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Recent Advances in Wave Modelling for the North Sea and German Bight

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Joanna Staneva, Arno Behrens and Nikolaus Groll

Summary

The ocean wave modelling has shown impressive developments, both on the theoretical aspects as in the quality of the results available to users. The state-of-the-art development of the WAM wave model for forecasts applications at operational services and for hindcasts and climate assessments for the North Sea and the German Bight is presented here. The ocean waves control the exchange of energy, momentum, heat, moisture, gas, etc. between the ocean and the atmosphere in the earth system. The impact of waves on currents and water levels in coastal areas is demonstrated. Therefore first steps towards a fully coupled atmosphere-wave-ocean model have been carried out. The synergy between wave observations and models for the North Sea and German Bight is increased on the road to improving the ocean state estimate and predictions in the coastal areas and generating up-to-date information, products and knowledge. Sea state reconstructions and climate scenarios computations with the WAM model have created a huge interest to use the data in industrial applications.

Keywords

wave modelling, coastal ocean forecasting, wave climate reconstructions, wave climate scenarios, wave-circulation interaction, North Sea, German Bight

Zusammenfassung

Die Modellierung der Wellen an der Meeresoberfläche ist durch beeindruckende Entwicklungen gekennzeichnet, sowohl vom theoretischen Aspekt her als auch in der Qualität der Resultate, die für die Nutzer zur Verfügung stehen. Der neueste Stand der Technik in der Entwicklung des spektralen Wellenmodells dritter Generation WAM, für Anwendungen in der Vorhersage der operationellen Dienste, für Hindcasts und für Bewertungen des Wellenklimas für die Nordsee und die Deutsche Bucht, wird hier vorgestellt. Die Wellen an der Meeresoberfläche kontrollieren den Austausch von Energie, Impuls, Wärme, Feuchte, Gas usw. zwischen dem Ozean und der Atmosphäre des Erdsystems. Der Einfluss der Wellen auf Strömungen und Wasserstand ist nachgewiesen. Daher sind erste Schritte in Richtung auf ein vollständig gekoppeltes Atmosphären-Wellen-Ozean-Modell unternommen worden. Die Synergie zwischen Wellen-Beobachtungen und Ergebnissen numerischer Modelle für die Nordsee und die Deutsche Bucht ist angestiegen im Zuge der Verbesserungen in der Abschätzung des Zustandes des Ozeans, der Vorhersagen in Küstengewässern und in der Gewinnung von aktuellen Informationen, Produkten und Kenntnissen. Berechnungen zu Rekonstruktionen des Meereszustandes und von Klimaszenarien mit dem WAM Modell haben zu einem großen Interesse geführt, die erzeugten Daten in industriellen Anwendungen zu nutzen.

Schlagwörter

Wellenmodellierung, Vorhersagen im Küstenbereich, Wellenklima-Rekonstruktionen, Wellenklima-Szenarien, Wellen-Zirkulation-Wechselwirkung, Nordsee, Deutsche Bucht

Contents

1 Introduction

The ocean wave modelling has shown impressive developments during the last decades, both on the theoretical aspects as in the quality of the results available to users. The state-of-the-art Wave Model (WAM) for forecasts applications at operational services and for hindcasts and climate assessments is presented with focus on the new advances in the wave model development and applications in the Helmholz-Zentrum Geesthacht (HZG) for the North Sea and German Bight regions.

During the last decade the north European coasts has been affected by severe storms which caused serious damages on the North Sea coastal areas. Additionally, human activities, e.g. offshore wind power plants (BERGENHAGEN et al 2010; BSH 2010), offshore oil industry, coastal recreations urges information about the sea state with a high detail (resolution) in the coastal environment. Predictions of extreme events like storm surges and flooding caused by storms are very important in order to avoid or at least minimize losses and human and material damages. Therefore, reliable wave forecasts and long term statistics of extreme wave conditions are needed for the coastal areas where various human activities are carried out, e.g. coastal securities, harbor activities, offshore wind energy, search and rescue, etc.

For the North Sea and German Bight regions the past and future wave conditions cannot be fully assessed from the analyses of observational data only, which, as it is well known, are sparse in both, time and space. Even more, statistics of long term changes in extreme wave conditions require long and homogenous wave data at high spatial and temporal resolution, which cannot be done based on the available observational records (WEISSE and GÜNTHER 2007). Numerical wave model systems have become the most common tool for producing high quality forecasts and long term hindcast wave data and to analyze trends and capability in severe extreme events (WEISSE and GÜNTHER 2007; GÜNTHER et al. 1998; WASA-Group 1998; GROLL et al. 2014). The climate change can influence the multidecadal wave conditions in the North Sea and thus may lead to the intensification of wave extremes in the future which will increase the risk in the coastal area. Potential changes in the wave climate in the North Sea under different climate scenarios are studied in GROLL et al. 2014, GRABEMANN and WEISSE (2008), DOBERNARD and ROED (2008). High-resolution small scale versions of WAM have been introduced by LUO and SCLAVO (1007) and MONBALIU et al. (2007). MOGHIMI et al (2005) applied the WAM and K-model for the North Sea and German Bight in order to study whether they were able to predict the near-shore wave conditions accurately. BEHRENS and GÜNTHER (2009) evaluated the capability of the wave model to predict extreme events as severe winter storms for the North Sea and Baltic Sea.

The ocean waves control the exchange of energy, momentum, heat, moisture, gas, etc. between the ocean and the atmosphere in the earth system. Understanding these processes is of utmost importance towards fully integrating of the atmosphere-wave-ocean models and their further coupling with biological, morphological, hydrographical systems. This topic reflects the increased interest in operational oceanography on order to reduce prediction errors of state estimates at coastal scales. The uncertainties in most of the presently used models result from the nonlinear feedback between strong tidal currents and wind-waves, which can no longer be ignored, in particular in the coastal zone where its role seems to be dominant. A nested modelling system is used in HZG to producing reliable now- and short-term forecasts of ocean state variables, including wind waves and hydrodynamics .Analysis of observations, as well as the results of numerical simulations are presented in STANEV et al. 2011.

The structure of the paper is as follows. The WAM is described in Section 2. Section 3 describes the short-term pre-operational wave model for the North Sea and German Bight. Results from the multi-decadal regional wave simulations are presented in Section 4. Section 5 covers ocean-current interactions followed finally by concluding remarks.

