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Operational Wave Forecasts Over Baltic and North Sea

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Abstract

The operational wave model has been put on service at the Danish Meteorological Institute since June 1, 1999. This report describes the operational version of the model: its model setup, calibration and operationalization.

The third generation wave model (WAM-cycle4) is applied in the operational forecasts with a limited domain which covers the Baltic Sea and North Sea with a spatial resolution of 10 minutes in latitude and longitude. The model runs in a operational mode with a hot start and is updated every 12 hours with the wind input from the DMI's HIRLAM model. The model has been calibrated in Baltic Sea, inner Danish waters and North Sea. 14 buoy data sets were used in the calibration. Model-data comparison shows that the model agrees well with buoy measurements. At the North Baltic Proper, the peak error for the significant wave height is about 8.6%. In the North Sea, the peak error is 3.0% in the south of 55°N and 12.4% in the north of 55°N. The model tends to under-predict the peaks. The root mean square error (RMSE) is 0.30m in the southern and 0.38m in the northern North Sea, together with a model-data correlation of 0.85 and 0.92 as well as a mean under-prediction of 0.02m and 0.20m, respectively. In the inner Danish waters, calibration for 5 months at Drogden shows a mean error of 0.03m, RMSE of 0.16m and correlation of 0.84 between the modeled and observed significant wave height. Error sources were analyzed in different regions and the results were used to optimize the model, such as selecting the reasonable location of the northern boundary and model parameters.

1 Introduction

Many operational wave models (WAM) are based on the WAM-cycle4 (e.g., European Center for Medium-Range Weather Forecasts (ECMWF) WAM, National Center for Environment Prediction (NCEP, USA) WAM etc.), a research version developed by the WAM Group since 1991 [Günther et al., 1992]. In the application of operational forecasts, the WAM-cycle4 is improved according to users' operational requirements. For example, European Center for Medium-Range Weather Forecasts (ECMWF) has implemented the data assimilation, parallel computation and short-fetch improvements in its operational WAM version.

The issue of wave prediction at the Danish Meteorological Institute (DMI) was raised on January 1999. Weather Service Department at the DMI decided to start its own wave forecasts, which will be provided for customers in Danish waters. Several general steps have been taken to produce the forecasts, which include model selecting, model calibration and rationalization and model operationalization.

To select a WAM model for the operational prediction, a model survey has been conducted. At the time several wave models were available, which included WAM-cycle4, ECMWF operational WAM as well as the second and third generations of WAM from the Danish Hydraulic Institute (DHI).

The ECMWF WAM is the most comprehensive operational wave model, which was developed for global wave prediction. It has advantages in parallel computation and data assimilation. However we are not able to directly use these facilities on DMI's NEC supercomputer. The parallel computation of ECMWF WAM is performed on Fujitsu supercomputer, which needs some work before it can be used on the NEC. The data assimilation can not be implemented in DMI's operational WAM at present since the DMI has not an access to the real-time satellite wave height products.

The WAM-cycle4 has the same model physics as the ECMWF WAM. It has a friendly user environment where we can easily debug and/or modify the code. It also has a nesting facility.

Both ECMWF WAM and the Cycle4 have been well calibrated in open seas. However only a few calibrations have been done for short-fetch wave simulations. Short-fetch condition is common in the coastal zone. DHI and Risø National Laboratory had conducted some field campaigns in 1992 and 1994 in Belts. With model-data comparison, Hansen et al. [1998] found that the WAM-cycle4 over-predicted the significant wave height by about 30-40% in Belt areas for strong wind ($U_{10} \sim 15m/s$). The DHI WAM was developed to improve the shallow water and short-fetch wave simulations. However their results are contradictory with those from Hersbach and Janssen [1999]. The latter indicated that the WAM model under-predicted the significant wave height over restricted-fetch.

It is not explicit in choosing a better model for short-fetch wave modeling. Thus the main criterion to choose a model is the user environment and its feasibility to couple with a weather model (such as HIRLAM). Therefore the WAM-cycle4 becomes our first choice. Other facilities such as parallel computation, data assimilation and restricted-fetch improvement can be added later during the model development, if it is necessary.

The second step is to set-up the model and calibrate it. The model domain should be large enough to eliminate the model bias caused by the swell from the North Atlantic. The model resolution should be fine enough to resolve most of the inner Danish waters. As the WAM-cycle4 has not been validated thoroughly in the Baltic Sea, inner Danish waters and North Sea, the operational model set-up has to be fully calibrated. There will be several factors contributing to the model error, such as the swell from the north border, using the same bottom friction coefficient for both deep and shallow waters, model's limitation on restricted-fetch and spatial resolution etc. These error sources will be analyzed by using the calibration results and the WAM model will be optimized based on the analysis.

The third step is to operationalize the model. This includes to customize the interfaces between HIRLAM and the WAM and between the WAM products and data presentation and delivery system, to run the WAM-cycle4 with a hot start and put all the procedures in an automatic operational job-flow.

The rest of the report is organized as follows: section 2 describes the operational model set-up; section 3 deals with model calibration and error mechanism analysis and section 4 gives conclusions and discussions on the future work.

2 Operational Model Set-up

2.1 Model physics

A full description of the WAM-cycle4 can be found in the technical report written by the WAM Group [Günther, 1992]. Here only a summary of the model is given. The WAM-cycle4 is based on the full wave energy equation:

$$\frac{\partial F}{\partial t} + \frac{\partial}{\partial \phi}(\phi F) + \frac{\partial}{\partial \lambda}(\lambda F) + \frac{\partial}{\partial \theta}(\theta F) = S \tag{1}$$

where

$$S = S_{in} + S_{nl} + S_{dis} + S_{cu} + S_{bf} \tag{2}$$

and

$F(f, \theta, \phi, \lambda)$: spectral density, a function of frequency (f),
direction (θ), latitude (ϕ) and longitude (λ)
S_{in}: wind input
S_{nl}: nonlinear interaction
S_{dis}: white cap dissipation
S_{cu}: wave-current interaction
S_{bf}: bottom friction

In the operational version, the shallow water friction and depth refraction are selected. The current refraction is not included since the operational three dimensional current model is not available yet. The wave spectrum is discretized in 25 frequencies and 12 directions (ECMWF uses 24). The time step is 240 seconds.

