WAVE FORECASTING FOR OFFSHORE WIND FARMS

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1 INTRODUCTION

Marine operations in connection with the construction and maintenance of offshore wind farms require accurate wave forecasts. As offshore wind farms are generally located in shallow coastal area, and often on top of shoals or reefs, the wave forecast model need to consider the local bathymetric features and include all shallow water dynamics, requirements which are not always met by general open sea forecast models.

The forecasting service developed and operated at DHI, “The Water Forecast”, has included wave forecasting since June 2001. In addition to users of open sea wave forecasts (the offshore industry, international ferry operators a.o.), users with operations in shallow waters and coastal waters (like offshore wind farm operators) have also increased.

Driven partly by the need for very accurate shallow water forecasts for offshore wind farms operators, and partly by other user groups, the wave models applied for the forecasting service have been developed and improved since 2001. The paper describes this development of the shallow water wave forecasts for offshore wind farms, a development which the open sea wave forecasts have also benefited from.

2 REQUIREMENTS TO WAVE FORECASTS FOR OFFSHORE WIND FARMS

When placing the different parts of a wind turbine (foundation, tower, generator, and wings) at its offshore location there are strict operating limits to the waves (among other metocean parameters). Limits may apply to wave heights and periods, swell heights and periods, and their relative direction. Furthermore, the transport of the different parts of the wind turbine to their final location requires windows in time of a given length with the sea and/or swell below a given limit. Other restrictions may apply during maintenance. For all of these marine operations accurate wave and swell forecasts are required.

In order to meet these requirements the wave forecast models have been improved from the start in 2001 to date to include:

- a flexible computational mesh with a high resolution in shallow areas and a coarser resolution in open sea areas
- an improvement of the short term (0 to about 24 hours) forecasts using online measurements
- a definition of swell in accordance with user experience

Each of these improvements is described in the following sections.

3 DEVELOPMENT OF WAVE FORECAST MODELS

The wave forecast models within The Water Forecast are all based on WAM Cycle 4 (see Komen et al (1998)). The implementation of WAM at DHI is called MIKE 21 SW. The first model set-up of June 2001 (see Figure 1) used three nested cartesian grid with a resolution varying from 27 nautical for the entire Baltic Sea and North Sea to 9 and 3 nautical miles for the inner parts of the Danish territorial waters. Wind input came from a high resolution meteorological model (ETA) run by the meteorological company Vejr2, Denmark. Initial field and boundary conditions for this model came from the global GFS model run by NCEP, US.

In order to be able to resolve local bathymetric variations (with a resolution of 1-2 km) and at the same time use a coarser resolution in open seas (15-20 km) a second model was set-up, but this time with a flexible computational mesh. This was introduced in May 2002 (see Figure 1). The new model only covered the North Sea and was used for wave forecasting together with the first model set-up.

The third step was taken in December 2004 when a flexible mesh model (see Sørensen et al (2004)) covering the North Sea and the Baltic was introduced (see Figure 1). Additionally, boundary conditions at the open boundaries of the wave forecast model to the North and to the West were extracted from the

North Atlantic wave forecast model also running within The Water Forecast. The model bathymetries for the two forecast models are shown in Figure 2. Also shown in Figure 2 is a zoom-in on the Horns Rev area on the Danish West coast. This was the first area, for which wave forecasts were provided for an offshore wind farm, starting with the second model set-up in May 2002.