2 Model Description WAM

WAM is a third generation wave model which solves the wave transport equation explicitly without any presumptions on the shape of the wave spectrum. It represents the physics of the wave evolution in accordance with our knowledge today for the full set of degrees of freedom of a 2D wave spectrum. WAM computes the 2d wave variance spectrum through integration of the transport equation in spherical coordinates:

$$\frac{\partial F}{\partial t}+\left(\cos\phi\right)^{-1}\frac{\partial}{\partial\phi}\left(\dot{\phi}\cos\phi F\right)+\frac{\partial}{\partial\lambda}\left(\dot{\lambda}F\right)+\sigma\frac{\partial}{\partial\sigma}\left(\dot{\sigma}\frac{F}{\sigma}\right)+\frac{\partial}{\partial\theta}\left(\dot{\theta}F\right)=S \quad (1)$$

with

$F\left(\lambda,\phi,\sigma,\theta,t\right)$ wave energy density spectrum

(λ,ϕ) Longitude, Latitude

$\left(\sigma,\theta\right)$ intrinsic frequency, wave direction

$$\begin{aligned}
\dot{\phi} &= \left(c_g\cos\theta+u_{North}\right)/\mathrm{R} \\
\dot{\lambda} &= \left(c_g\sin\theta+u_{East}\right)/\left(\mathrm{R}\cos\phi\right) \\
\dot{\theta} &= c_g\sin\theta\tan\phi/\mathrm{R}+\dot{\theta}_D+\dot{\theta}_C \\
\dot{\sigma} &= \dot{\sigma}_C
\end{aligned} \quad (2)$$

The source functions on the right of the transport equation comprise the contributions of wind input (S_{in}), nonlinear interaction (S_{nl}), dissipation (S_{dis}), bottom friction (S_{bf}) and wave breaking (S_{br}):

$$S = S_{in} + S_{nl} + S_{dis} + S_{bf} + S_{br} \tag{3}$$

The last release of the third generation wave model WAM Cycle 4.5.4 is an update of the WAM Cycle 4 wave model, which is described in KOMEN et al. (1994) and GÜNTHER et al. (1992). The basic physics and numerics are kept in the new release. The source function integration scheme made by HERSBACH and JANSSEN (1999), and the up-dates model (BIDLOT et al. 2005) are incorporated. Other main improvements introduced in WAM Cycle 4.5.4 are technical improvements, which take into account the new possibilities of Fortran 95 and the MPI (**M**essage **P**assing **I**nterface) for parallelization purposes. On request from the user community a number of additional options are added in the model. A big advantage of the new state-of-the-art version WAM Cycle 4.5.4 is its high-grade modular composition which allows an easy replacement of individual parts of the code.

3 Short-term pre-operational wave model for the North Sea and German Bight

Within the framework of COSYNA a pre-operational wave forecast system has successfully been implemented at HZG and is running continuously since December 2009. It provides 24 hour wave forecasts twice a day and makes the results available in the web under http://www.coastlab.org. The system includes a regional WAM model for the North Sea (spatial resolution: $\Delta\varphi * \Delta\lambda = 0.05° * 0.08333° \sim 5$ km) and a finer meshed local model for the German Bight ($\Delta\varphi * \Delta\lambda = 0.00928° * 0.015534° \sim 900$ m). The driving wind fields for both are provided by the German Met Service (DWD: Deutscher Wetterdienst), computed as U10-fields by the atmospheric model COSMO_EU. The model area of the COSMO_EU is shown in Fig. 1 (upper left). It provides forecast results for 78 hours with a spatial resolution of about 7 km.

The required boundary information used 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. The depth distribution in the model grid for EWAM is given in Fig. 1 (upper right). The local model for the German Bight receives its boundary values from the North Sea wave model. The model grids and the depth distributions (Fig. 1, North Sea on the lower left and German Bight on the lower right side) for the two wave models correspond to those used in the setup for the GETM circulation model in order to simplify the coupling of both for the German Bight. The complete setup of the pre-operational COSYNA forecast system is concentrated in Fig. 1.

