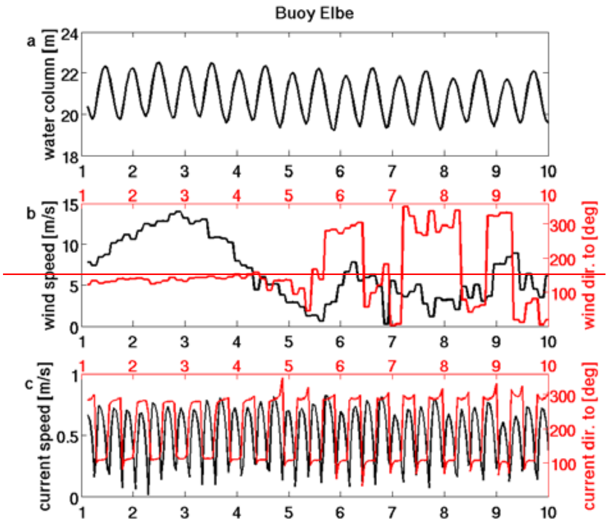

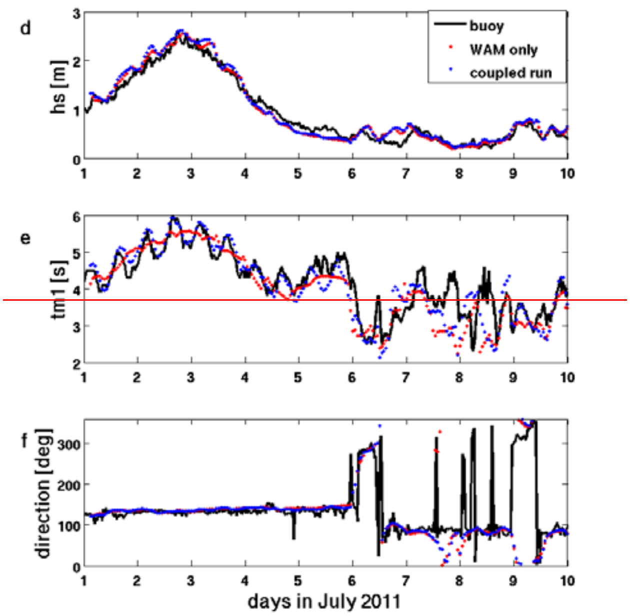

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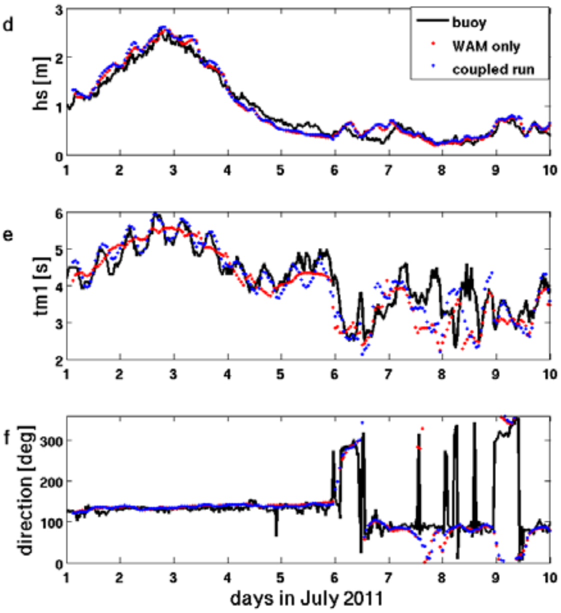

~~Figure 3~~

Figure 2: Time series at the buoy Elbe station (see Fig. 1 for its location) from 01.07.2011 to 10.07.2011) of: (a): water column [m], (b) wind speed [m/s] (black line-left axis) and wind direction [deg.] (red line, left axis; (c) surface current magnitude (black line-left axis) and current direction (red line, left axis) (d) significant wave height [m]; (e) mean period-tm1 [s]; and (f) wave direction [%]. For the patterns (d-f) black line corresponds to the buoy measurements, red dots– coupled model simulations, blue – wave model only.