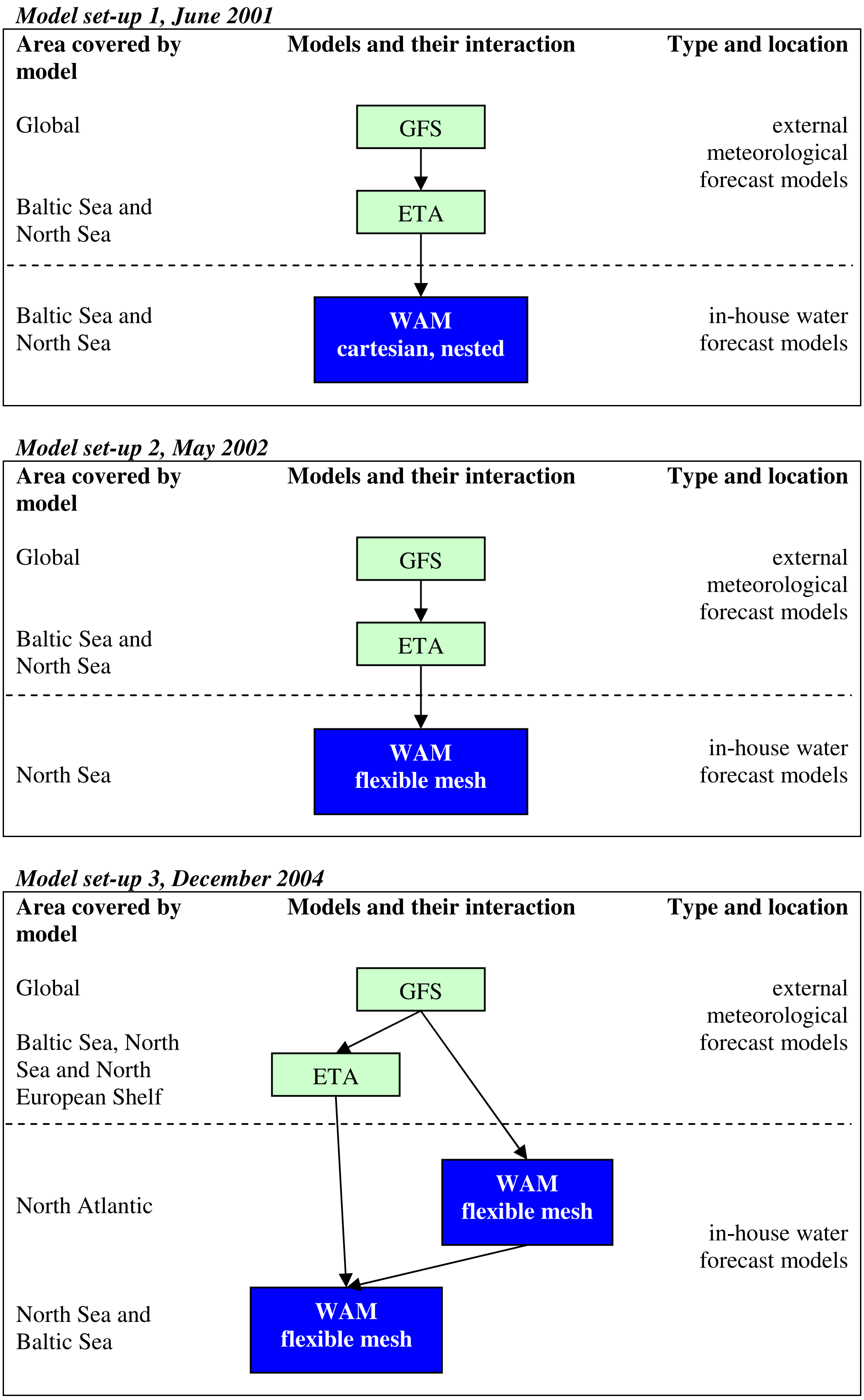


Figure 1 Interaction between meteorological models and water forecast models

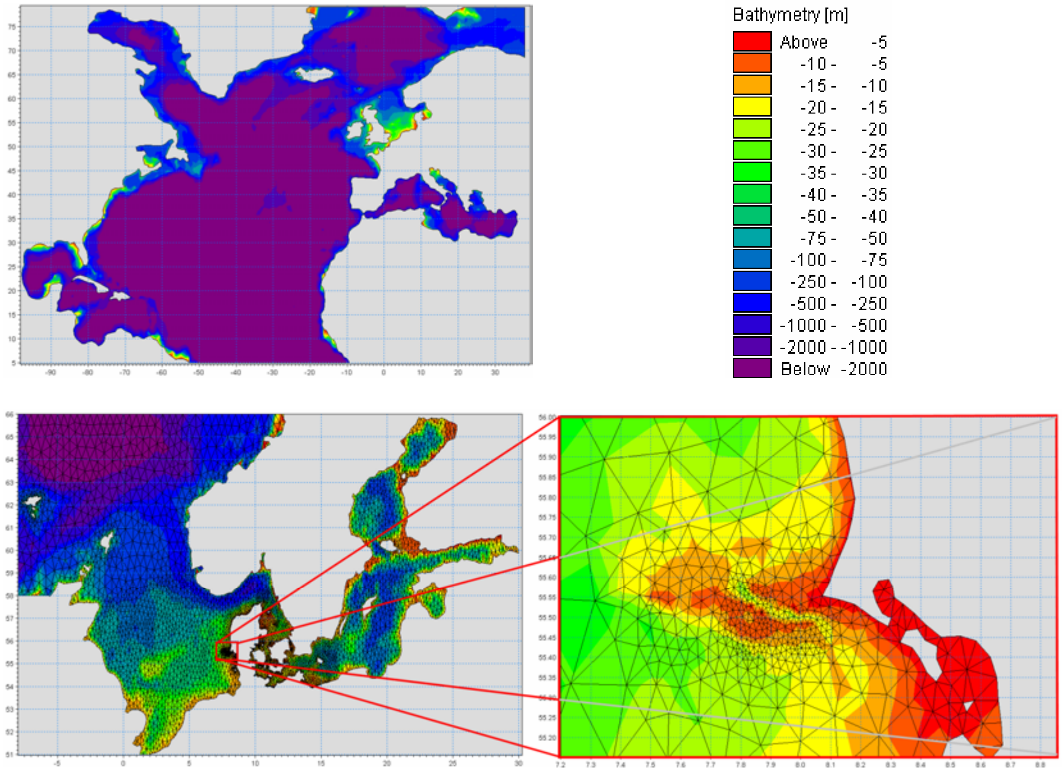


Figure 2 North Atlantic wave model area (top) and model area for North Sea and Baltic Sea with zoom-in on Horns Rev area showing flexible mesh elements (bottom).

The last step so far was taken in July 2006 with the extension of the wave model area to include the North European shelf and at the same time include the effects of varying water level. The forecast water levels were provided from a 3-dimentional hydrodynamic model (a part of The Water Forecast) covering the European Shelf area and the Eastern part of the North Atlantic (see Figure 1 and 3).