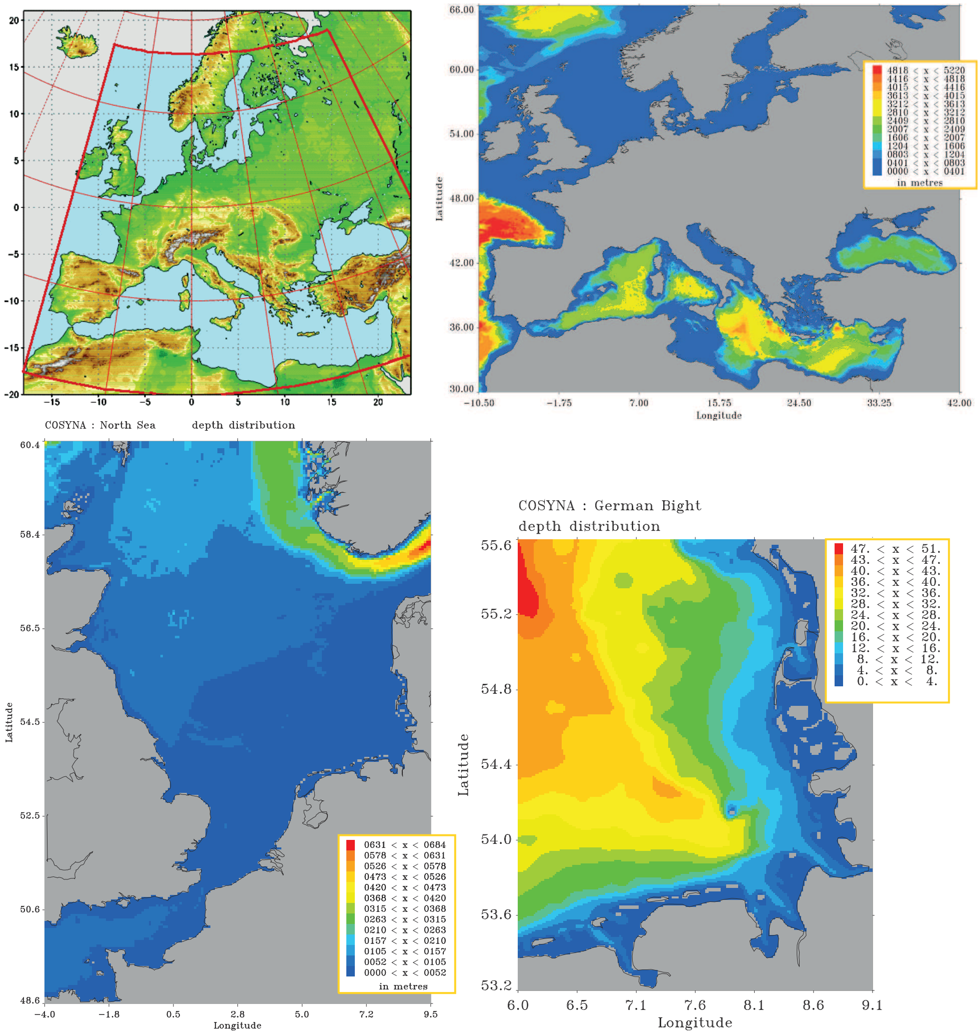

Figure 1: Setup of the pre-operational COSYNA wave forecast system for North Sea and German Bight. Driving wind fields are provided by the COSMO_EU model (upper left, the red line denotes the location of the EWAM in COSMO_EU), boundary values by the regional European wave model EWAM (upper right: EWAM depth distribution). Depth distribution of the model for the North Sea (lower left) and for the German Bight (lower right).

The wave models run in shallow water mode including depth refraction and wave breaking and calculate the two dimensional energy density spectrum at the active model grid points in the frequency-/direction space. The solution of the WAM transport equation is provided for 24 directional bands at 15° each with the first direction being 7.5° measured clockwise with respect to true north and 30 frequencies logarithmically spaced from 0.042 Hz to 0.66 Hz at intervals of $\Delta f/f = 0{,}1$.

Fig. 2 shows an example of the horizontal distribution of the significant wave height in the the North Sea and in the nest for the German Bight on the 15th of February 2012 at 06 UTC with significant wave heights up to 6.8 m.

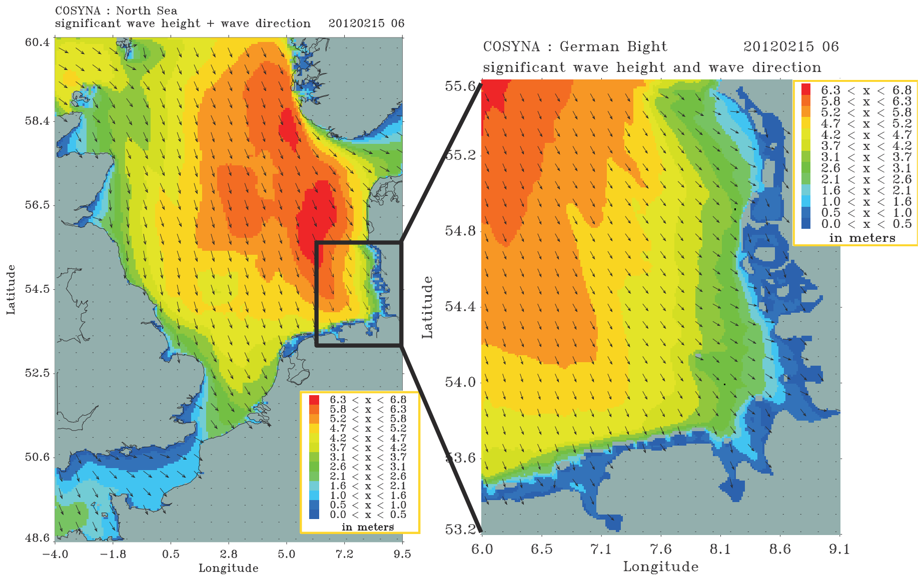

Figure 2: COSYNA wave forecast system for North Sea (left) and German Bight (right).

The results of both wave models include the full two dimensional spectral information and 29 integrated parameters which are included in Tab. 1. The latter are saved 3-hourly at each of the active model grid points and the spectral information is saved every 12 hours (restart file for the next forecast).

Table 1: Integrated parameters of the wave model output.

Parameter No.	Parameter	Dimension
1	Wind speed U10	m/s
2	Wind direction	Degree from North (towards)
3	Friction velocity	m/s
4	Drag coefficient	
5	Water depth	m
6	Current speed	m/s
7	Current direction	Degree from North (towards)
8	Dummy	
9	Significant wave height	m
10	Wave peak period	s
11	Wave mean period	s
12	Wave Tm1 period	s
13	Wave Tm2 period	s
14	Wave direction	Degree from North (towards)
15	Directional spread	Degree
16	Normalized wave stress	%

Parameter No.	Parameter	Dimension
17	Sea significant wave height	m
18	Sea peak period	s
19	Sea mean period	s
20	Sea Tm1 period	s
21	Sea Tm2 period	s
22	Sea direction	Degree from North (towards)
23	Sea directional spread	Degree
24	Dummy	
25	Swell significant wave height	m
26	Swell peak period	s
27	Swell mean period	s
28	Swell Tm1 period	s
29	Swell Tm2 period	s
30	Swell direction	Degree from North (towards)
31	Swell directional spread	Degree
32	Dummy	

The wave model results (integrated parameters) are validated against buoy data available in the area of the model grids. As a representative example the time series of the measured and computed significant wave heights H_s at two locations in the model grid for the North Sea for December 2010 is demonstrated at Fig. 3. The agreement between measured and modelled values is fairly well. Here we have to take into account that the measurements are compared with wave model forecasts: the first 12 hours of each forecast have been used, respectively. The measurements for validation of the North Sea model results are obtained from the GTS (Global Telecommunications System) net that provides continuously wind and wave data worldwide. The wave model simulations of the fine resolution German Bight set-up have been validated with measurements recorded by the buoys of the BSH (Bundesamt für Seeschifffahrt und Hydrographie, Hamburg) and by the buoys of the HZG. The main focus of attention in the COSYNA project is directed on the conditions in the German Bight, therefore the discussion of the comparisons between the wave model results with measurements will be more detailed for that area. Fig. 4 indicates the buoy locations in the German Bight where wave measurements are available.

As representative examples for the validation of the wave model results in the German Bight some comparisons with measurements will be discussed for October 2013. In the end of that month the severe storm Christian afflicted the coasts of Germany with high wind speeds above 30 m/s and significant wave heights of about 8 m. Time series of wind and wave heights at FINO station are given on Fig. 5. At 28th of October during storm Christian the wind speed increases rapidly to 30 m/s causing brake down of several buoys and making impossible to provide measurements for this extreme event.

