A high-resolution hindcast study for the North Sea, the Norwegian Sea and the Barents Sea

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Background

Reliable historical wind and wave data are important in designing offshore installations and in planning offshore operations. But often there are not sufficient measurements to make good estimates of the probability distribution for wind and wave parameters necessary to make accurate calculations of design loads on offshore structures. The measured time series are also too short to make realistic simulations of offshore operations, e.g. calculate the probability of a weather window that is needed for an offshore operation. Hindcast data are produced by running numerical models based on historical data. A hindcast archive properly evaluated against reliable measurements represents a powerful proxy for long instrument time series. Hindcast statistics can be used to plan operations and design of structures. Furthermore, a hindcast archive is area-covering and as such will yield statistics for whole regions and locations not specifically planned in advance. In previously unexplored areas like the Barents Sea where reliable measurement series are patchy or lacking entirely, a hindcast archive becomes even more important for assessing the climatology and the exceedance criteria for various geophysical parameters. The Arctic poses a particular challenge to hindcast and climate estimates as small-scale polar lows and the precise location of the ice edge demand high-resolution models of the atmosphere and the wave field.

Previous hindcast projects at the Norwegian Meteorological Institute

The Norwegian Meteorological Institute has from the mid seventies carried out several hindcast projects to meet the need for long term time series of wind and waves from the oil industry. In the first extensive hindcast project at met.no (Haug and Guddal, 1981) wind and wave data were computed from air pressure fields in a 150 km grid using the first generation wave model NOWAMO. The air pressure fields were digitised from operational weather maps. To improve the estimates of atmospheric fields a new project was initiated in 1982 (Eide *et. al.*, 1985). Observations of air pressure were collected and used in an objective pressure analysis with the old pressure fields as first guess. However, the most significant improvement was the introduction of the second generation wave model WINCH. The second hindcast project established a data base of wind and waves for the years 1955-1981. This archive has since been regularly updated. The homogeneity of such long data series is always a problem. Even when the same methods are applied, different data coverage and data quality may create statistics with nonstationary error terms. There are several sources of inhomogeneities in the current hindcast data, among those the shift to pressure analyses from the numerical weather prediction introduced in 1982 (Reistad and Iden, 1998).

Since the previous Norwegian hindcast project was completed more than 20 years ago, great strides have been made in the field of numerical weather and wave prediction. Numerics, assimilation techniques and the spatial resolution have been much improved in the models. Meanwhile, computing power has grown exponentially. The advent of high quality boundary data through global reanalysis projects and improved datasets (e.g. ice edge data from satellite) has now opened the possibility to build a new hindcast archive for Norwegian waters which resolves spatial scales an order of magnitude smaller than previous hindcast archives.

The ERA40 global hindcast project

The ERA40 reanalysis project produced a set of global analyses describing the state of the atmosphere and the wave field for the 45 years from September 1957 to August 2002. ERA40 is a comprehensive global dataset generated by reanalysis of past observations using the same data assimilation techniques that are applied in numerical weather prediction. The reanalysis was carried out by The European Centre for Medium-Range Weather Forecasts (ECMWF), of which met.no is a member organization, using the Integrated Forecasting System version T159L60. The reanalysis represents the states of the atmosphere and the wave field after iteratively adjusting the background towards observations in a way that is optimal, given estimates of the accuracy of the background and observations. Atmospheric fields are available every six hours with approximately 1.125 degrees horizontal resolution. ERA40 wave fields were computed with the WAM model (see WAMDI, 1988, for a description of the WAM model) coupled to the atmospheric model. The horizontal resolution of the wave model is 1.5 degrees. The ERA40 reanalyses are produced in a consistent fashion throughout the 45-year integration. The errors should thus be statistically stationary. However, the amount of data that has gone into the assimilation is not constant over the whole period. In particular the amount of satellite data has increased dramatically during the last two decades. The ERA40 reanalysis was completed in 2003. See Uppala *et. al.* (2003) for a comprehensive overview of ERA40. The archive is relatively coarse compared with operational high-resolution data assimilation systems, but gives a good reproduction of most large-scale dynamical features.

The new high-resolution hindcast project

The new high-resolution hindcast archive covers the Norwegian Sea, Barents Sea and the North Sea. The archive period coincides with the ERA40 period. The atmospheric model is a version of HIRLAM (see HIRLAM-5 Scientific Documentation, 2002) with 10km horizontal resolution on a rotated spherical grid. A description of the model setup can be found in Bjørge *et. al*. (2003). The vertical is resolved by 40 vertical levels. Temperature, wind velocity, specific humidity and liquid cloud water in the boundary zone are relaxed towards ERA40. A digital filter is applied to maintain some of the large-scale features of the ERA40 fields. Sea surface temperature and sea ice cover are interpolated from ERA40 or from the ice data archives at The Norwegian Meteorological Institute. The ice cover is updated weekly.