A standard WAM test was run to test the model sensitivity to the number of the wave direction in a rectangular domain with constant water depth. Increasing of the number of directions almost linearly increases the CPU time. The preliminary results showed that the increasing of the number of wave direction slightly improve the model results. For example, the error of significant wave height decreases by about 3% when the current number of direction is doubled. It should be noted that this may not be applicable for the areas around islands [Bidlot et al., 1997].

2.2 Bathymetry and boundary condition

The model has been set up in a limited domain [($51°N$,$8°W$)- $68°N$,$30°E$), Fig. 1], which covers both the North Sea and Baltic Sea. The northern boundary of the model is selected based on the model calibration results, which suggest that the current location of the boundary ($68°N$) can include most of the swell effects in the North Sea (see details in section 3). The model is discretized on a latitude-longitude grid with a resolution of $10' \times 10'$, which is about 10 nautical miles (nm) in latitude and 6 nm in longitude. The bathymetry is based on ETOPO5, a global topography data set with 5 minutes resolution generated by National Geophysical Data Center (NGDC, USA). 10 minutes resolution is required to resolve most of the model area. However, it can not resolve small islands, such as the one in Øresund. To resolve these small islands, at least a 2.5 minutes resolution is needed.

Some places of the ETOPO5 data were manually adjusted. The lakes were turned to be land points. If one, two or three water points are surrounded by land then these points are turned to be land. On the open boundaries, the wave spectrum is diagnosed from wind at 10m height by using a parameterized JONSWAP [Hasselmann et al., 1973] spectrum.

2.3 Input and output

The only time-dependent input data to the WAM-cycle4 is the wind velocity at 10m elevation, which is obtained from the D15-HIRLAM output with hourly interval and a spatial resolution of about 15km. The 10m wind field is then interpolated onto the WAM grid bilinearly.

The model output is stored in an operational (Grib) format which is the same format as that of the HIRLAM operational output. The Grib format can be retrieved and plotted by using Metview software. Output components, such as wind wave height and direction, swell wave height and direction and mean wave height etc, are presented with different codes, which are shown as follows:

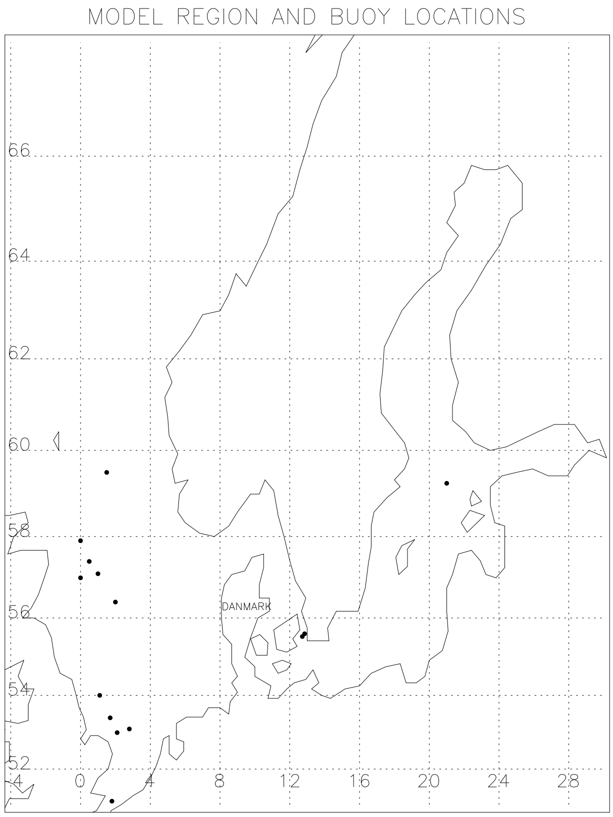

Figure 1: Model domain and Buoy locations for calibration

229 = mean significant wave height
230 = mean wave direction
231 = peak wave period
232 = mean wave period
233 = drag coefficient
234 = wind sea wave height
235 = wind sea wave direction
236 = wind sea wave mean period
237 = swell wave height
238 = swell wave direction
239 = swell mean period

A example of the model output with significant wave height (SWH) and mean wave direction (MWD) is shown in Fig. 2. The figure shows a snapshot of forecast at 6hour when a storm is moving into the domain.

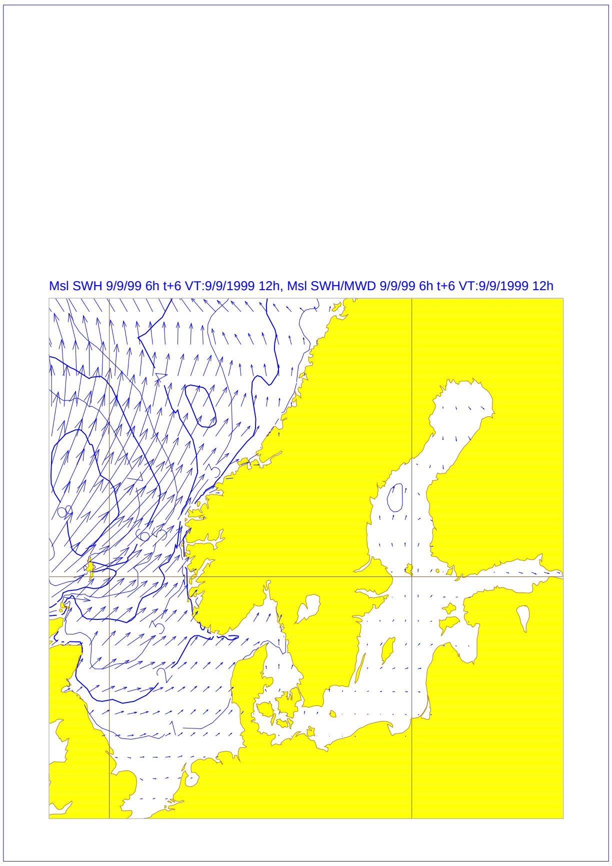

Figure 2: The model forecasts on the SWH and MWD. SWH is shown in contours with an interval of 1m and the MWD is indicated by arrows

2.4 Flow chart of the operational forecasting system

The operational flowchart of wave prediction is shown in Fig. 3. The first step is to get wind data from HIRLAM. The WAM model then interpolates the wind onto WAM grids. The second step is to run the WAM for 48 hours prediction. The initial condition is derived from initial wind field and the fetch by using a parameterized spectrum. The 48 hours forecasts takes about 17 minutes cpu on the NEC SX-4. The WAM products are then sent to an IRIX machine (GDB) by using print queue for further results presentation and data delivery service. The operational flow is run with a C-shell script on NEC SX-4. The model was compiled with Fortran90 compiler and run in a vectorized mode. Currently the forecast is updated every 12 hours.

