Wave modelling for the German Bight coastal-ocean predicting system

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Abstract. Ocean wave modeling has shown impressive developments, both in theoretical aspects as in the quality of the results available to users. The recent advances in development of the WAM wave model for forecasts applications at operational services and climate assessments for the North Sea and the German Bight are presented here. 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. This is an important step towards a fully coupled atmosphere-wave-ocean modelling system. 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.

1. Introduction
Ocean wave modeling has shown impressive developments during the last decades, both in 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 for the North Sea and German Bight areas.

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, the human activities, e.g. offshore wind power, 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. 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 [10]. The climate change can influence the multi-decadal wave conditions in the North Sea and thus may lead to the intensification of wave extremes in the future which will increase the risk

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in the coastal area [4]; and the capability of the wave model to predict extreme events as severe winter storms for the North Sea and Baltic Sea has been evaluated in [1].

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-grid modelling system is used to producing reliable now- and short-term forecasts of ocean state variables; including wind waves and hydrodynamics. Analyses of observations, as well as the results of numerical simulations are presented in [8].

The structure of the paper is as follows. The WAM is described in Section 2. Section 3 shows the results from wave model forecasts for the North Sea and German Bight. Section 4 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:

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

with:
\[ \dot{\phi} = \left( c_e \cos \theta + u_{north} \right) / R \]
\[ \dot{\lambda} = \left( c_e \sin \theta + u_{east} \right) / \left( R \cos \phi \right) \]
\[ \dot{\theta} = c_e \sin \theta \tan \phi / R + \dot{\theta}_D + \dot{\theta}_C \]
\[ \sigma = \dot{\sigma}_c \]

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 \( S_{br} \):

\[ S = S_{in} + S_{nl} + S_{dis} + S_{bf} + S_{br} \]

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 [7] and [5]. The basic physics and numeric are kept in the new release. The source function integration scheme made by [6] and the up-dates model [2] are incorporated. 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. The wave model code is freely available under http://mywave.github.io/WAM/.

3. Short-term pre-operational wave model for the North Sea and German Bight
Within the framework of Coastal Observing System for Northern and Arctic Seas (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: \( \Delta \phi \times \Delta \lambda = 0.05^\circ \times 0.08333^\circ \sim 5 \text{ km} \)) and a finer meshed local model for the German Bight (\( \Delta \phi \times \Delta \lambda = 0.00928^\circ \times 0.015534^\circ \sim 900 \text{ m} \)). The driving wind fields for both areas are provided by the German Met Service (DWD: Deutscher Wetterdienst).

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 figure 1 (left panel). The local model for the German Bight receives its boundary values from the North Sea wave model. The model grids and the depth distributions for the North Sea and German Bight COSYNA model areas are given on figure 1, (in the middle and right panels correspondingly).

Figure 1. Setup of the pre-operational COSYNA wave forecast system for North Sea and German Bight. Boundary values by the regional European wave model EWAM (left: EWAM depth distribution). Depth distribution of the model for the North Sea (middle) and for the German Bight (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 Δf/f = 0.1. Figure 2 shows an example of the horizontal distribution of the significant wave height in 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 and German Bight (right)
The wave model simulations of the fine resolution German Bight set-up have been validated with measurements recorded by the buoys within the German Bight area (figure 3 indicates the location of the buoys 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 German coast 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 figure 3. At 28th of October during storm Christian the wind speed increases rapidly to 30 m/s causing break down of several buoys and making impossible to provide measurements for this extreme event. The agreement between measured and modelled values is very good. Here we have to note that the measurements are compared with wave model forecasts: the first 12 hours of each forecast have been used, respectively.

![Figure 3. Buoy locations with measurements in the German Bight](image1)

![Figure 4. Time series of wind and wave heights at FINO station (storm Christian).](image2)

At Elbe station (see figure 4 for their coordinates) the wave heights were lower than the ones at FINO station during storm Christian and the buoy continuously recorded the wave parameters during the storm. Figure 5 includes the corresponding comparisons for significant wave heights, $Tm_2/Tz$-periods and total wave directions at the location Elbe. The agreement between measured and modeled wave parameters indicates that the model is capable in reliable forecasting wind waves. The peak on the 28th of October (3 pm UTC) in $Hs$ of about 6 m and in $Tm_2$ of about 8 s is well predicted by the wave model. The statistical analysis of the comparisons (see table 1) supports the good quality of the wave forecasts for the German Bight area.
Figure 5. Time series of measured and computed wave parameters at the location Elbe

Table 1. $H_s$ 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 |
|-------------|-----------------------|----------------------|------|------------------------|-------|---------------|
| 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            |

skill : reduction of variance, scatter index : standard deviation*100/mean of the measurements

4. 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, which is the General Estuarine Transport Model (GETM, [3]) 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 [9]). 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 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 figure 7). 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 Xavier, 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 7. 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 Xavier at 06.12.2013.

5. 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. 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 COSYNÄ data base that are being actively used by partners from industry, administration and research.
6. References

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