Model set-up 4, July 2006

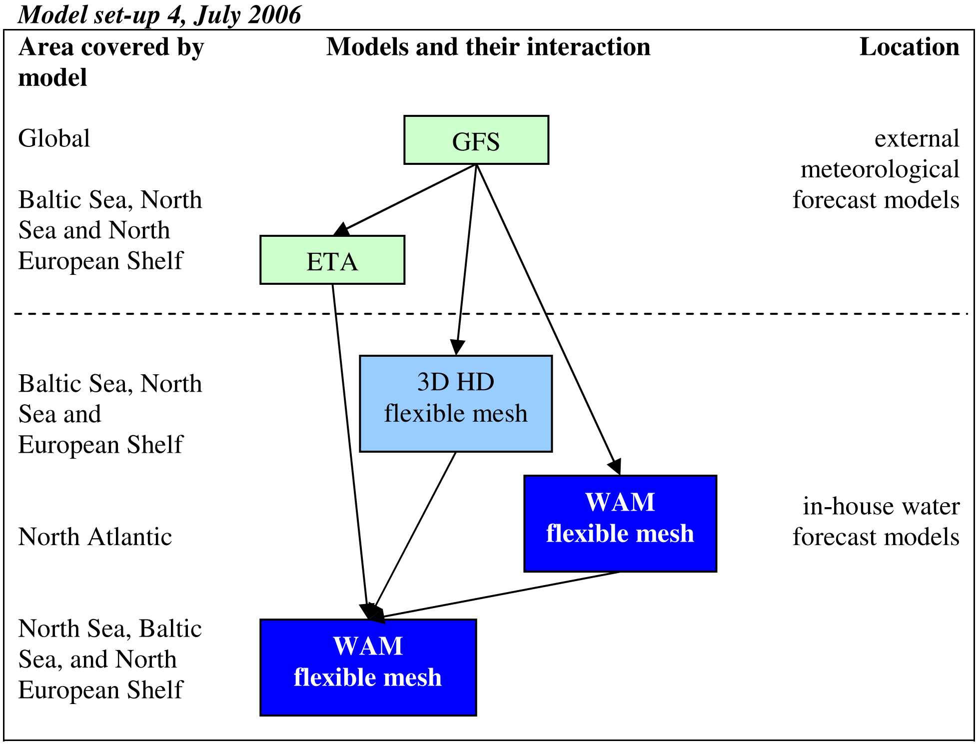


Figure 3 Interaction between meteorological models and water forecast models

In Figure 4 the model areas of the applied models are depicted together with a zoom-in on the Irish Sea, where wave forecasts are being provided for an offshore wind farm. With a tidal range up to 10 m or more the inclusion of the varying water level in the wave model computations is important for producing accurate wave forecasts.

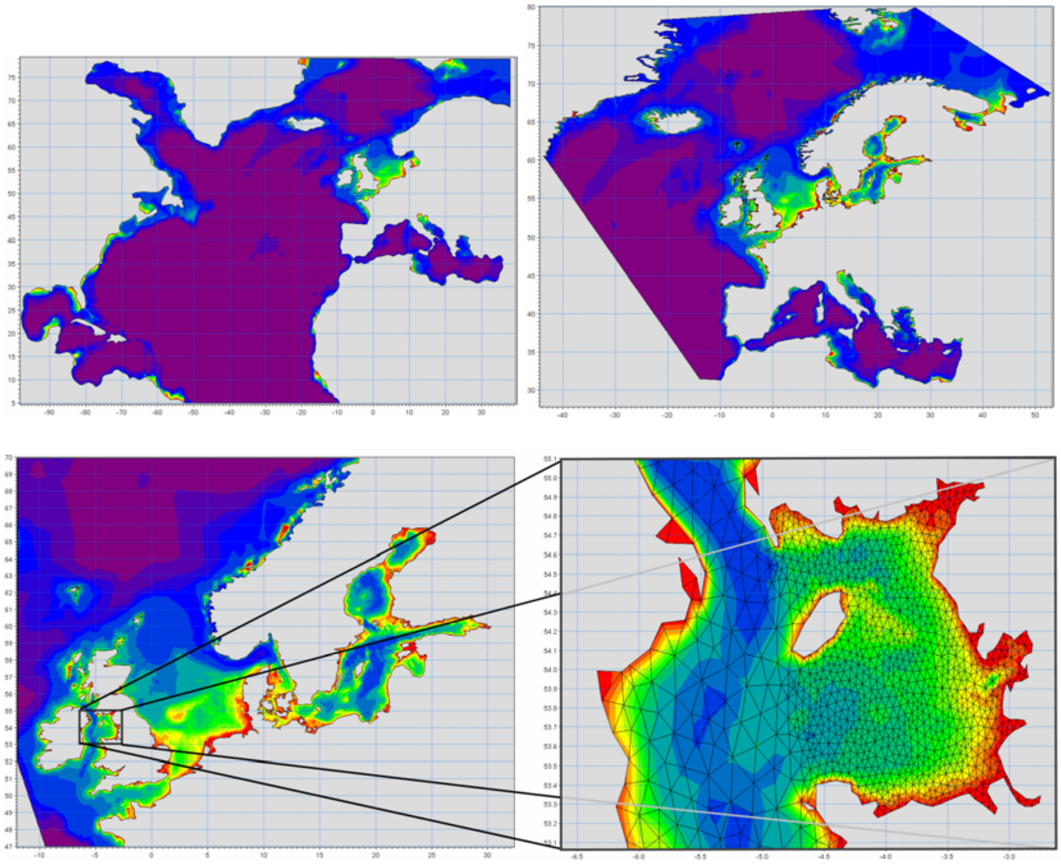


Figure 4 North Atlantic wave model area (top left), 3-dimensional hydrodynamic model area (top right) and model area for North European Shelf, the North Sea and the Baltic Sea with zoom-in on Horns Rev area showing flexible mesh elements (bottom).

4 OPERATIONAL WAVE FORECASTS FOR OFFSHORE WIND FARMS

Wave forecasts are being provided (as of September 2006) for the offshore wind farms as listed in Table 1 and as shown in Figure 5 (except for Nysted 1, where the service covered the construction from May through November 2003).

Table 1 Offshore wind farms for which wave forecasts are being delivered (Nysted 1 only May to November 2003). [1]: Artificial neural network correction. [2]: Wave Rider / ADCP being installed

Offshore Wind Farm	Model set-up	ANN[1]	Capacity	Status (Sep 2006)
Nysted 1, Baltic Sea, Denmark	1	No	72 turbines, 166 MW	operational
Horns Rev 1, North Sea, Denmark	2 and later 3	Yes	80 turbines, 180 MW	operational
Scroby Sands, North Sea, UK	3	No	30 turbines, 60 MW	operational
Kentish Flats, North Sea, UK	3	No	30 turbines, 90 MW	operational
Lillgrund, The sound, Sweden	3	Yes[2]	48 turbines, 110 MW	under construction
Horns Rev 2, North Sea, Denmark	3	Yes	~100 turbines, 200 MW	being designed
Burbo, Irish Sea, UK	4	Yes[2]	25 turbines, 90 MW	under construction

The capacity of the offshore wind farms and the model set-up applied are also listed in Table 1. For ANN correction, see Section 5.