The wave component of the hindcast system is a modified version of the WAM cycle 4 model (WAMDI 1988, Komen *et. al*. 1994, Gunther *et. al*., 1992) set up on the same rotated spherical grid as the atmospheric component. The model is nested inside a 50km resolution WAM model covering most of the North Atlantic to allow realistic swell propagation from the North Atlantic. A new nesting procedure has been developed to allow arbitrary orientation of outer and inner model domains (see Figure 2). The model is set up with 24 directional bins and 25 frequencies spanning the range 0.0420 to 0.4137Hz. The model domains are shown in Figure 1.

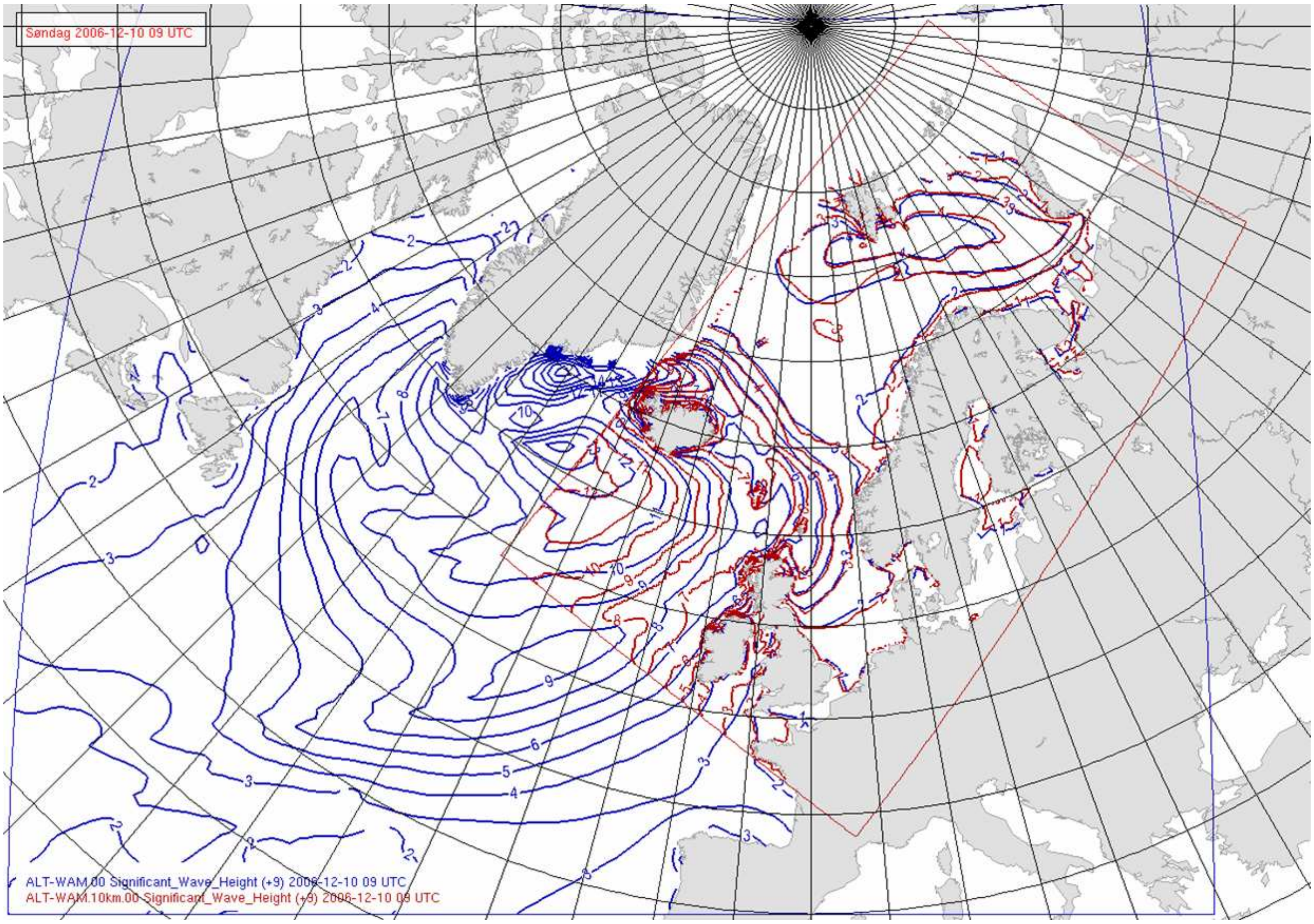


Figure 1 Model domains. The HIRLAM10 and WAM10 model domains are shown in red. The WAM50 model domain is shown in blue. HIRLAM10 and WAM10 grids are identical. Both domains are rotated spherical projections.