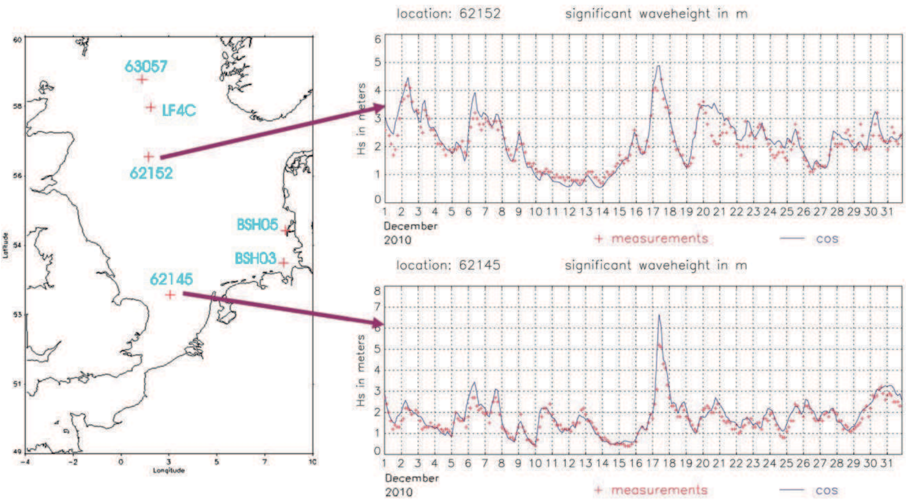

Figure 3: Time series of H_s for two locations in the North Sea model grid.

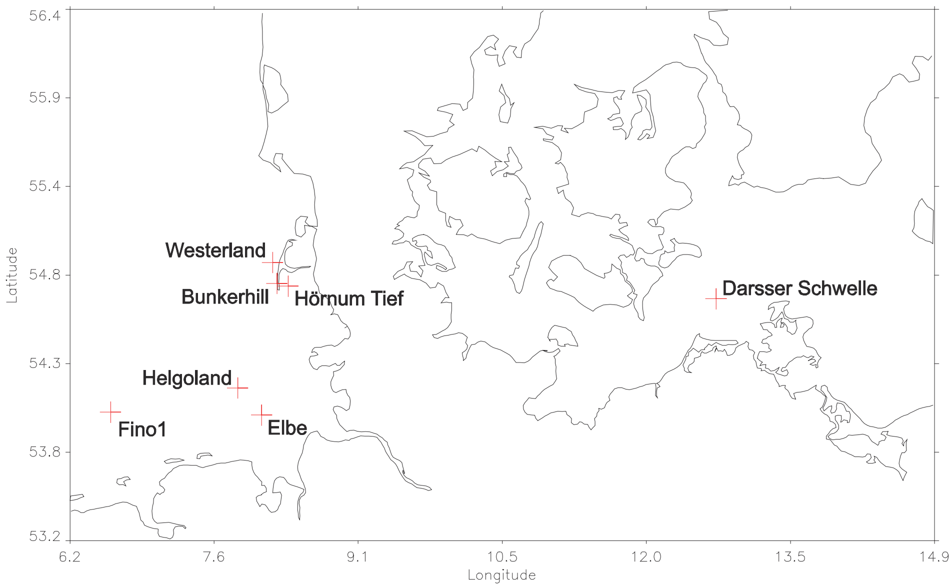

Figure 4: Buoy locations with measurements.

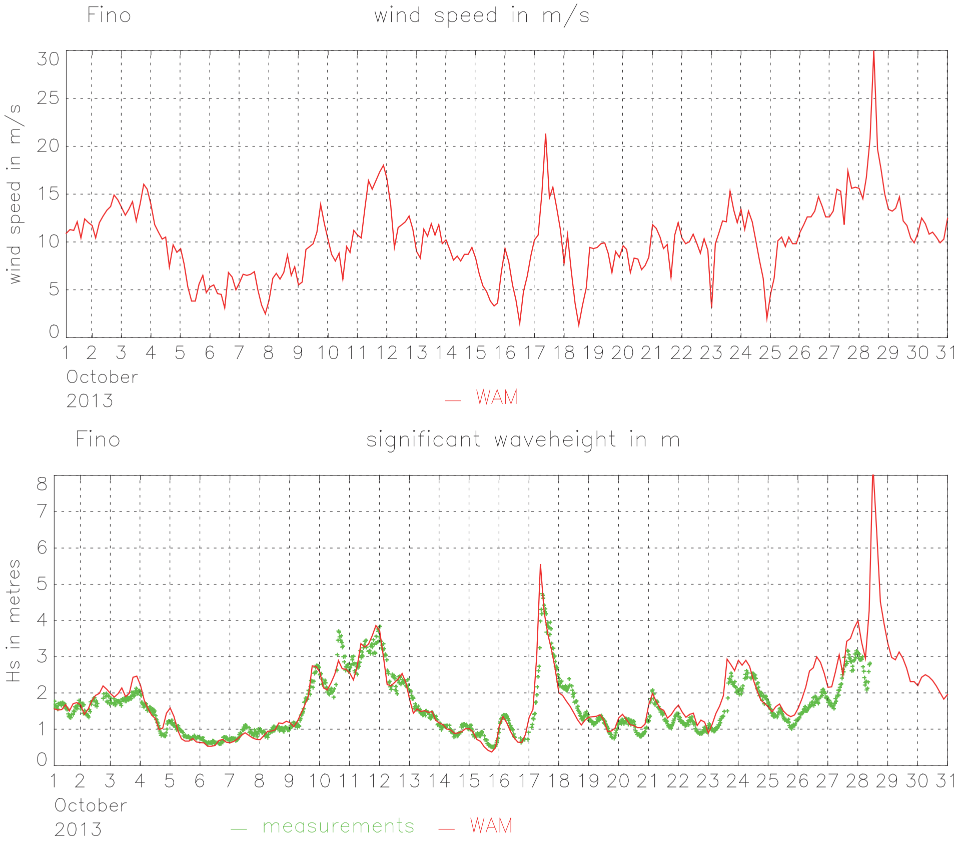

Figure 5: Time series of wind and wave heights at FINO station (storm Christian).

At Elbe and Helgoland stations (see Fig. 4 for their coordinates) the wave heights were lower than the ones at FINO station during Christian and they continuously recorded the wave parameters during the storm event. Fig. 6 includes the corresponding comparisons for significant wave heights, Tm_2/T_z-periods and total wave directions at the location Elbe. The agreement between measured and modeled wave parameters is very good. The peak on the 28th of October (3 pm UTC) in H_s of about 6 m and in Tm_2 of about 8 s is well predicted by the wave model.