In the operational mode, a hot start is required. This is based on tests for model spin-up time. The tests indicate that the model spin-up time ranges from several hours to several

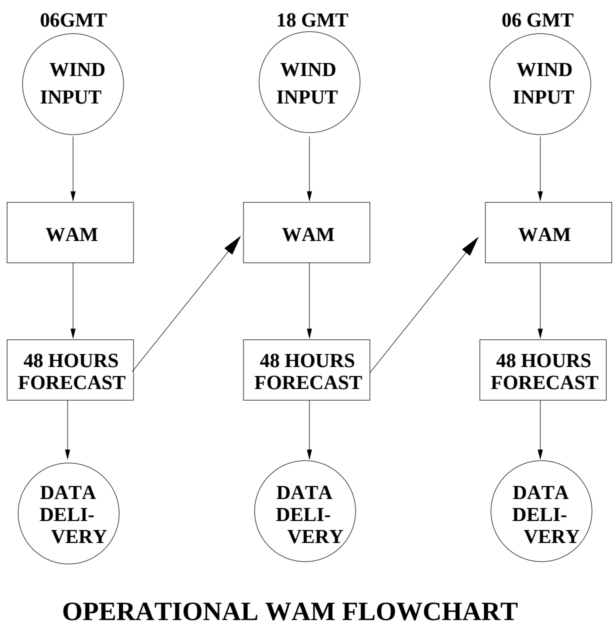

Figure 3: The operational flow chart of WAM (version 2.0)

days, which means the influence of initial condition on the model results can last up to several days. The hot restart files are saved every 12 hours and are used in the next 48-hour forecasts. Therefore the model needs only to be initialized once. The model has a facility to check the correct present prediction time, over-run missing time intervals and produce the forecasts for the present time, in case of model cracking down.

3 Model calibration

It is well known that a main concern on a operational model is its accuracy. The operational WAM is expected to produce high quality wave forecasts in both shallow, short-fetch waters as well as in deeper open seas in the model domain. The model needs to be carefully calibrated before it is applied in the operational forecasts. Because the relative importance of swell, bottom friction, short fetch condition and model resolution on the wave modeling vary in Baltic Sea, inner Danish waters and North Sea, it is therefore necessary to calibrate the WAM-cycle4 in the three regions separately.

3.1 Data and methods

All the calibration data are based on buoy measurements. As shown in Fig. 1, there are totally 14 buoys' measurements which are used in the study: one in the Baltic Sea, two in the inner Danish waters and eleven in the North Sea. In the Baltic Sea, the buoy is located in the middle of the northern Baltic Proper (hereafter referred to as NBP). The Finnish Institute of Marine Research (FIMR) is responsible for operating the buoy. Because the digital data sets are not available for DMI, we used published figures of the buoy measurements. The figures cover a period of 3 months: July, August and October 1998.

Two buoy stations are located in south Sound: Drogden and Oskarsgrundet. The data is available for one year during June, 1998 - May, 1999. The buoys were operated as a part of field campaign during the construction of the link between Denmark and Sweden. The data were kindly provided by Øresundskonsortiet. The observation interval is 3 hours at Drogden but varies from half to 3 hours at Oskarsgrundet.

In the North Sea, a buoy chain with 11 buoys covers the entire domain along the dateline. The buoy data were obtained from ECMWF and the buoys are operated by United Kingdom Meteorology Office (UKMO). Generally the data sets can be accessed in real time through GTS-network. In the present study only one month data (March 1999) is used. The time interval of the buoy measurements ranges from half a hour to 3 hours.

Most verification studies calculated statistical parameters for the significant wave height and the peak period to determine the skill of a wave model. Among the parameters that are most commonly used are: the mean error (ME) or bias; the root-mean-square error (RMSE); the Scatter Index (SI) defined as the ratio of RMSE to the mean observed value of the parameter; the peak error (PE) and the sample linear correlation coefficient (r) between the model and the observed value. In this study only the significant wave height is calibrated since observations of peak period or swell component are not available in the data sets. Please notice that in this report, the peak error is defined as the ME for the peaks which are higher than a subjective criterion (such as 3m or 4m). Only the highest peak in each synoptic event is used in the calculation when multi-peaks occur in the event.

3.2 Baltic Sea

The Baltic Sea is an almost-closed shallow sea. The calibration model domain was ($8°E - 30°E$, $53°N - 66°N$), which covers the entire Baltic Sea. This eliminates the problem of swell through open boundaries since the swell from Skagerrak to the Baltic Sea is negligibly small. There are both shallow and deep waters in the model domain. The mean depth of the

Baltic is about 50m. The maximum depth in Baltic Sea is about 450m. Around the NBP the depth is about 180m. Figure 4 shows the significant wave height hindcasted by the DMI WAM-cycle4 at the NBP for July, August and October, respectively. The model run does not cover the entire July due to discontinuity in the wind data. Correspondent observations at the NBP are shown in Fig. 5, which were cited from Tuomi et al. [1998]. The solid line is the simulated significant wave height from FIMR WAM model and the cross points are buoy measurements.