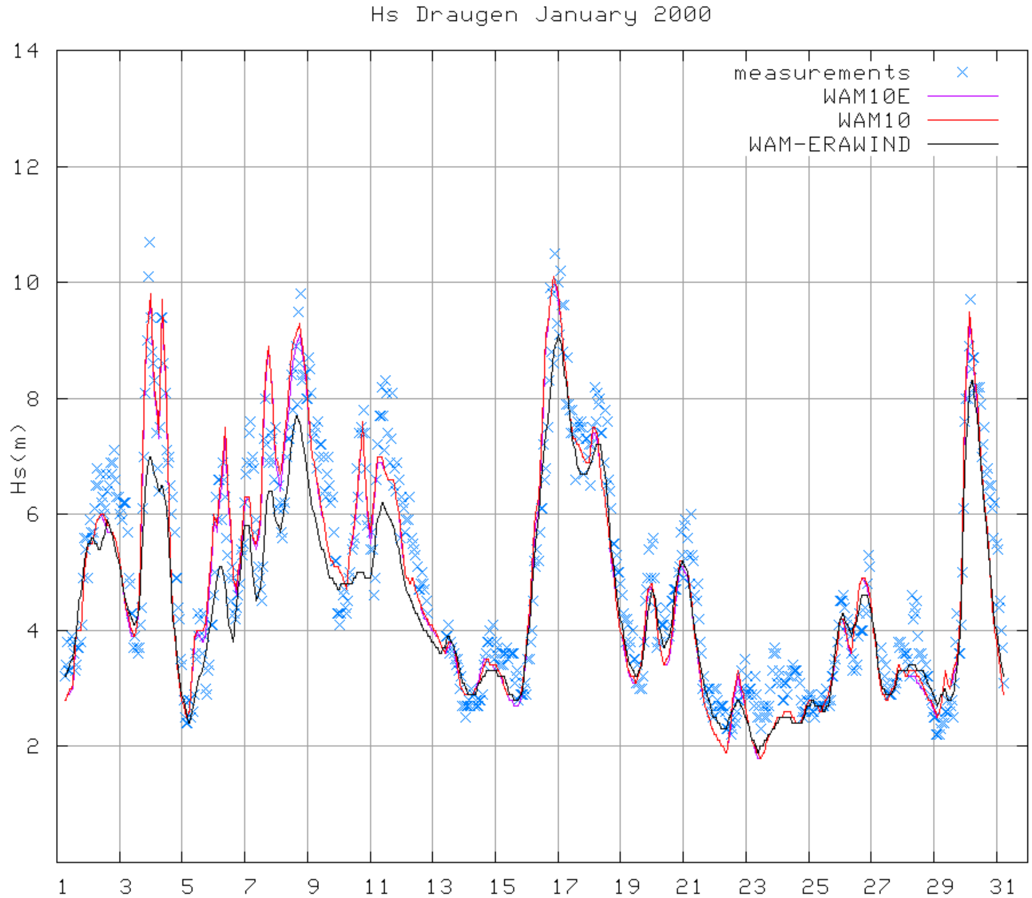


Figure 2 Time series from Draugen, January 2000, showing excellent agreement between the 10km WAM (red) model run and the observations (crosses). WAM10 and WAM10E are 10km resolution WAM simulations with reanalyzed winds from HIRLAM10. Note the storm 30 January and how the model closely tracks the observations near the peak. The black line is WAM50 with ERA40 winds.

Wind statistics

The agreement between HIRLAM10 10m wind and offshore stations Draugen, Heidrun and Norne (locations indicated in Figure 5 and Figure 6) is generally better than for ERA40 for the period 1990-2002. Figure 3 summarizes the mean error, mean absolute error and root mean square error for the three stations. The anomalously poor agreement during the first year must be due to poorly calibrated observations (the statistics are based on only one station before 1996). The mean absolute error and the RMSE both exhibit a strong seasonal variation as it blows harder in the winter time. In general, HIRLAM10 is closer to the observations throughout the period, although the gap narrows markedly after 1997. Upper percentiles and mean statistics for offshore station Ekofisk in the middle North Sea are presented in Table 1 Station Ekofisk 2000-2001 (56.5°N, 003.2°E) HIRLAM10 model *v* wind observations.. The wind extremes for the period 2000-2001 are very well reproduced by HIRLAM10.