The same is valid for the comparisons done at Helgoland station despite the small underestimation at the peak by the model. The measured peak is higher here (7.7 m) compared with the Elbe station peak. The statistical analysis of the comparisons (see Tab. 2) supports the good quality of the pre-operational wave forecasts for the German Bight area.

Figure 6: Time series of measured and computed wave parameters at the location Elbe.

Figure 7: Time series of measured and computed wave parameters at the location Helgoland.

Table 2: H_s statistics for October 2013 at buoys located in the German Bight.

buoy	number of comparisons	mean of measurements	bias	root mean square error	skill	scatter index
H_s	-	(m)	(m)	(m)	-	(%)
Fino	218	1.59	0.11	0.33	0.86	19
Elbe	247	1.23	0.08	0.31	0.84	25
Westerland	247	1.17	0.14	0.28	0.88	21
Helgoland	247	1.45	-0.03	0.30	0.90	20
Tm_2/T_z		(s)	(s)	(s)		
Fino	218	4.53	-0.15	0.50	0.74	11
Elbe	247	3.92	-0.23	0.52	0.71	12
Westerland	247	4.07	-0.12	0.74	0.74	18
Helgoland	247	4.27	-0.11	0.52	0.80	12
skill : reduction of variance, scatter index : standard deviation*100/mean of the measurements						

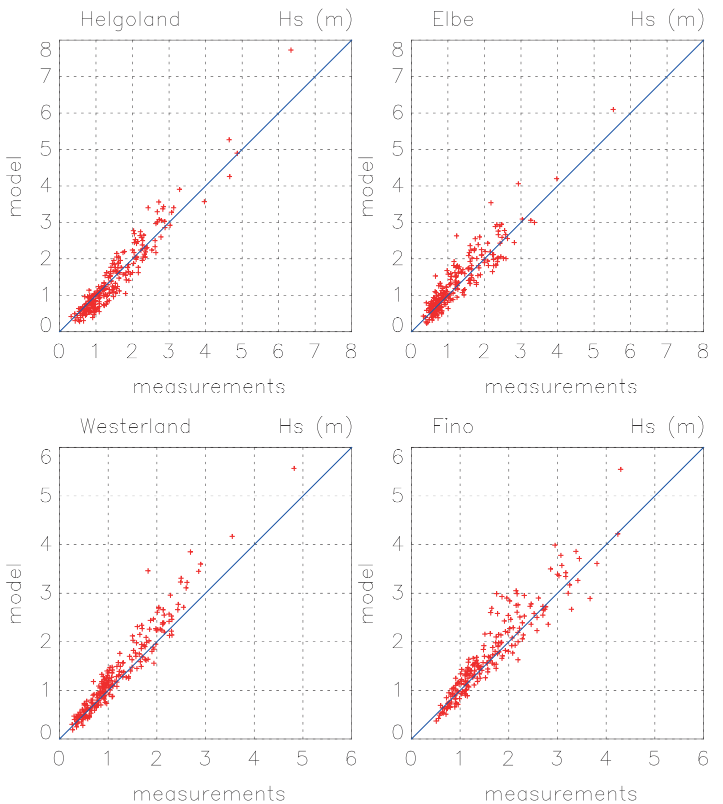

Figure 8: Scatterplots for measured and computed wave heights for October 2013.

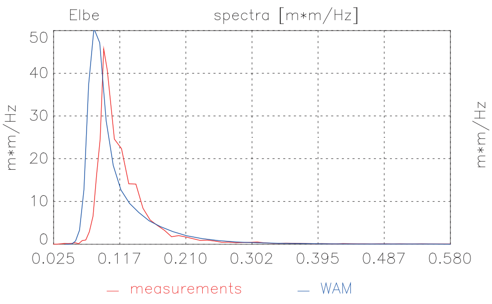

Figure 9: Comparison of measured and computed one-dimensional wave spectra at location Elbe (left) at the peak of storm Christian on 20131028 15:27 UTC (model results: 15:00 UTC) and at location Helgoland (right) at an intermediate peak on 20131017 11:46 UTC (model results: 12:00 UTC).

4 Multi-decadal regional wave simulations

Within coastDat (http://www.coastdat.de/) multi-decadal wave hindcasts and scenarios are provided as part of consistent meteo-marine reanalyses and scenarios. The objectives are to provide an assessment of ongoing and potential future changes in wave climate and to aid the development of adaptation options. Data from wave hindcasts are an essential part of the coastDat data base (WEISSE et al. 2009) that is used by more than 60 external partners from industry, administration and research. See Tab. 3 for which wave data is available within coastDat, the available wave parameters are given in Tab. 1.

Table 3: CoastDat wave datasets.

data set	**time period**	**forcing**	**reference**
Hindcast run-coasDat1	1958-2007	NCEP/NCAR Reanalyse	WEISSE and GÜNTHER (2007)
Hindcast run-coastDat2	1948-today	NCEP/NCAR Reanalyse	in progress
Scenario run-coastDat1	1961-1990/ 2071-2100	2x A2; 2x B2	GRABEMANN and WEISSE (2007)
Scenario run–coastDat2	1961-2100	4xA1B; 2x B1	GROLL et al. (2014); GRABEMANN et al. (2014)

The WAM model is used with nested grids for the North Sea for both hindcasts and future scenario simulations. The coarse grid covering the North East Atlantic takes into account for swell entering the North Sea, with about 50 km x 50 km spatial resolution. The fine grid simulations are using the spectral wave informations from the coarser model and has a resolution of about 5.5 km x 5.5 km. The hindcast simulations (WEISSE and GÜNTHER 2007) are driven by wind fields at 10 m height from the NCEP/NCAR global reanalyses regionalized by a regional climate model (FESER et al. 2005). The future scenario simulations are calculated by different combinations of GCMs, RCMs and emission scenarios (GRABEMANN and WEISSE 2008; GROLL et al. 2014 and GRABEMANN et al. 2014).