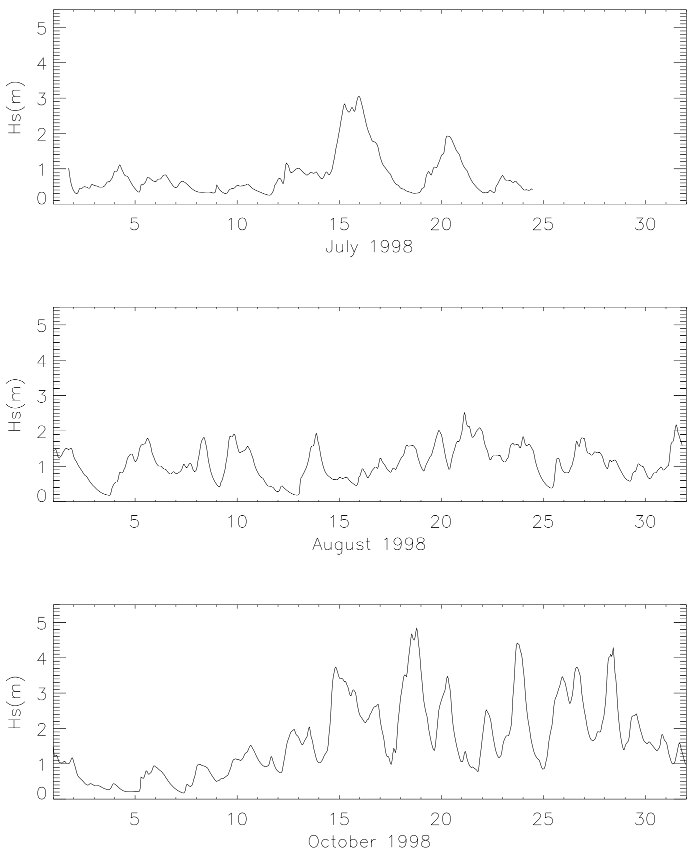

Figure 4: Significant wave height hindcasted by the DMI WAM at the NBP

The sea was relatively calm in July and August. The maximum significant wave height during the two months is about 3.1m at the NBP. The model simulation in July and August (Fig. 4) agrees well with the measurements both for the average and the peaks. There is no obvious systematic error in the simulations. During October there are six events with maxima greater than 4m. The modeled significant wave height is about 8.6% lower than the observations for its 6 peaks in average.

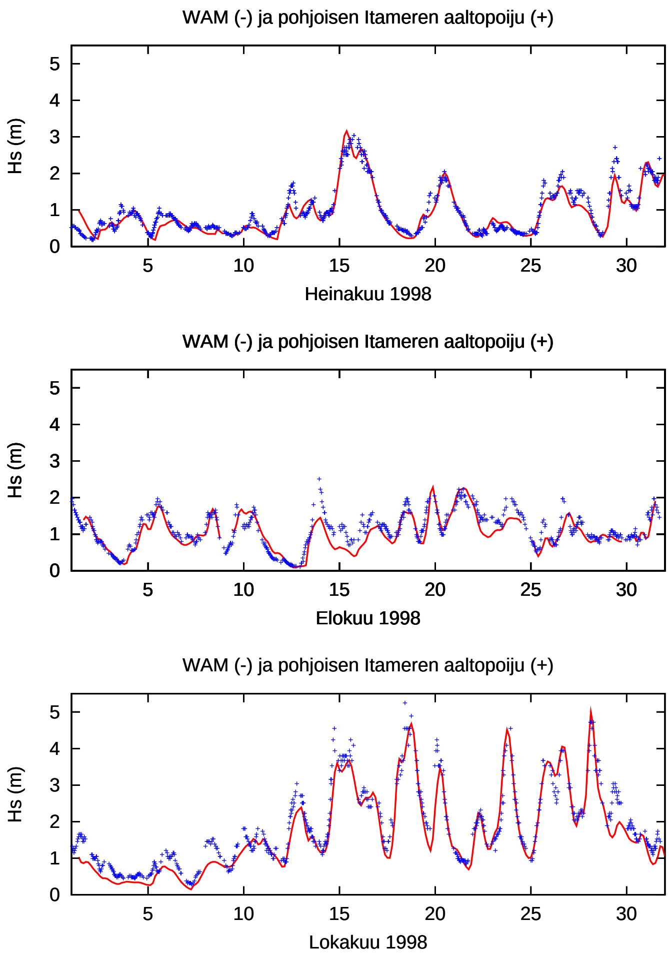

Figure 5: Model-data comparison by FIMR at NBP (after Tuomi et al., 1998) for July (upper panel), August (mid-panel) and October (lower panel)

3.3 North Sea

The model-data comparison is shown in Fig. 6 and Fig. 7 for the eleven buoy stations in the North Sea, where solid lines represent the modelled significant wave height while the dots are the buoy measurements. Figure 6 includes 5 buoys in southern North Sea (south of 55°N) and Fig. 7 is for northern North Sea (north of 55°N). The error statistics, which include the RMSE, ME, SI, PE and r for the SWH, are also estimated for the two regions (Tab. 1 and Tab. 2). In the southern North Sea (Tab. 1), the model provides wave height simulations with RMSE of 0.31m and scatter indices of about 30%, while the mean error is about -0.01m. The correlation between the modeled significant wave height and the observations is about

0.85. However, the correlation at buoy E (0.68) is much worse than the average. The reason for this is presently not clear. It is noticed that the wave measurements at F is more irregular than other buoys. This may suggest that the data quality at F is not as good as that at other buoys. Yet it is still early to make any conclusions before longer period data are calibrated. In the northern North Sea, the RMSE of the SWH is 0.40m with scatter indices of about 19%. The model underestimate the observation of about 0.23m. The model-data correlation of wave height is about 0.92. For high waves, the peak error is about -3% in the southern North Sea for the SWH maxima over 3m and 12.4% in the northern North Sea for the SWH maxima over 4m.

Table 1. Error Statistics From DMI WAM-Cycle4 in the southern North Sea during March, 1999. M is the sample number used in the calibration

Station	M	Lat.	Lon.	RMSE	ME	SI	R
		(°N)	(°E)	(m)	(m)		
A	686	51.10	1.80	0.21	0.03	0.37	0.90
B	539	53.00	2.10	0.31	0.05	0.29	0.86
C	598	53.10	2.80	0.25	-0.05	0.21	0.93
D	599	53.40	1.70	0.29	-0.11	0.25	0.89
E	562	54.00	1.10	0.47	0.01	0.40	0.68
Average				0.31	-0.01	0.30	0.85

Table 2. The same as in the Tab. 1 except for the northern North Sea

Station	M	Lat.	Lon.	RMSE	ME	SI	R
		(°N)	(°E)	(m)	(m)		
F	620	56.40	2.00	0.39	-0.26	0.20	0.94
G	640	57.00	0.00	0.45	-0.31	0.21	0.91
H	613	57.10	1.00	0.32	-0.11	0.17	0.91
I	613	57.40	0.50	0.41	-0.27	0.19	0.92
J	116	57.90	0.00	0.33	-0.10	0.16	0.89
K	618	59.50	1.50	0.52	-0.32	0.19	0.93
Average				0.40	-0.23	0.19	0.92