It is expected that a high-resolution weather prediction model will start to resolve topographic effects in the coastal zone that ERA40 is unable to reproduce. A closer look at one of the coastal stations (Sula, see Figure 4) reveals that this is indeed the case where topographically induced wind effects are important. In such locations HIRLAM10 clearly outperforms ERA40.

HIRLAM10 also shows very good agreement with the upper percentiles of the wind distribution (Table 1)

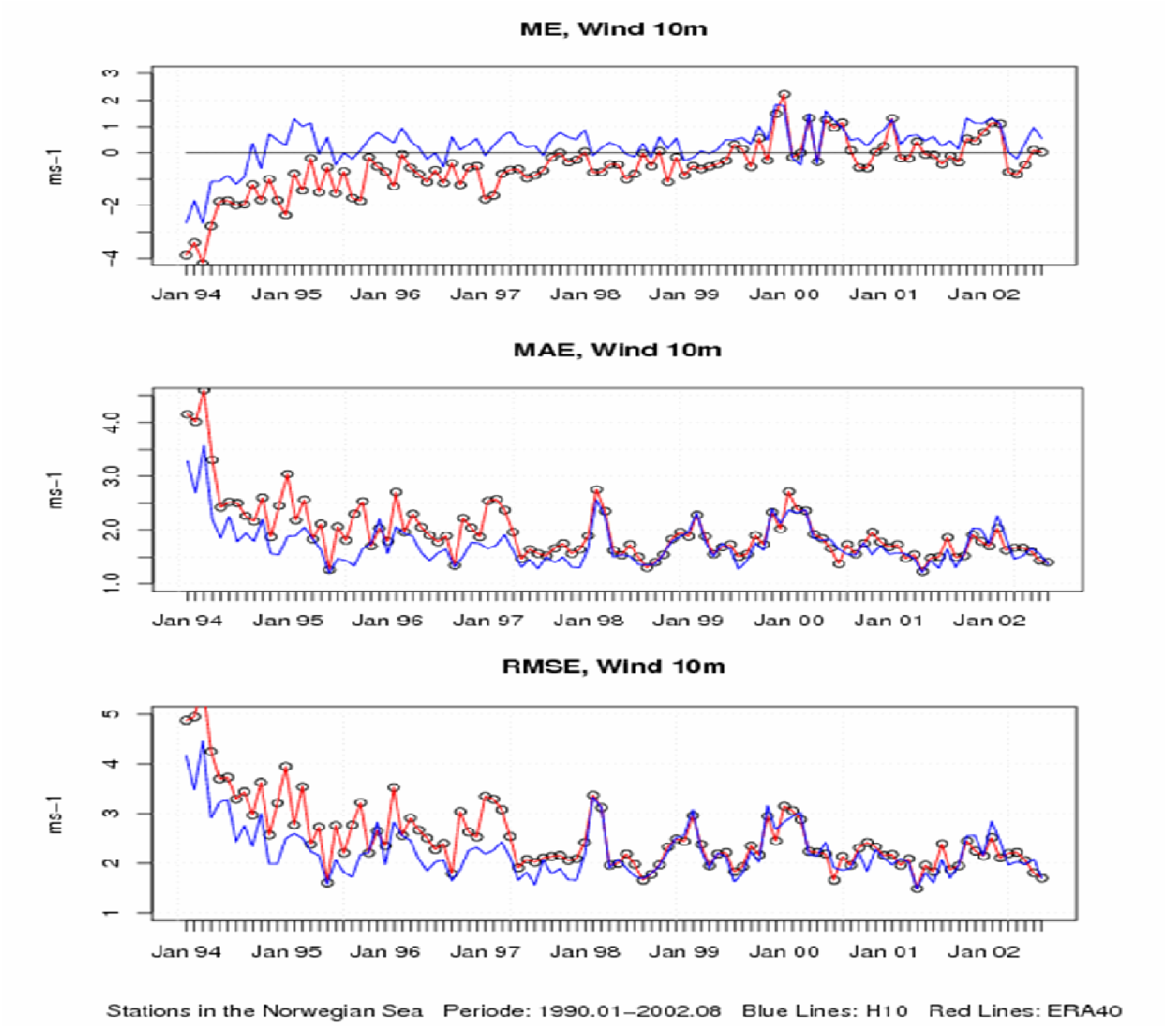
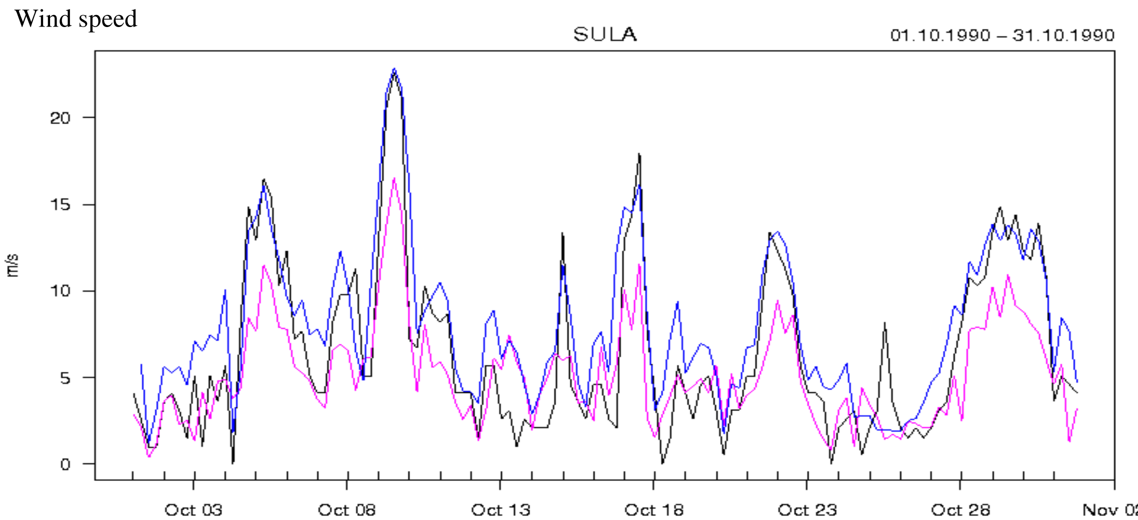