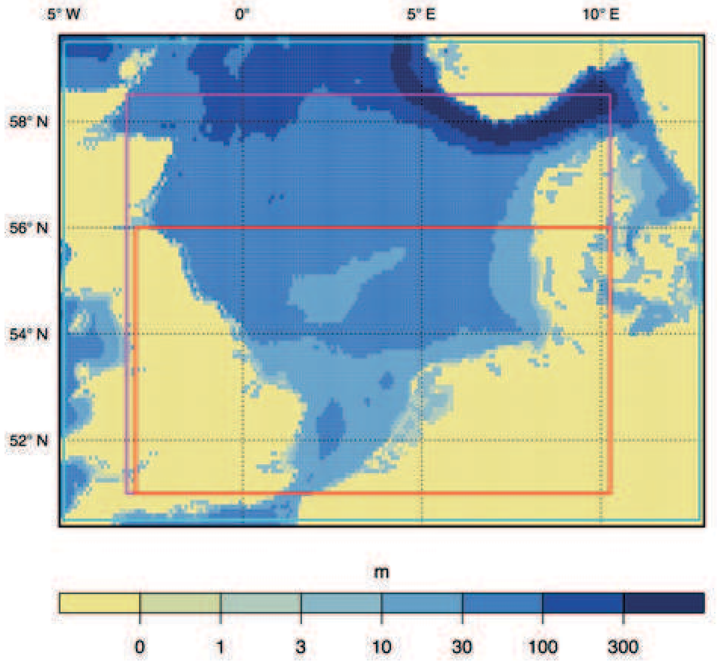

Figure 10: Simulated domains for the North Sea. Red box showing the domain in WEISSE and GÜNTHER (2007), the magenta box shows the domain for the cliamte change scenario simulations (GRABEMANN and WEISSE 2007; GROLL et al. 2014; GRABEMANN et al. 2014). The cyan box shows the new updated hindcast which is in progress and will be available soon.

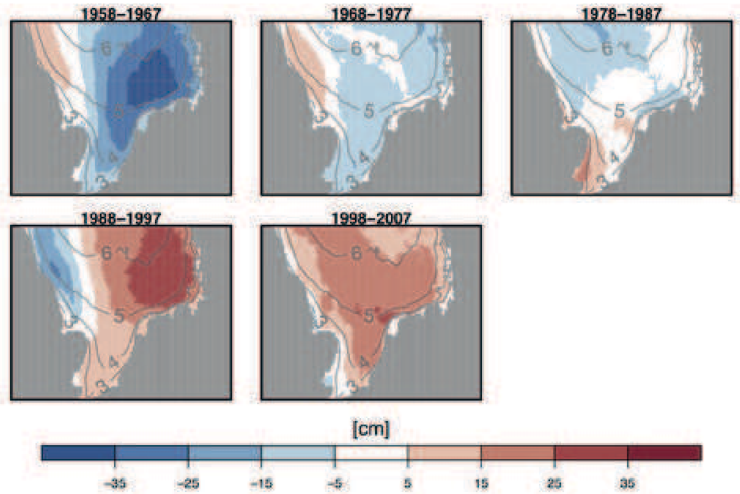

Figure 11: Difference of the 10-year-mean annual 99 %tile of significant wave height relative to the long-term-mean 1958-2007 (shown by contour lines) in the hindcast simulations (see WEISSE and GÜNTHER 2007).

To investigate long term changes of the waves parameters it is important to provide a database as much consistent as possible. This however is difficult to be done on the information based on observational data only. Using wave model simulations, one can minimize the effects of inhomogeneity caused by changes in instrumentation or measurement techniques.

Using WAM simulations Weisse and Günther (2007) studied the decadal variability of the wave parameters for the North Sea during the last decades. The differences of the ten-year-mean annual 99 percentile significant wave height of five periods relative to the long-term-mean 1958-2007 are demonstrated at Fig. 11. The results show an increase of the significant wave height towards the end of the 20th century, but also a weaker tendency to increase in the last ten years for the German Bight. In the newly available wave model hindcast, (work in progress), which will cover a longer period and the whole North Sea it will be possible to further investigate the wave climate variability in the North Sea region.

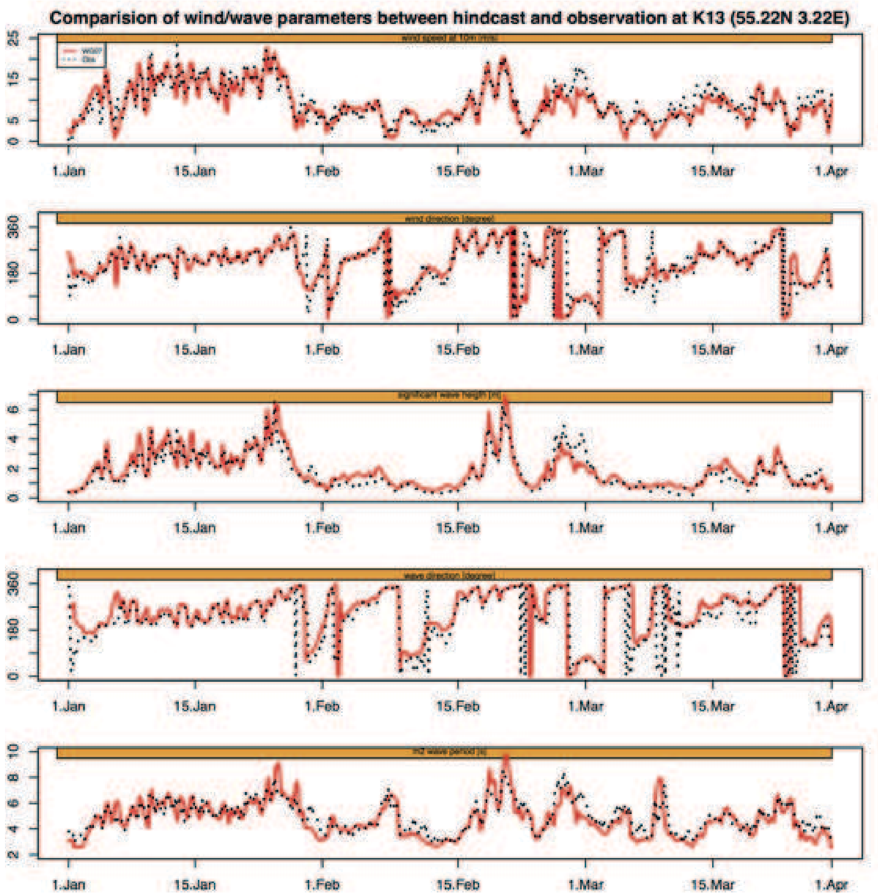

Figure 12. Time series of wind speed (m/s), wind directions (degrees, going to), significant wave height (m), wave direction (degrees, going to) and m2 (s) wave period at K13 for a 3-month period from 1 Jan 1993 to 31 Mar 1993. Observations (dotted black) and model results (red) (see WEISSE and GÜNTHER 2007).