Figure 5 Location of offshore wind farms for which wave forecasts are being delivered as of September 2006 (Nysted 1 only May to November 2003)

The accuracy of the wave models applied is illustrated below, where "analysis" fields ("now-casts") are compared to measurements at two locations ("West" and "Centre") at Horns Rev 2 Offshore Wind Farm. The two locations are depicted in Figure 6, while their location and the depths are listed in Table 2. Comparisons of time series of measurements and wave model now-casts are shown in Figure 7 to 9.

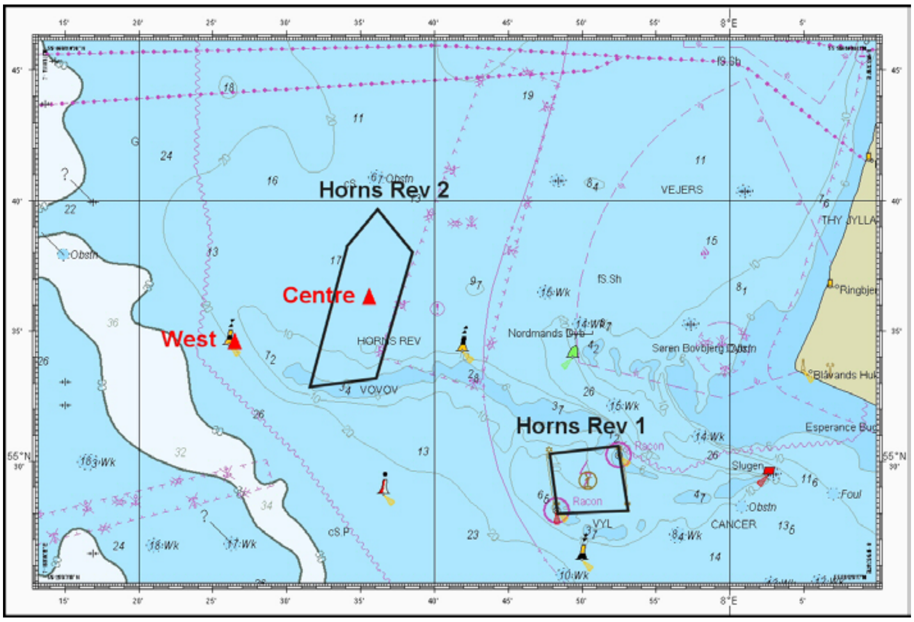


Figure 6 Location of Horns Rev 1 and Horns Rev 2 Offshore Wind Farms. Also shown are location of ADCP ("Centre") and Wave Rider ("West").

Table 2 Locations of wave recorders at Horns Rev 2 Offshore Wind Farm

Station	Longitude	Latitude	Depth (m)
Horns Rev 2 West (Waverider SG)	07° 26.281'E	55° 34.514'N	22
Horns Rev 2 Centre (ADCP)	07° 35.433'E	55° 36.455'N	14

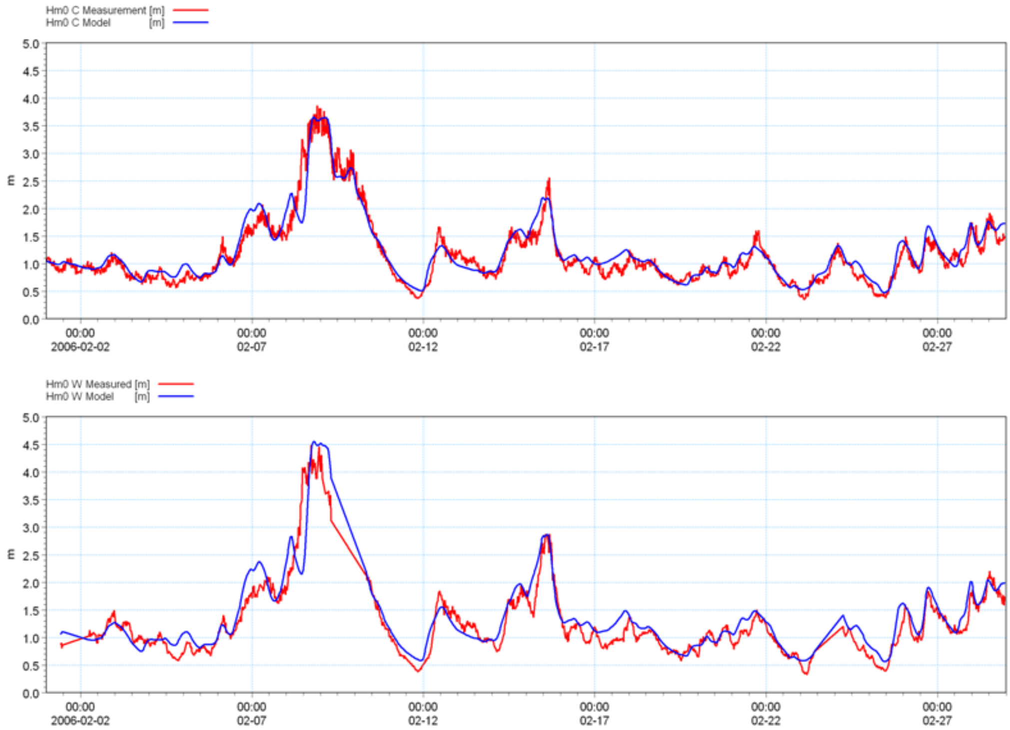


Figure 7 Comparison of significant wave heights from wave model (blue) and measurements (red) at Centre (top) and West (bottom)