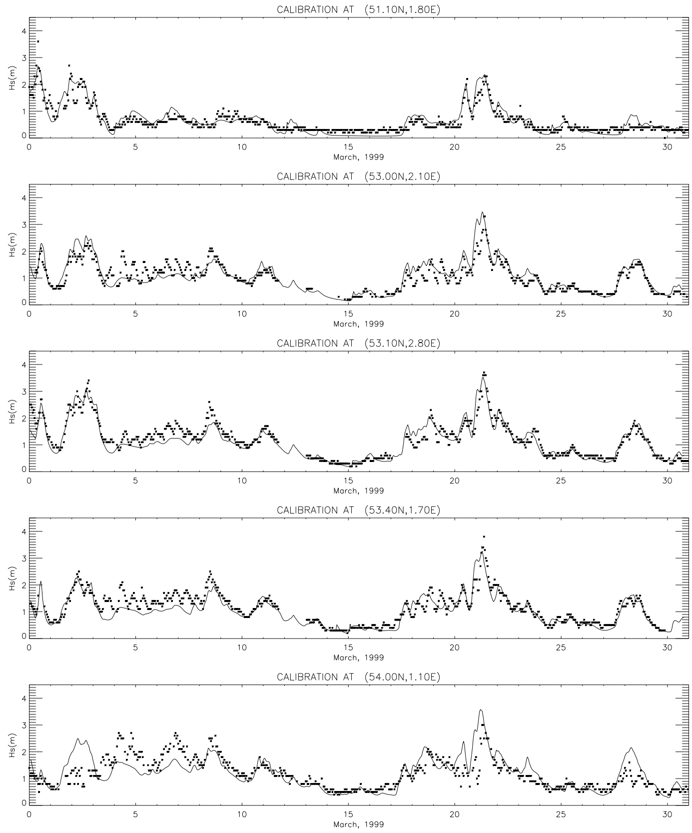

Figure 6: Model-data comparison by DMI WAM in southern North Sea

3.4 Inner Danish Waters

The previous studies showed (see section 1) contradictory results about the WAM simulations in short-fetch and shallow water areas. Hersbach and Janssen [1999] showed that the WAM-cycle4 model tends to under-predict the wave heights in the short fetch cases while Hansen et al. [1998] found that WAM-cycle4 over-predicts the wave height by 30-40% in Belt seas. It is hard to compare their results because their calibration periods, wind input models and the model resolutions are quite different. It is our interests to see the performance of our operational WAM in the inner Danish waters.

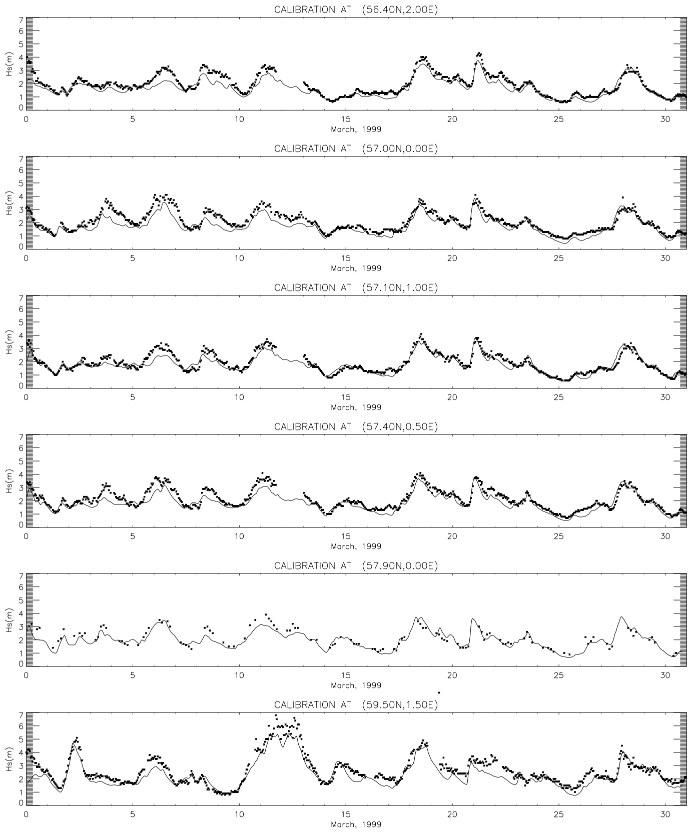

Figure 7: Model-data comparison by DMI WAM in northern North Sea

Table 3. Error Statistics From DMI WAM in Inner Danish Waters

Station	Period	Latitude	Longitude	RMSE	Rel. Error	Correlation
		(°N)	(°E)	(m)	(m)	
Drogden	9807	55.53	12.72	0.151	0.037	0.858
Drogden	9808	55.53	12.72	0.148	0.074	0.828
Drogden	9810	55.53	12.72	0.241	0.006	0.751
Drogden	9812	55.53	12.72	0.153	0.036	0.900
Drogden	9903	55.53	12.72	0.126	-0.005	0.861
Oskar.	9807	55.60	12.85	0.212	0.109	0.777
Oskar.	9808	55.60	12.85	0.159	0.091	0.737
Oskar.	9810	55.60	12.85	0.351	0.213	0.463
Oskar.	9812	55.60	12.85	0.167	0.103	0.802
Oskar.	9903	55.60	12.85	0.172	0.069	0.643

The model was integrated for 5 separated months: July, August, October and December of 1998 as well as March 1999. The model-data comparison is shown in Fig. 8 and Fig. 9 and error statistics in Tab. 3. There are large differences between the two buoy stations. The modelled SWH agrees well with the measurements at Drogden but not at Oskarsgrundet. At Drogden, the results show no obvious systematic bias both in average and high waves. For the average, the relative error is about +3cm. For the waves higher than 1m, the relative error is about +2.6cm which means a model over-prediction of about 2%. The averaged correlation coefficient at Drogden from Tab. 3 is about 0.84. The lowest correlation occurs on October, when the wind has the largest temporal variations. At Oskarsgrundet, the observed SWH is much lower than that at Drogden, which may be caused by bathymetry difference. Oskarsgrundet is located much closer to the island of Saltholm (Fig. 12). The model over-predicts the SWH by 11.6cm in average, which means a model over-prediction of about 31.4% (Tab. 3). This result is similar to that obtained by Hansen et al. [1998] in Great Belt. The correlation between the model and the observations at Oskarsgrundet is about 0.68. The worst correlation occurs also in October 1998.

3.5 Error analysis

The above model-data comparison indicates that the model error varies in different regions. The error mechanisms in correspondent areas also vary. In this section we focus on error mechanisms in Baltic Sea, inner Danish waters and North Sea. This will provide a basis for further model improvement.