Table 4: Set of ten climate change wave projections calculated within the framework of coastDat (see GRABEMANN et al. 2014).

acronym	time period	forced by RCM	forced by GCM	references
C20_1C A1B_1C B1_1C C20_2C A1B_2C B1_2C	1961-2000 2001-2100 2001-2100 1961-2000 2001-2100 2001-2100	COSMO-CLM ROCKEL et al. (2008)	ECAHM5/MPI-OM RÖCKNER et al. (2003) MARSLAND et al. (2003) with two initial conditions	GROLL et al. (2014) GRABEMANN et al. (2014)
C20_3R A1B_3R C20_3H A1B_3H	1961-2000 2001-2100 1961-2000 2001-2099	REMO JACOB at al. (2007) HIRHAM CHRISTENSEN et al. (2007)	ECAHM5/MPI-OM RÖCKNER et al. (2003) MARSLAND et al. (2003) with the third initial conditions	GRABEMANN et al. (2014)
C_E A2_E B2_E C_H A2_H B2_H	1961-1990 2071-2100 2071-2100 1961-1990 2071-2100 2071-2100	RCAO RUMMUKAINEN et al. (2001) RÄISÄNEN et al. (2004)	ECHAM4/OPYC3 RÖCKNER et al. (1999) HadAM3H GORDON et al. (2000)	GRABMANN and WEISSE (2007) GRABEMANN et al. (2014)

Validation of the hindcast simulations with wave observations at the platform K13 for a three month period in 1993 is demonstrated on Fig. 12. Beside some differences the hindcast simulations show a relatively good agreement with observations. A comparison of the 3-hourly significant wave height observations at the platform K13 and the results from the hindcast simulation or the period 1980-2000 is given in Fig. 13. For mean conditions a relatively good agreement can be found, whereas the higher waves show a small overestimation by the numerical simulations.

Within the framework of coastDat several wave studies with climate change scenarios have been compiled. GRABEMANN and WEISSE (2007) calculating time slice experiments for the period 2071 to 2100 and the reference period 1961-1990 with two emission scenarios (A2 and B2) and two different GCMs and one RCM. GROLL et al. (2014) were calculating transient simulations (1961-2100) with one GCM but with different initial conditions and two emission scenarios (A1B and B1) and with one RCM (CCLM). GRABEMANN et al. (2014) compared and discussed these eight wave experiment together with two wave simulations, using one GCM, one emission scenario (A1B) but different RCMs. See Tab. 4 for more details.

The difference of the 30-year-mean annual 99.9 percentile significant wave height between the period 2071-2100 and the corresponding reference climate 1961-1990 for these ten climate change simulations is shown in Fig. 14. Focusing at the German Bight all ten simulations show an increase towards the end of the 21th century, but the magnitude of the increase is much more uncertain and vary between almost zero and up to one meter. Also in other parts of the North Sea the spatial variability between the ten simulations is evident. Generally an increase in the eastern part of the North Sea can found, whereas in the western parts the changes are less strong and even a decrease in some of the simulations can be found. Analysis of the six transient simulations show also an strong multi-decadel variability throughout the whole simulation period and point to the internal climate variability of the climate system (GROLL et al. 2014 and GRABEMANN et al. 2014).

The data generated within the framework of coastDat delivers a long, consistent and homogenous as possible description of the North Sea wave climate, which is important to investigate and understand the climate variability in data sparse regions, like the North Sea. Wave data that are generated within these climate change and hindcast simulations are available to external clients and are used for a variety of offshore and coastal purposes. For instance during the planning and design phase of offshore wind farms wave data from the hindcast are used to calculate return values of extreme events and to estimate time windows for certain wave conditions that are necessary for construction and maintenance. The wave data is also used by ship yard companies to optimize the ship profiles. For details see WEISSE et al. (2009). Beside a regular update of the hindcast simulation, in the future, simulations with higher resolution, which is important for near-coastal applications are planned.

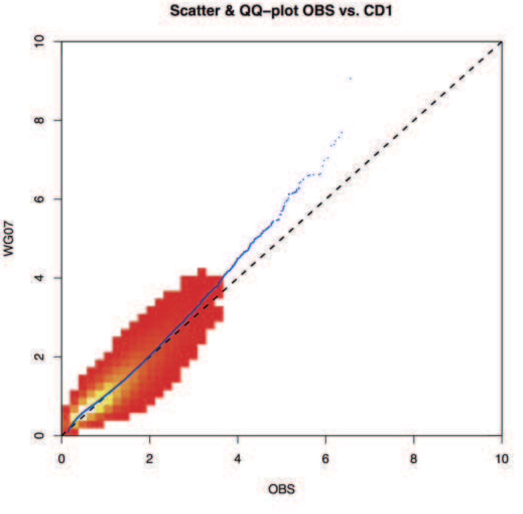

Figure 13: Scatter of 3 hourly significant wave height for the period 1980-2000 between observations at platform K13 and simulated data from the hindcast (WEISSE and GÜNTHER 2007). Blue dots showing the quantile-quantile plot for tenth percentiles wave height (0,0.1,0.2,.....99.8,99.9,100).

Not only wave climate simulations are part of the coastDat framework and are used by clients, but also other important marine climate variables, e.g. marine surface wind, water level, are considered, for more information see www.coastdat.de.