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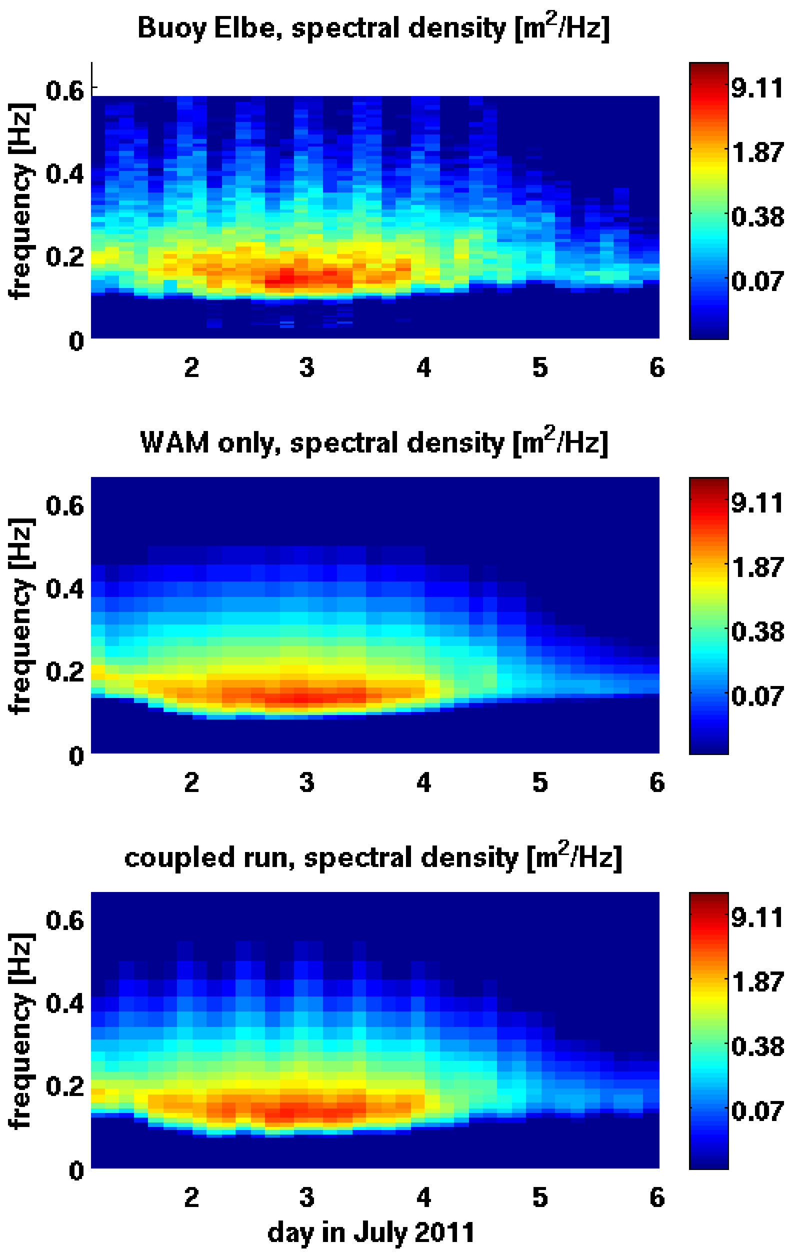

Figure 43. Comparison of measured (top) and computed values of the spectral energy density at the buoy ‘Elbe’, -(see Fig. 1 for its location))).

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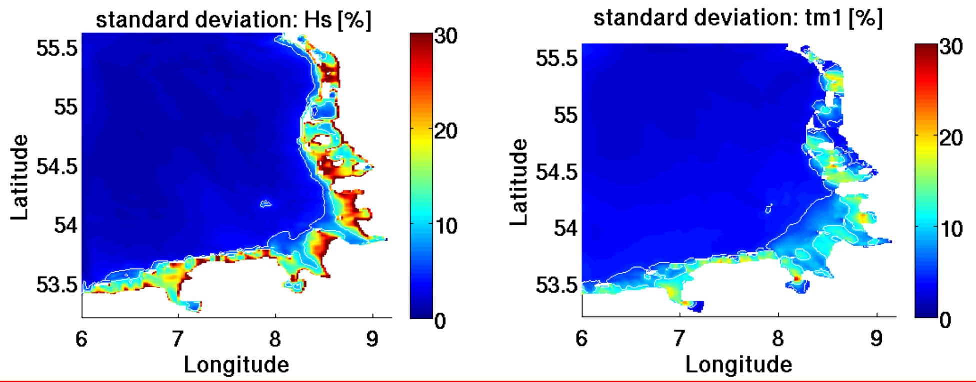

Figure. 4. Impact of hydrodynamics on waves: Normalized standard deviation (estimated as the difference between the control run and the coupled run relative to the control run values) of significant wave height (*Hs*, left) and mean period (*tm1*, right) between coupled wave-circulation model and wave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