In central Baltic Sea, the model under-predicts the peak significant wave height by 8.6%. However this under-prediction is not apparent for the average. The main error sources are wind forcing and bottom friction. As pointed out by Janssen [1999], wind input is the main error source in ECMWF's global wave forecasts. In Baltic Sea, the weather model may have larger error for moving cyclonic system than for the average. The second error source is the bottom friction term. Since the model uses shallow water bottom friction, this may overestimate the bottom friction in deep waters which may cause a model under-prediction for wave heights. Another error source is the discret spectrum in 12 directions, which may cause a model error of several percent. Finally, the difference between the average error and the peak error suggests that the error sources are more significant for the high waves. This is consistent with Janssen [1999]. His weather-wave model coupling study showed that the significant coupling only happens in high waves rather than average. Big improvement occurs both in wave and wind forecasts but only for high waves. This consistence suggests

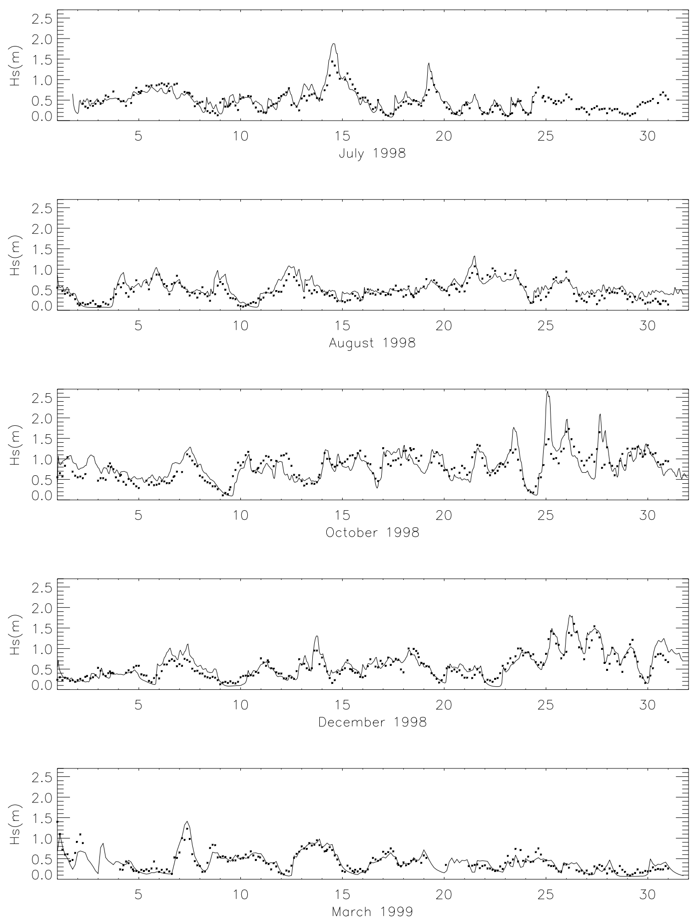

Figure 8: Model-data comparison by DMI WAM at Drogden

that coupling WAM with weather model may improve the current wave forecasts.

North Sea will be analyzed in 2 parts: the southern North Sea (south of 55°N) and the northern North Sea (north of 55°N). In the southern North Sea, the error mechanisms are similar to that in the central Baltic Sea. In the northern North Sea, the model under-prediction increases as buoy locations get closer to the northern boundary. A new error source in the northern North Sea is the swell from North Atlantic to the North Sea. The swell at the open boundaries is totally neglected. The swell within the model domain is internally generated. This means that the model should be large enough to include the swell effects. However, the model domain can not be too large due to the limited computer sources. Several tests were run to determine the north and west model boundaries. It is found that the present model boundaries can catch most of the swell effects in the North Sea. To identify this point of view, a comparison test is shown below. A small model domain is chosen in the

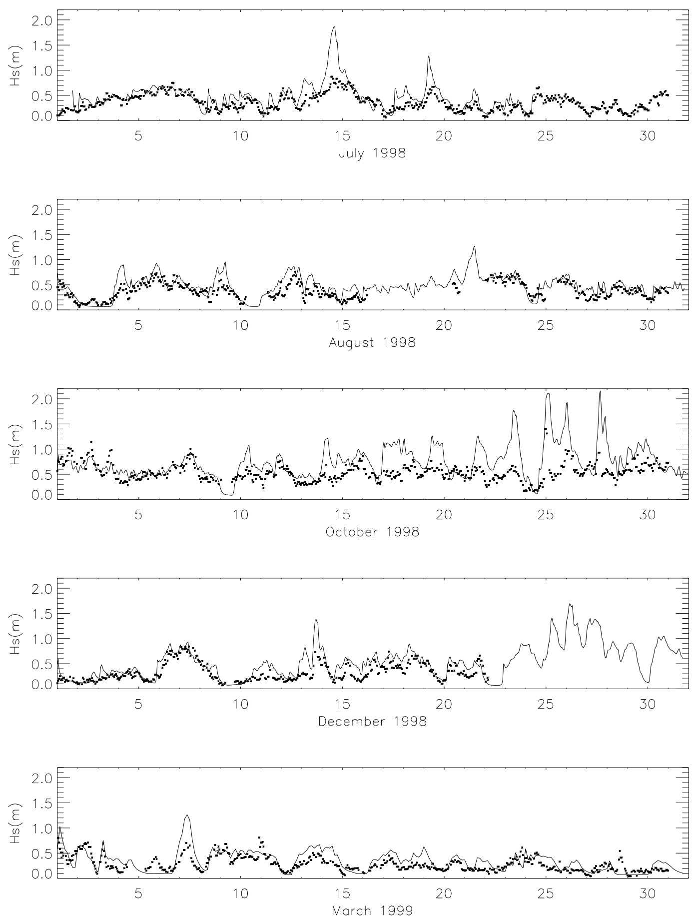

Figure 9: Model-data comparison by DMI WAM at Oskarsgrundet

test. The western boundary is at 4°W and northern boundary is at 61°N. The model-data comparison for the SWH is shown in Fig. 10 and Fig. 11 and correspondent error statistics is shown in Tab. 4 and Tab. 5. Note that the 3-hourly interval data are used in the error statistics, which may lead to a slightly higher correlation coefficient. Comparing Tab. 1 and Tab. 4, we found no significant difference, which means that swell influence in the southern North Sea is small and can be accounted with a small model domain. However, there are big differences in the northern North Sea (Tab. 2 and Tab. 5). With the small model domain, the RMSE increases to 0.59m, which is about 50% more than the large domain. The ME is -0.43m which is almost double the ME in large domain model (Tab. 2). The model error caused by swell is significant in the northern North Sea with the small domain, which is clearly shown in Fig. 11 where the largest systematic under-prediction of the model occurs after the wave peaks. It is noted that even with a large domain, we still have errors of about