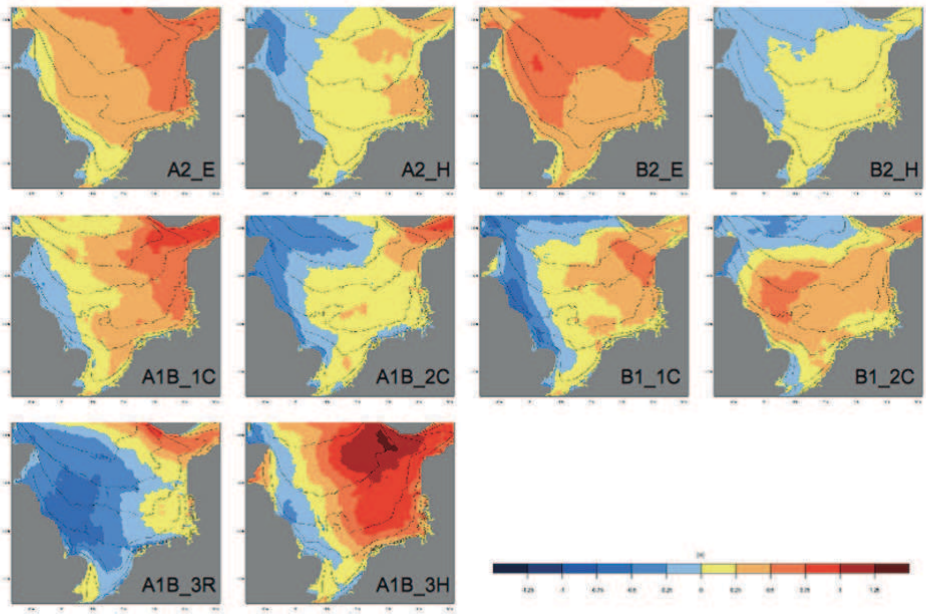

Figure 14: Differences of the 30-year mean of annual 99.9 percentile significant wave height in meters for the period 2071-2100 relative to 1961-1990 for each of the 10 projections. Black contour lines indicate the 30-year mean of annual 99.9 percentile significant wave height in meters for the corresponding reference period (see GRABEMANN et al. 2014).

5 Wave-current interaction

The role of the coupling of wave and circulation models on improving the ocean forecast is demonstrated for the German Bight region. The German Bight (southern North Sea) is characterized by wind-waves and strong tidal currents. As a result, processes like nonlinear feedback between currents and waves play an important role in this area. The coupling between the wave model (WAM) and hydrodynamical model (GETM, BURCHARD et al. 2002) improves the estimates of ocean state variables, especially in coastal areas like the Wadden Sea and estuaries (for more details about the model configuration see STANEVA et al. 2009). The coupling takes into consideration both: the effect of currents on waves and the effects of waves on upper ocean dynamics, in particular on mixing and drift currents. In WAM the depth and/or current fields can be non-stationary, grid points can fall dry and refraction due to spatially varying current and depth is accounted for in the quasi-stationary approach. GETM was modified to account for wave effects by introducing the depth dependent radiation stresses and Stokes drift. The terms were calculated from the integrated wave parameters according to MELLOR (2008). The gradient of the radiation stresses serves as an additional explicit wave forcing term in the momentum equations for the horizontal velocity components. The transfer of momentum by waves becomes important for the mean water level setup and for the alongshore currents generated by waves in the surf zone.

We demonstrate the role on coupling by analyzing the impact of waves on extreme events (storm on 06.12.2013, see Fig. 15). The radiation stress increases the average water levels, which is much pronounced in the coastal area. During normal conditions the differences of the sea level due to the coupling with wave model maximum 10-15 cm in the Elbe area. However, during the storm Xaver on 06.12.2013 (left), the differences of simulated sea level when considering waves are about 30-40 cm along the whole German coast. Therefore the uncertainties in most of the presently used models result from the nonlinear feedback between strong tidal currents and wind-waves, which can no longer be ignored in the operational oceanography, in particular in the coastal zone where its role seems to be dominant.

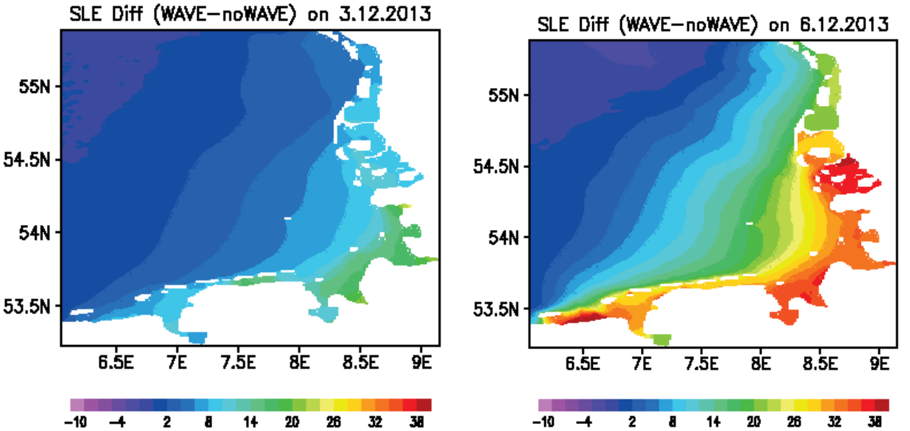

Figure 15: Sea surface elevation (SLE) difference between coupled wave-circulation model (WAM-GETM) and only circulation model (GETM) for the German Bight at 03.12.2013 (left) and during the storm Xaver on 06.12.2013.

6 Conclusions

Wave hindcasts and forecasts 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 impacts on the on the coastal and marine environment. The population living in the coastal areas is recently concerned with the impacts of erosion and flooding, and activities of what can be done to predict and further to minimize them. Important driving forces that cause serous damages on coastal environment are the wave conditions. Latter can be determined by using as a tool coastal numerical wave model systems. In this paper we summarized the recent advances in the field of wave modelling for the North Sea and German Bight regions. The state-of-the-art development of the WAM wave model for forecasts applications at operational services and for hindcasts and climate assessments for the North Sea and the German Bight in HZG is demonstrated. The synergy between observations and models for the North Sea and German Bight is increased on the road to improving the ocean state estimate and predictions in the coastal areas and generating up-to-date information, products and knowledge. The very good agreement between observations and model simulations is being demonstrated for both the long term wave hindcasts and short term wave forecasts for the North Sea and German Bight area. It enables to provide reliable predictions as well as to analyze long term changes of wave conditions, including extreme events. The performance of the forecasting system is illustrated for the cases of several extreme events. Effects of ocean waves on coastal circulation are investigated during extreme events, as well. The improved skill resulting from the recent wave model developments, in particular during storms, justifies further enhancements of the both forecasts applications at operational services and long-term hindcasts and climate for the North Sea and the German Bight.

Short-term wave forecasts, sea state reconstructions and climate scenarios computations with the WAM model have created a huge interest to use the data in industrial applications. Within CoastDat multi-decadal wave hindcasts and scenarios are provided as part of consistent meteorological-marine reanalyses and scenarios aiming to provide an assessment of ongoing and potential future changes in wave climate and to aid the development of adaptation options. The pre-operational COSYNA wave forecast system for the North Sea and the German Bight provides wave forecasts twice a day delivering a number of wave parameters such as wave height, period and direction and is a very good example of how wave modelling products can support coastal management in the context of climate change and human activities. Data from wave forecasts and hindcasts form an essential part of the COSYNA and coastDat data base that are being actively used by partners from industry, administration and research

7 References

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