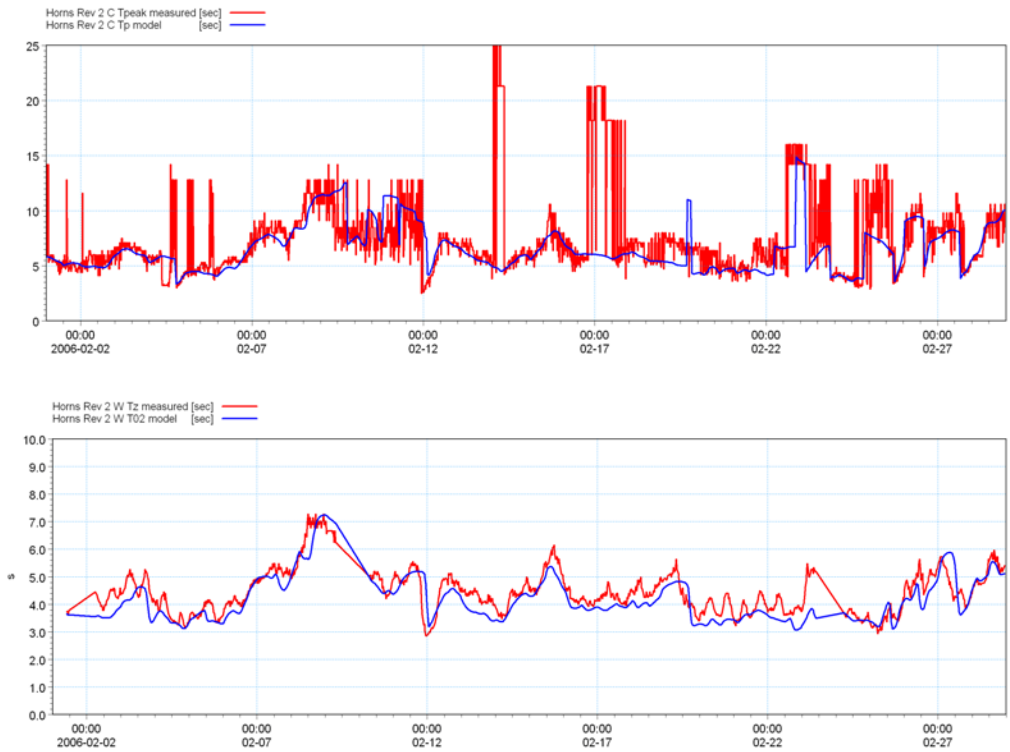


Figure 8 Comparison of wave periods from wave model (blue) and measurements (red) at Centre (top) and West (bottom)

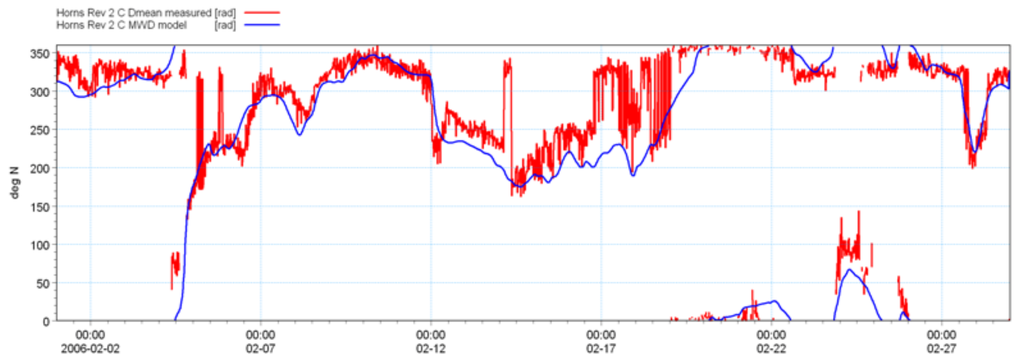


Figure 9 Comparison of mean wave direction from wave model (blue) and measurements (red) at Centre

The comparisons between measured and now-cast data are very favourable. It is especially noted that the fine mesh in the area captures the local in change in wave height between the two stations.

The statistical parameters quantifying the comparisons are listed in Table 3. With scatter indices of 0.20 or less and small biases the wave model is found to be in good agreement with the measurements.

Table 3 Statistical parameters describing the accuracy of wave model

Parameter	**Mean (m) or (s)**	**Bias (m) or (s)**	**Bias/Mean**	**RMS (m) or (s)**	**Scatter Index**	**Corr. Coeff.**	**Time Steps**
H_{m0} West	1.25	0.10	0.08	0.25	0.20	0.94	1191
H_{m0} Centre	1.16	0.05	0.04	0.18	0.16	0.96	2014
T_{02} West	4.44	-0.28	-0.06	0.51	0.12	0.86	1191

5 IMPROVEMENT OF WAVE FORECASTS USING ONLINE WAVE MEASUREMENTS

Improvements to a wave forecast for an area like an offshore wind farm can be carried out in several ways, when wave measurements are available for that location/area:

a) Calibrating the wave forecast model using the measurements. In order to do this the measurements need not be available on-line.
b) Assimilating the measurements into the initial conditions for the wave forecast model. For this the measurements must be available on-line.
c) Post-processing wave forecasts using measurements. The measurements must also be available on-line.