Figure 3 Average wind statistics for stations Draugen, Heidrun and Norne 1994-2002. Note that the anomalously high errors found in the first year must be due to calibration of observations. Only one station reported data before 1996.



	Min	Avg	Max	Std dev	*N*	ME	Std err	RMS err	MAE
Synop	0.0	6.5	22.6	4.9	124	-	-	-	-
ERA	0.4	5.2	16.5	3.0	124	-1.3	2.8	3.1	2.4
H10	1.2	8.0	22.9	4.4	123	1.5	2.2	2.7	2.1

Figure 4 Sula, coastal station at 63.85°N, 008.47°E, October 1990. ERA40: pink line, HIRLAM10: blue, synoptic observations: black.

10m wind	*N*	Mean	St.dev.	Mean abs. difference	RMS diff	Corr. coefficient	P90	P95	P99
Obs.	8364	8.4	4.2	-	-	-	14.2	15.9	19.5
HIRLAM10	8364	9.2	4.1	1.6	2.1	0.89	14.9	16.5	19.3

Table 1 Station Ekofisk 2000-2001 (56.5°N, 003.2°E) HIRLAM10 model *v* wind observations.

Wave statistics

The general agreement between observations and WAM10 is very good with correlation coefficients ranging from 0.94 to 0.97 for offshore stations (see Figure 5). Upper percentile distributions closely follow the observed distribution of significant wave height.

Table 2 compares the statistics for six different wave model configurations. Such simulations were only performed for selected periods as a preamble to the hindcast project to assess the quality of a high-resolution hindcast archive. WINCH refers to the old hindcast archive described by Reistad and Iden (1998). “WAM50 hindcast wind” refers to coarse simulations (see WAM50 domain in Figure 1) where winds were derived from digitized pressure fields. “WAM50 ERA40 wind” refers to simulations on the same domain but with winds from ERA40. “ERA40” refers to wave statistics from the ERA40 archive. Finally, “WAM10 + ocean model” and “WAM10” refer to two configurations of the new hindcast archive, the first with winds from HIRLAM10 with sea surface temperature (SST) and ice cover was computed using an ocean model, the second with winds from a HIRLAM10 run with SST and cover from ERA40. The ocean model had negligible effect on the wave statistics and was subsequently dropped. WAM10 scores very well on correlation, RMS error as well as the upper percentiles of the distribution.

Table 3 summarizes the statistics for the station Ekofisk in the middle North Sea for two periods from 1990-1992 and 2000-2001 and Draugen in the Norwegian Sea. The statistics for Ekofisk appear stationary throughout the model period. Draugen was built in the mid 1990s, hence no data exist for the first period.

Draugen January 2000								
Significant wave height	Mean	St.d	RMS	Corr	P90	P95	P99	Max.
Obs	4.95	1.95	-	-	7.8	8.4	9.6	10.0
WINCH	5.34	1.71	1.05	0.86	7.8	8.1	10.3	10.8
WAM50 hindcast wind	5.16	2.16	1.08	0.87	8.0	9.1	12.0	13.5
WAM50 ERA40 wind	4.46	1.61	0.86	0.94	6.8	7.2	8.8	9.1
ERA40	4.23	1.48	1.02	0.94	6.4	6.9	7.6	8.0
WAM10 + ocean model	4.80	2.02	0.72	0.94	7.8	8.9	9.8	10.1
WAM10	4.77	2.01	0.71	0.94	7.7	8.8	9.7	10.1

Table 2 Statistics of significant wave height at station Draugen for six different wave model configurations, January 2000.