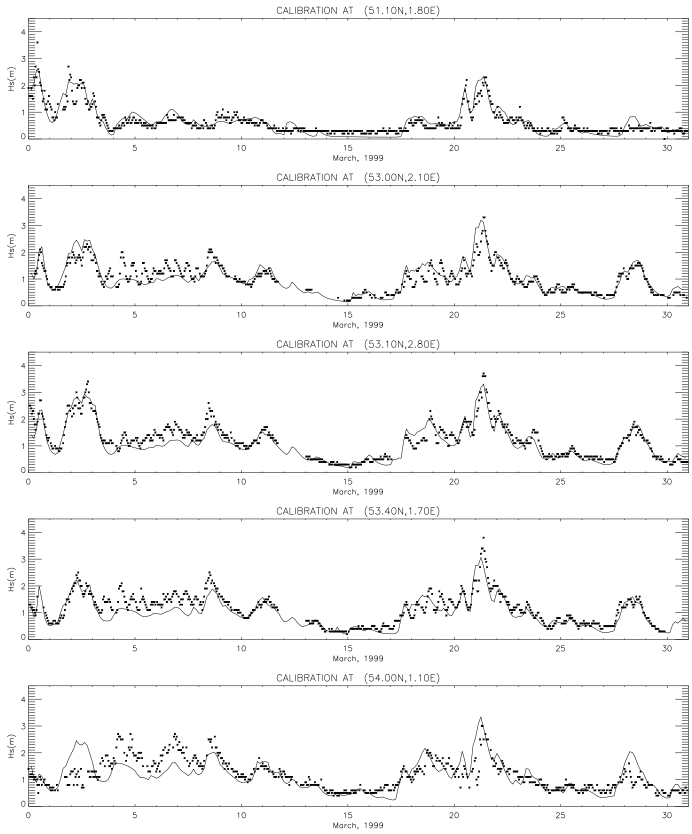

Figure 10: The same as Fig. 6 except for the small model domain

-23cm which is related to the model treatment of swell.

Table 4. Error statistics in southern North Sea for the small domain

Station	M	Lat.	Lon.	RMSE	ME	SI	R
		(°N)	(°E)	(m)	(m)		
A	200	51.10	1.80	0.19	0.01	0.38	0.89
B	177	53.00	2.10	0.25	0.03	0.26	0.90
C	184	53.10	2.80	0.24	-0.07	0.22	0.93
D	182	53.40	1.70	0.28	-0.12	0.26	0.90
E	198	54.00	1.10	0.38	-0.06	0.33	0.79
Average				0.27	-0.04	0.29	0.88

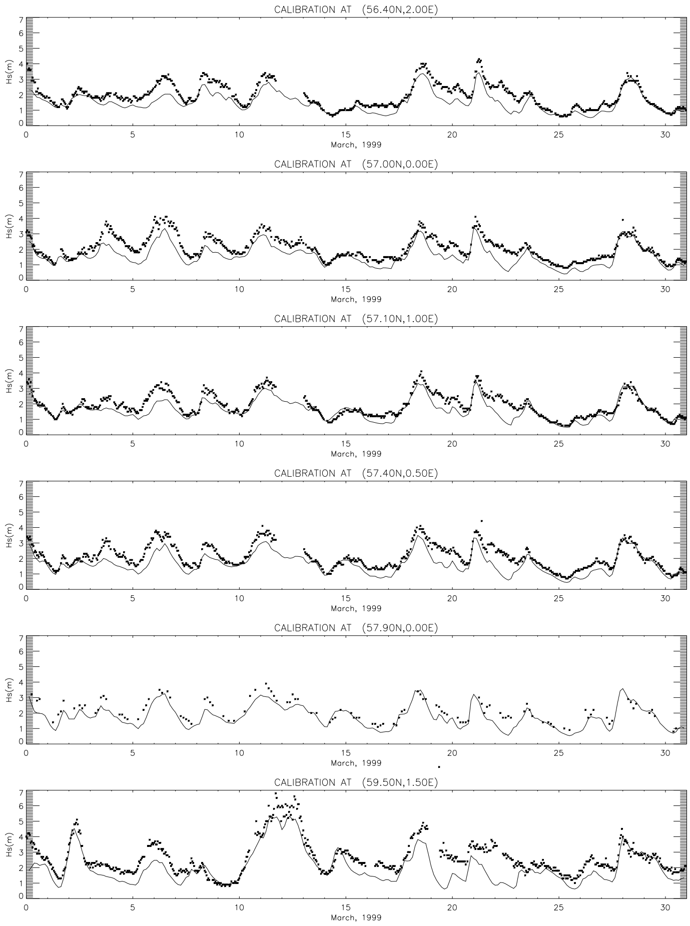

Figure 11: The same as Fig. 7 except for the small model domain

Table 5. Error statistics in northern North Sea for the small domain

Station	M	Lat.	Lon.	RMSE	ME	SI	R
		(°N)	(°E)	(m)	(m)		
F	189	56.40	2.00	0.57	-0.44	0.30	0.90
G	200	57.00	0.00	0.56	-0.47	0.27	0.91
H	189	57.10	1.00	0.49	-0.30	0.26	0.87
I	189	57.40	0.50	0.58	-0.45	0.28	0.89
J	99	57.90	0.00	0.47	-0.32	0.23	0.89
K	187	59.50	1.50	0.88	-0.62	0.33	0.85
Average				0.59	-0.43	0.28	0.89