While calibration generally improves the accuracy of a forecast model, the use of on-line measurements can improve the short term forecasts (the first 12-24 hours) considerably more. Assimilating wave measurements into a wave model will, however, only be optimal shortly after a wave forecast has been run, which presently is done twice a day within The Water Forecast. Therefore the third possibility of post-processing has been investigated and developed. (As sown in the previous section the wave model has been calibrated using off-line measurements. Furthermore, the wave model is capable of assimilating measurements from buoys and satellites.)

Based on Artificial Neural Network (ANN) techniques a correction algorithm has been developed and is being used for a number of offshore wind farms (see Table 1). The procedure is as follows:

a) Online measurements are obtained once an hour
b) The latest wave forecast for the coming days are extracted
c) Using the measurements the forecast is corrected with the ANN algorithm
d) Thus an updated forecast is available once an hour to the users

The principle is also visualised in Figure 10, where a corrected forecast is produced on 2002-09-01 12:00 based on the just measured wave height (which was 1.3m). The uncorrected forecast from the wave model is shown in blue, while the corrected forecast is shown in black.

The increased accuracy obtained from this procedure is illustrated in Figure 11, where the standard deviation of the error of the forecast significant wave height is used as the accuracy measure. Using the wave forecasts without any correction will result in a standard deviation of 0.28m to 0.30m within the first 24 hours. Using the measurement as the forecast (i.e. no change) will be better that using the uncorrected forecast for the first 6 hours, while using a corrected forecast will be the optimum choice. The data used for deriving the standard deviation has been extracted from Horns Rev 1 Offshore Wind Farm.

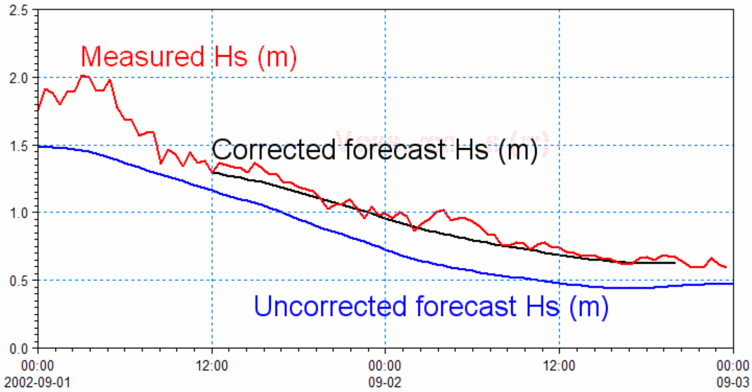


Figure 10 Description of wave forecast correction based on online measurements

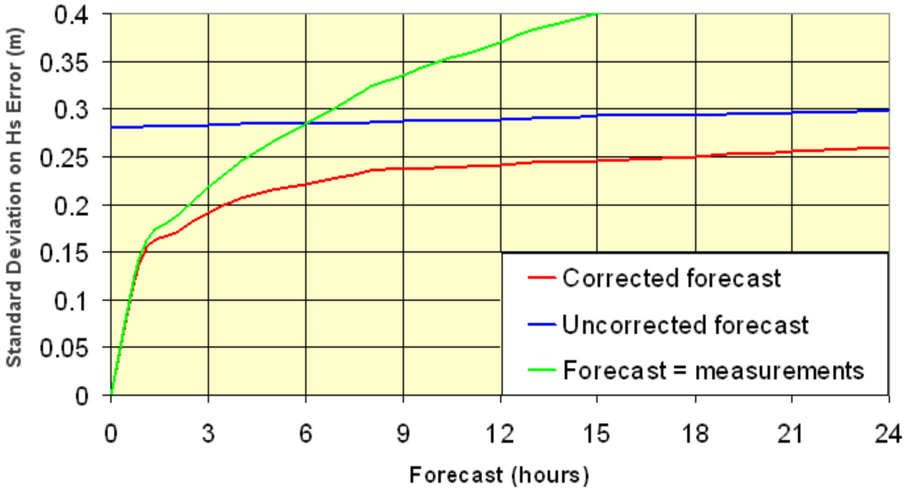


Figure 11 Increased accuracy of wave forecast obtained by using online measurements

The ANN algorithm derived for Horns Rev 1 Offshore Wind Farm reads:

$$H_{m0,corr} = H_{m0,f} + (H_{m0,m} - H_{m0,f}) / (1+\alpha\,\Delta t) \qquad (1)$$

where

$H_{m0,corr}$ is the corrected H_{m0}
$H_{m0,f}$ is the forecast H_{m0} at time t_f
$H_{m0,m}$ is the measured H_{m0} at time t_m

$$\alpha = 0.12\ F\ (1+0.24\ \Delta t/24) \qquad (2)$$

$$\Delta t = t_f - t_m \quad \text{[in hours]} \qquad (3)$$

$$F=1.0 \text{ for } (H_{m0,m} - H_{m0,f})*(H_{m0,m} - H_{m0,f}) > 0 \qquad (4)$$
$$F=7.0 \text{ for } (H_{m0,m} - H_{m0,f})*(H_{m0,m} - H_{m0,f}) \leq 0$$

6 EVALUATING SWELL DESCRIPTIONS

There is no scientific definition of swell, and different institutions apply different algorithms for separating the wind sea part and the swell part of a wave energy spectrum. From the users of wave forecasts from The Water Forecast feed-back have been received, which has resulted in the testing of several ways of separating the wave energy spectrum into wind sea and swell. The three types presently available are listed below. Where the first one employs a fixed frequency threshold, the two others use dynamic ones.

Type 1, constant threshold frequency
Swell wave components are defined as those components fulfilling the following criterion

$$f < f_{threshold} \text{ or } \cos(\theta - \theta_{wind}) < 0 \qquad (5)$$

where f is wave frequency, θ is wave direction, and θ_{wind} is wind direction.
$f_{threshold}$ can eg be set to 0.125 hz (corresponding to 8 s).