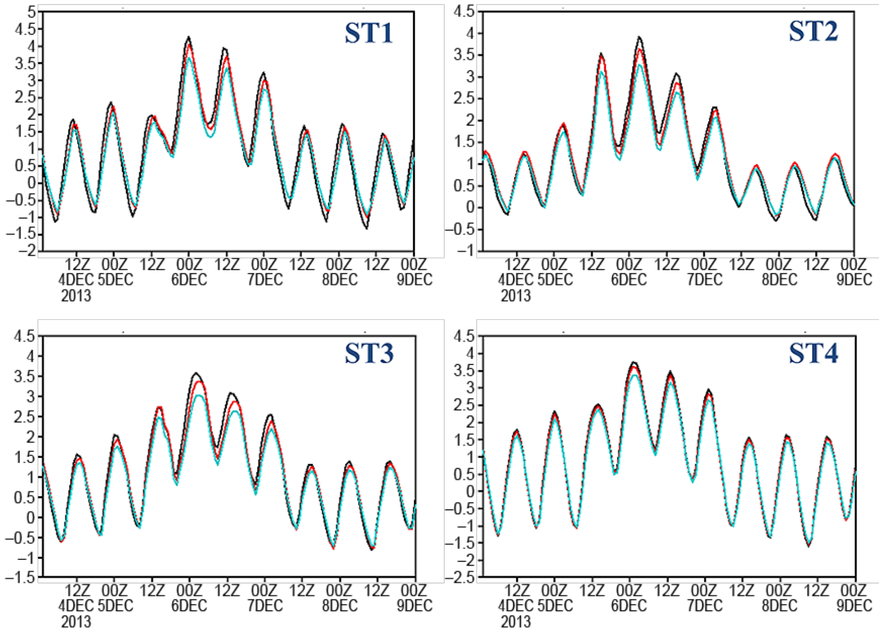

Figure 5: Time series of Sea Level Elevation (SLE) in [m] at four coastal stations of the German Bight (ST1-ST4, see Fig. 1 for the locations). Black line: tide gauge observations, red line: coupled wave-circulation model (WAM-GETM) and green line only circulation model (GETM).

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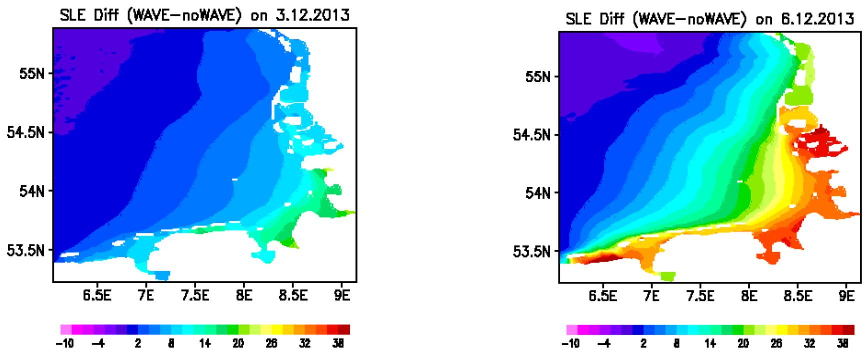

Figure 6: Sea level elevation (SLE) difference [cm] between coupled wave-circulation model (WAM-GETM) and ~~only~~ circulation only model (GETM)- for the German Bight on 03.12.2013 01:00 UTC (left) and during the storm Xavier on 06.12.2013, 01:00 UTC.

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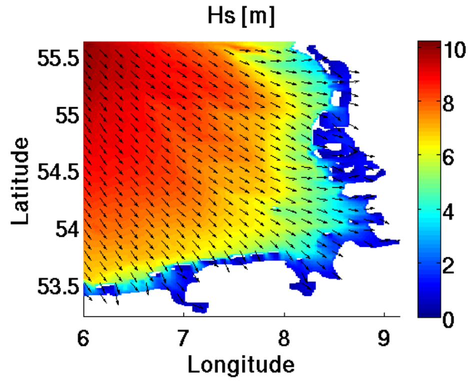
(a)



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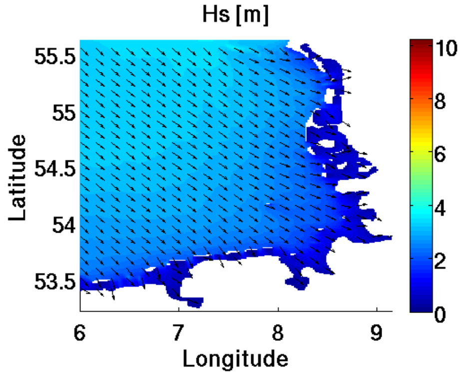

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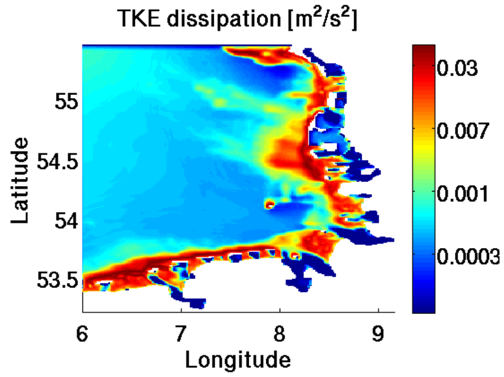