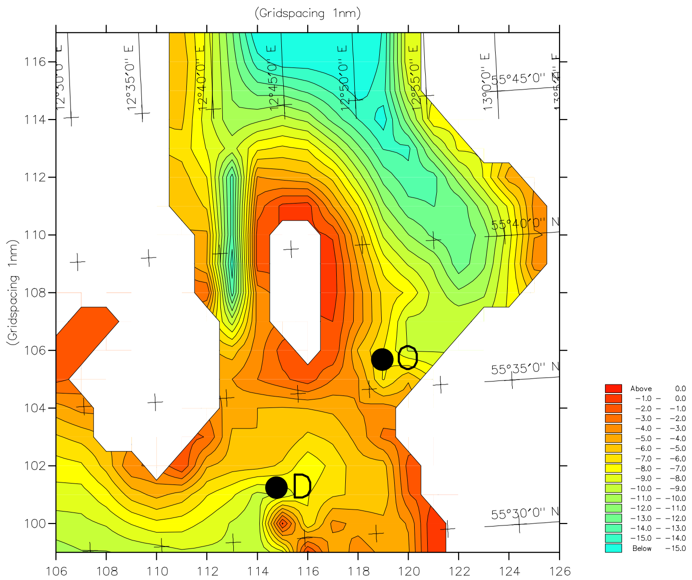

Figure 12: The bathymetry in Øresund with a 1nm×1nm resolution. D: Drogden and O: Oskarsgrundet

In the inner Danish waters, the error sources are even more complicated. The possible error sources may include: the error from the weather model, the short-fetch wave growth, the bottom friction coefficient, and the model resolution etc. An interesting phenomenon is that the wave behavior differs a lot at the two stations, which distance is about 11.3 km. Therefore the local behavior shown in measurements at Oskarsgrundet must be related to the local bathymetry. Figure 12 shows the bathymetry in Øresund with a resolution of 1nm×1nm. The water depth are about 7m both at Drogden and Oskarsgrundet. However the environment for the two stations is much different. Drogden is located in the south mouth of Øresund in a relatively open sea while Oskarsgrundet is in a narrow part between the Swedish west coast and Saltholm in the middle of Øresund. The fetch at Oskarsgrundet is therefore much shorter than that at Drogden. Waves at Oskarsgrundet can not grow-up as efficiently as at Drogden. An analysis of the model bathymetry shows that the ETOPO5 can not correctly describe the bathymetry around Oskarsgrundet and the island Saltholm in the west of Oskarsgrundet can not be resolved. This largely increases the fetch at Oskarsgrundet in the model for westerly wind. The island may also create a shadow zone where wave height is significantly reduced [Bidlot et al. 1997]. Without the island the model is expected to over-predict the waves near the island. The water depth at Oskarsgrundet is also incorrect, which is 1m in the ETOPO5 dataset. The above analysis indicates that the model over-prediction at Oskarsgrundet is mainly related to the bathymetry and low model resolution. A high resolution (nested) model should be used for the model validation at Oskarsgrundet.

4 Conclusion and Discussions

The operational version of DMI wave model (WAM-cycle4) has been described in this report. The model has been extensively calibrated in Baltic Sea, North Sea and inner Danish waters and then used in the operational wave forecasts. The 48 hour wave forecasts are made every 06GMT and 18GMT. It takes about 14 minutes cpu time on the NEC SX-4. The prediction is presented in the DMI's Internet and also provided to the television (Danish TV2) and other customers.

The model calibration shows that the model hindcasts fit the observations very well. The model tends to under-predict the high waves by about 8.6% in the central Baltic Sea, 3.0% in the southern North Sea, and 12.4% in the northern North Sea. There is little systematic error in average in the Baltic Sea and southern North Sea. The systematic error is about -0.23m in the northern North Sea. The main error sources in Baltic Sea and the southern North Sea are wind input and bottom friction in high waves and discreting of wave spectrum in 12 directions. In the northern North Sea, swell across the northern and western boundaries is a main source of systematic error.

In the inner Danish waters, model error varies with locations. At Drogden, a station in shallow and conditional short-fetch waters (for northwesterly or easterly wind), the model gives satisfactory results. There are no systematic errors for both the average and waves higher than 1m. The RMSE is about 0.16m. Oskarsgrundet is in a relatively strict short-fetch water. The model bathymetry can not describe the bathymetry around Oskarsgrundet and largely increases the fetch at Oskarsgrundet. This is the most important reason for a model over-prediction of 31.4% for the significant wave height at the Oskarsgrundet. Since the case of Oskarsgrundet is not general in most of the inner Danish waters, it is more appropriate to use the calibration results at Drogden to evaluate the model quality. There are also other error sources, such as bottom friction, wave growth limit and wind forcing error etc.

The above results suggest two possible immediate improvements for the current DMI operational WAM model. One is to improve the boundary condition so that the mean error caused by swell can be further reduced. There is a possibility to use ECMWF wave forecasts to improve the boundary condition. The other one is to increase the resolution in the inner Danish waters, which can improve the model performance in the strict short-fetch waters.

The resolution in Øresund and Belt areas should not be coarser than 2.5 minutes. It is practical to use a large model domain with coarse resolution and a nested domain in the coastal and inner Danish waters. The question of applying shallow water bottom friction in the entire domain also needs to be further investigated.

As pointed out by Janssen [1999], the wave model should be viewed as a part of a weather model. The wave model not only provides more accurate momentum boundary condition for weather model but also serves as a tool to validate the weather model. It is noticed that the 10% under-prediction for high waves are universal in both the Baltic Sea and the North Sea. This may be improved by coupling the WAM and the weather model. As shown in Janssen [1999], the high resolution wave-weather model coupling predicts deeper cyclonic system than non-coupled weather model. This means the wave-weather model coupling also improve the high wave prediction. Other issues, such as parallel computation and data assimilation etc, will also be concerned later.

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6 Appendix: Some practical points

6.1 Forecast update

The wave forecast is updated twice daily at 06GMT and 18GMT. Sometimes you may find that the wave direction does not agree with the wind direction so well in the Internet, especially when a fast moving meso-scale weather system is present. This is caused by different update time between WAM and HIRLAM forecasts. The later is updated 4 times a day. The wind forecasts between different updates within a day can be quite different in the case of fast moving meso-scale weather system.

6.2 Data presentation

The 48 hours wave forecasts are stored at a file called *grib.wam* on the NEC, which is then delivered to an IRIX machine for further services. The *grib.wam* can be viewed by *Metview*. The codes of the output components in the *grib.wam* are defined as in section 2.3.

The forecast is updated twice a day in the Internet:

http://www.dmi.dk/vejr/index.html

Under this page, click Sejlervejr-bølger then you get the one-day forecasts with significant wave height and mean wave direction in the Danish waters. Swell is a component of the model output but is not displayed in the Internet for the sake of simplicity.

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