Draugen 2000-2001									
Significant wave height	*N*	Mean	St.dev.	Mean abs. difference	RMS difference	Corr. coefficient	P90	P95	P99
Obs. (MIROS)	5177	2.60	1.67	-	-	-	4.8	6.1	8.2
WAM10	5117	2.61	1.59	0.39	0.54	0.95	4.7	6.0	8.1
Ekofisk 1990-1992									
Obs. (Waverider)	6345	2.18	1.26	-	-	-	3.8	4.6	6.2
WAM10	6345	2.16	1.33	0.25	0.34	0.97	4.0	4.7	6.4
Ekofisk 2000-2001									
Obs. (Waverider)	5689	2.05	1.17	-	-	-	3.8	4.4	5.8
WAM10	5689	2.03	1.25	0.26	0.36	0.96	3.9	4.6	5.8

Table 3 Stations Draugen and Ekofisk 1990-1992 and 2000-2001. WAM10 model *v* wave observations.

Figure 5 Offshore locations with wave and wind observations. The observations presented are taken from Ekofisk, Draugen, Heidrun, and Norne. Note that only small amounts of data are available from Varg and Draupner. Weather ship M (66°N, 002°E) is marked as "Polarfront".

Case: 10-11 Nov 2001

A low pressure system moving into the Norwegian Sea from the North Atlantic is setting up a significant wave height of more than 11m at 12UTC on November 10th (see Figure 6). This is in accordance with the wave growth expected for a wind speed of 25m/s (50 knots) blowing over a period of about 20 hours (Figure 4.1 in WMO, 1998). The strong wind field is moving roughly along a great circle path north of 66°N towards the Haltenbanken area (indicated by red line in Figure 9). During the evening of November 10th the wind is picking up to 28m/s (55 knots), see Figure 7. As the low pressure system continues eastwards, the wind weakens somewhat to 25m/s (50 knots) again (see Figure 8). The average speed of progression of the low pressure system over the 15 hours from 12UTC to 03UTC the following day is 13m/s. The peak period of the wave field (see Figure 9) varies between 15 and 17s which means the group speed of the peak waves is 11.5-13m/s, roughly coincident with the observed speed of progression of the low pressure centre. The situation is thus an example of enhanced wave growth due to moving fetch, with a strong wind field moving at roughly the same speed as the group speed at the spectral peak. This allows the waves to grow as if the fetch were significantly longer than the extent of the synoptic system. Also important for the evolution of the wave field was the linear progression of the storm track along a great circle path (Figure 9). It is also important to note that the winds observed are not extreme, but the wave height is significantly above the normal for storms found in this region. The observed and modelled wave height on Draugen (see location in Figure 6) is shown in Figure 10. WAM10 reproduces both the buildup and the decay of the storm very well. However, the highest observations are not matched by the model. It is unclear whether the observations are reliable at the peak of the storm.

Conclusion

We find that in general the new hindcast archive yields significantly better sea state statistics compared with the ERA40 data. In particular we find that the upper tail of the distribution of significant wave height corresponds better with observations. Improvement in wind field is particularly pronounced at coastal stations, but small-scale features in the open ocean such as polar lows are also better resolved.

Acknowledgements

This study has been funded by the Norwegian Deepwater Programme, Metocean Project under Contract No. C06200.