(d)

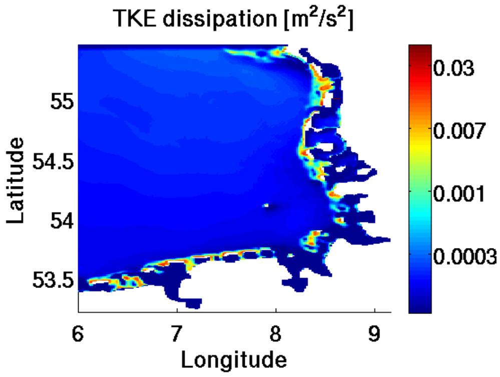

Figure7. (a) Significant wave height [m] in the German Bight during the peak of storm Britta on 01.11.2006 03:00 UTC (b) (a) Significant wave height [m] in the German Bight during normal meteorological conditions on 03.11.2006 03:00 UTC (c) TKE distribution in the German Bight during storm Britta on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

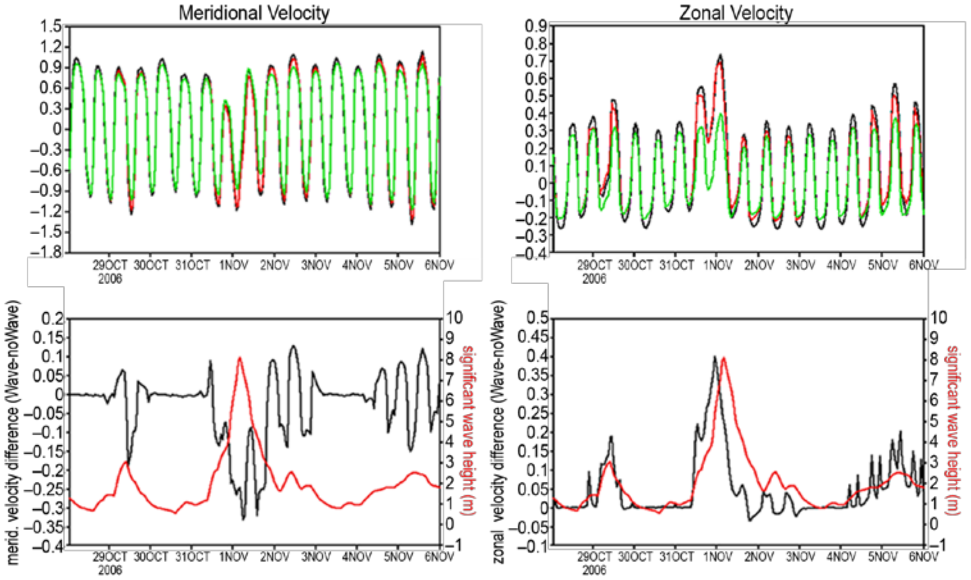

Figure 8: Top: Meridional (left) and zonal (right) velocity time series [m/s] on station W1 (see Fig. 1 for its location) from measurements (black line), coupled wave-circulation model (red line) and ~~hydrodynamical~~ hydrodynamic only model ~~only~~ (green line) during storm Britta. Bottom: Differences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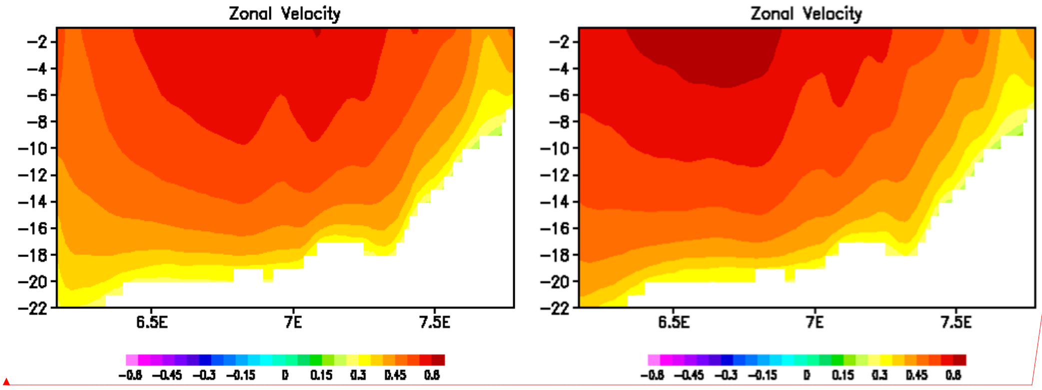

Figure 9: Zonal velocity vertical section [m/s] during Britta on 01.11.2006 03:00 UTC ~~-~~(the location of the section is shown on Fig. 1)~~-~~ from the ~~hydrodynamical~~hydrodynamic only model ~~only~~ (left) and coupled model (right).

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