Type 2, dynamic threshold frequency based on PM spectrum
Swell wave components are defined as those components fulfilling the following criterion

$$f < f_{threshold} \text{ or } \cos(\theta - \theta_{wind}) < 0 \qquad (6)$$

where $f_{threshold}$ is the dynamic threshold frequency defined by

$$f_{threshold} = 0.7\, f_{p,PM}\, (E_{PM}/E_{total})^{0.31} \qquad (7)$$

where $f_{p,PM}$ is the peak frequency for a fully developed wind-sea described by a Pierson-Moskowitz spectrum given by

$$f_{p,PM} = 0.14\, g/U_{10} \qquad (8)$$

where U_{10} is the wind speed at 10 meters height and g is gravity.
E_{PM} is the total wave energy in a fully developed Pierson-Moskowitz spectrum given by

$$E_{PM} = (U_{10}/1.4\, g)^4 \qquad (9)$$

and E_{total} is the models total wave energy for those components fulfilling the following criterion

$$f > f_{threshold} \text{ and } \cos(\theta - \theta_{wind}) > 0 \qquad (10)$$

Type 3, dynamic threshold frequency based on wave age
Swell wave components are defined as those components fulfilling the following wave-age based criterion

$$U_{10}/c \cos(\theta - \theta_{wind}) < 0.83 \qquad (11)$$

where c is the phase speed of the individual wave components.

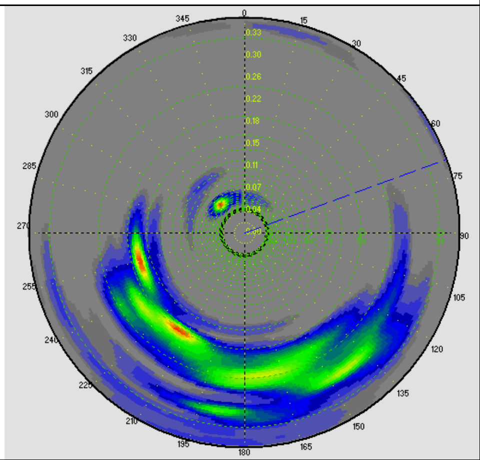
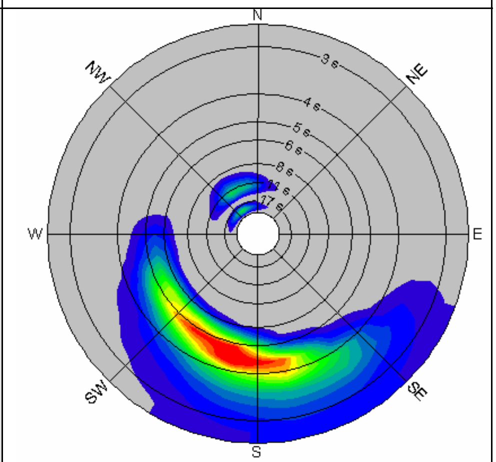
	Measured spectrum from ADCP	**Spectrum from wave model**
Total energy spectrum		

Figure 12 Measured and modelled wave spectrum from Horns Rev 2 C, 2006-02-14 08:00 UTC.

In order to illustrate the difference between the three, a modelled spectrum from Horns Rev 2 Centre at 2006-02-14 08:00 UTC has been separated using all three types and are shown in Figure 13. In Figure 12 the un-separated spectrum is shown together with the measured spectrum from the ADCP at Horns Rev 2 Centre.

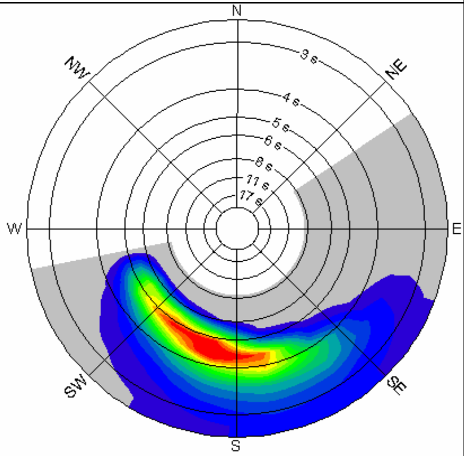
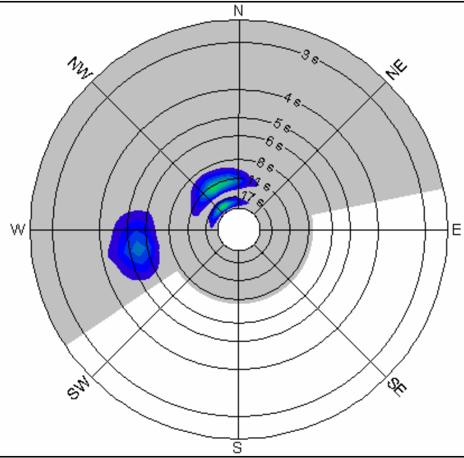
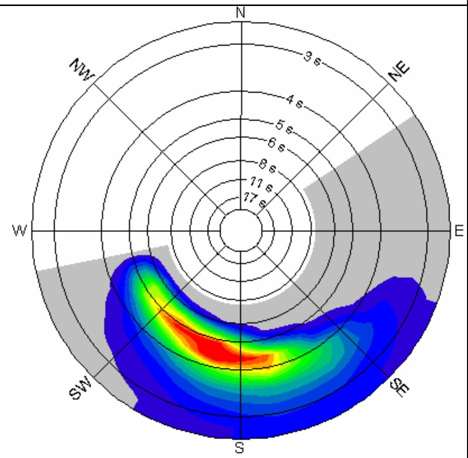
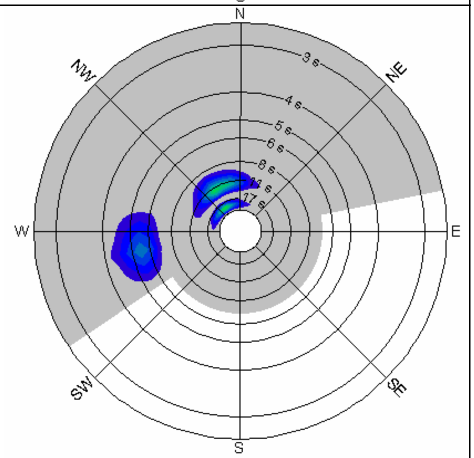
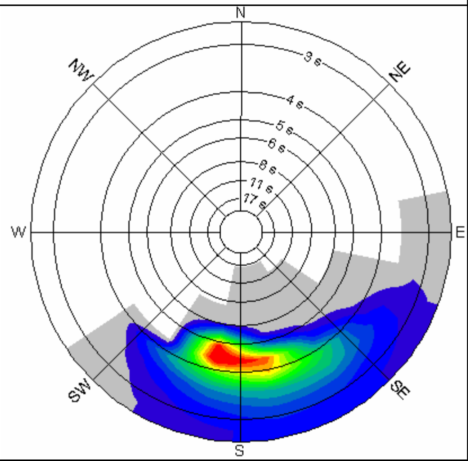
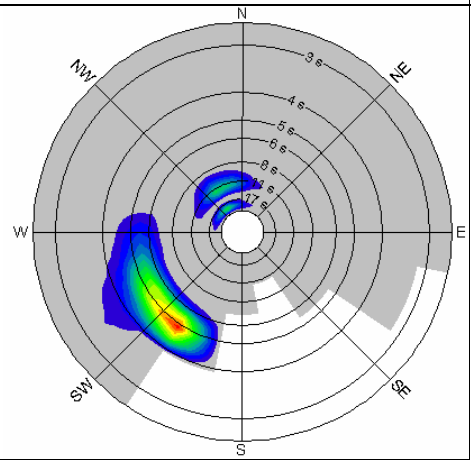
Swell separation	**Wind sea part of spectrum**	**Swell part of spectrum**
Type 1		
Type 2		
Type 3		