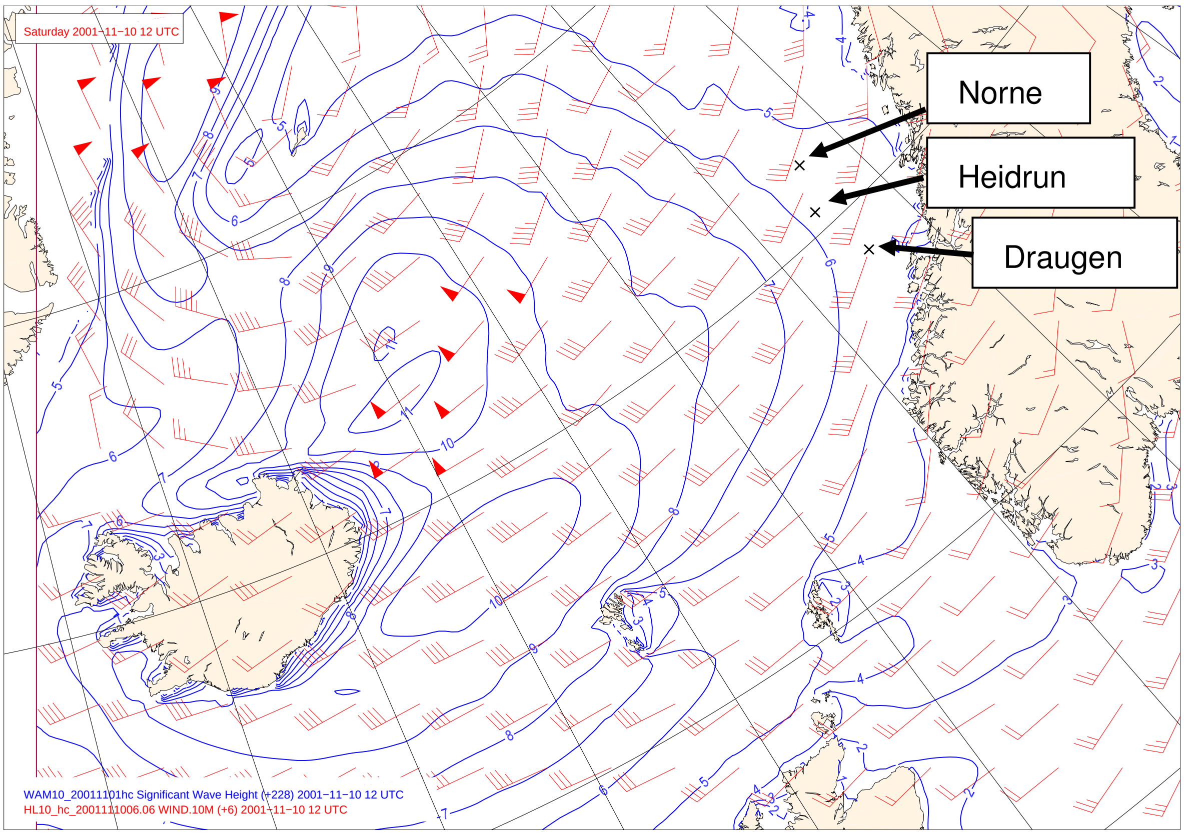


Figure 6 10m wind (knots) and significant wave height (blue) at 2001-11-10T12UTC. The wave field NE of Iceland has reached 11m. The maximum wind is around 25m/s (50 knots). Three offshore locations are indicated (crosses), Draugen at 64.3°N, 007.8°E, Heidrun at 65.3°N, 007.3°E and Norne at 66.0°N, 008.1°E.