Figure 13 Splitting the wave model spectrum into a wind sea and a swell part using three different separation types, 2006-02-14 08:00 UTC.

The differences between the three are also illustrated in Table 4, where wave parameters for the different types of separation are shown. The corresponding wind conditions are listed in Table 5.

Table 4 Wave parameters for three types of swell separation, and for the total spectrum (modelled and measured), Horns Rev 2 Centre at 2006-02-14 08:00 UTC.
[1]: Measured spectrum from following burst 20 minutes later. See note in text.

Type of separation	Part of spectrum	Hm0 (m)	T02 (s)	Tp (s)	θ_{mean} (deg)	θ_{peak} (deg)
1	**Wind sea**	1.07	3.2	4.5	172	180
1	**Swell**	0.50	5.5	20.3	293	248
2	**Wind sea**	1.07	3.2	4.5	172	180
2	**Swell**	0.50	5.5	20.3	293	248
3	**Wind sea**	0.92	2.9	4.1	161	180
3	**Swell**	0.74	4.7	5.1	244	225
Model	**Total**	1.18	3.4	4.6	183	180
Measured	**Total**	1.04	4.5	21.3	332	328
Measured[1]	**Total**	1.14	4.5	4.2	164	163

Table 5 Wind conditions at Horns Rev, 2006-02-14 08:00 UTC.

	Wind speed (m/s)	Wind direction (m/s)
Measured (at Horns Rev 1)	8	150
Model (at Horns Rev 2 Centre)	9	151

Comparing type 1 (where a constant frequency threshold of 8 s has been applied) and type 2 only a minor difference is found in the present case. With swell and wind sea coming from different directions (as in this case) and with relatively long period swell waves, the two types agree. However, both of them include a bit of the wind generated waves, as these are more that 90 degrees from the wind direction.

Comparing type 1 and 2 with type 3 some differences are found. Generally higher swell waves will be found using type 3, as the angle interval within which waves are considered to be wind sea is smaller.

The third type was introduced because of user feedback and dissatisfaction with type 2, and it resulted in swell heights, which more closely corresponded to what the users (captains) experienced as swell. Thus waves coming from a direction only 45 to 60 degrees away from the wind direction may be considered to be swell by the users, although the periods of these waves correspond to wind sea.

In Table 4 the wave parameters for two adjacent measured spectra have been included. Although there is only 20 minutes between the two the wave directions vary almost 180 degrees while there is only a small difference in wave energy. This variability in the ADCP processing results are also illustrated in Figure 9 with the often large variation between wave directions from one burst to the next one.

In addition to using the swell definitions in output to the users, a swell definition is also used inside the model code: White-capping is applied only to the wind sea part of the wave energy spectrum. For this purpose type 2 separation is presently applied.

7 CONCLUSIONS

With the construction of large offshore wind farms in Danish waters at first and then later on in the waters of other European countries, a new user group with demands for high accuracy wave forecasts has emerged. The special requirements of this new user group to wave forecasts and how they have been met have been described. Emphasis has been put on wave models with a flexible computational mesh, on post-processing using online measurements, and on the definition and interpretation of swell.

The flexible mesh model can cover the entire area influencing the waves at the specific shallow water site and at the same time resolve the detailed bathymetry in the area around the site. The result is improved accuracy in output, ease of model set-up and increased computational efficiency as compared to the more traditional nesting of models approach. The inclusion of dynamic water level variation (output from hydrodynamic model operated on similar mesh) is mandatory for obtaining accurate results in shallow waters with large tidal and surge variations.

ACKNOWLEDGEMENTS

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