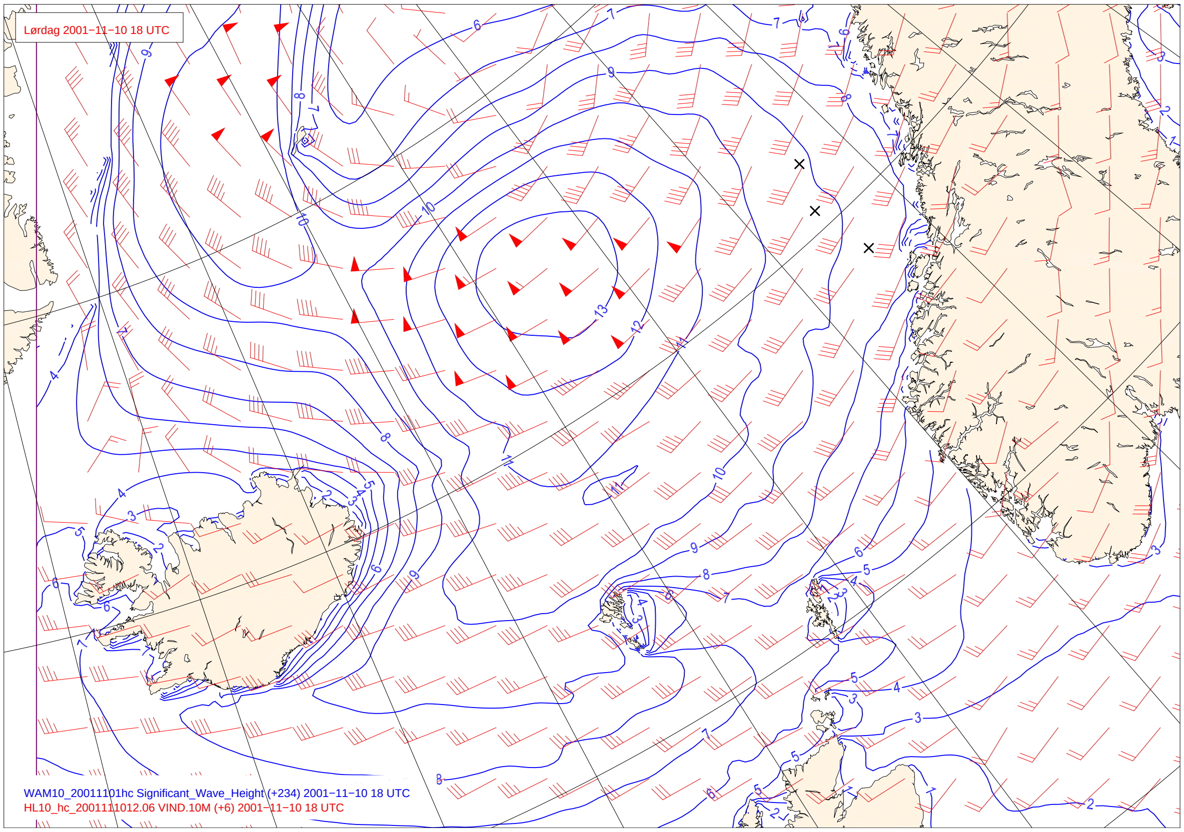


Figure 7 The wave and wind field six hours later at 2001-11-10T18UTC. The wind maximum has picked up to 28m/s (55 knots) whereas the wave field has a maximum of 13m significant wave height. The wind and wave maxima are seen to follow each other closely.

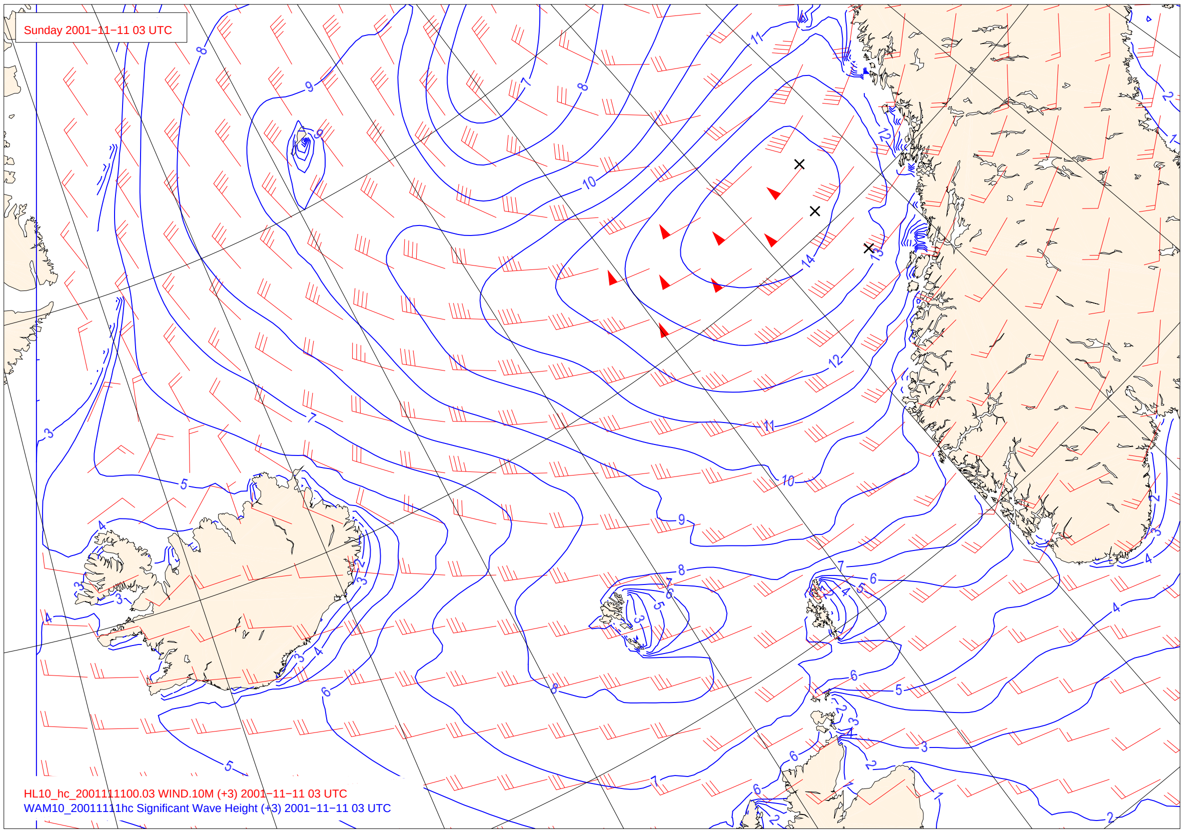


Figure 8 The modelled significant wave height reached 14.5m at 2001-11-11T03UTC.

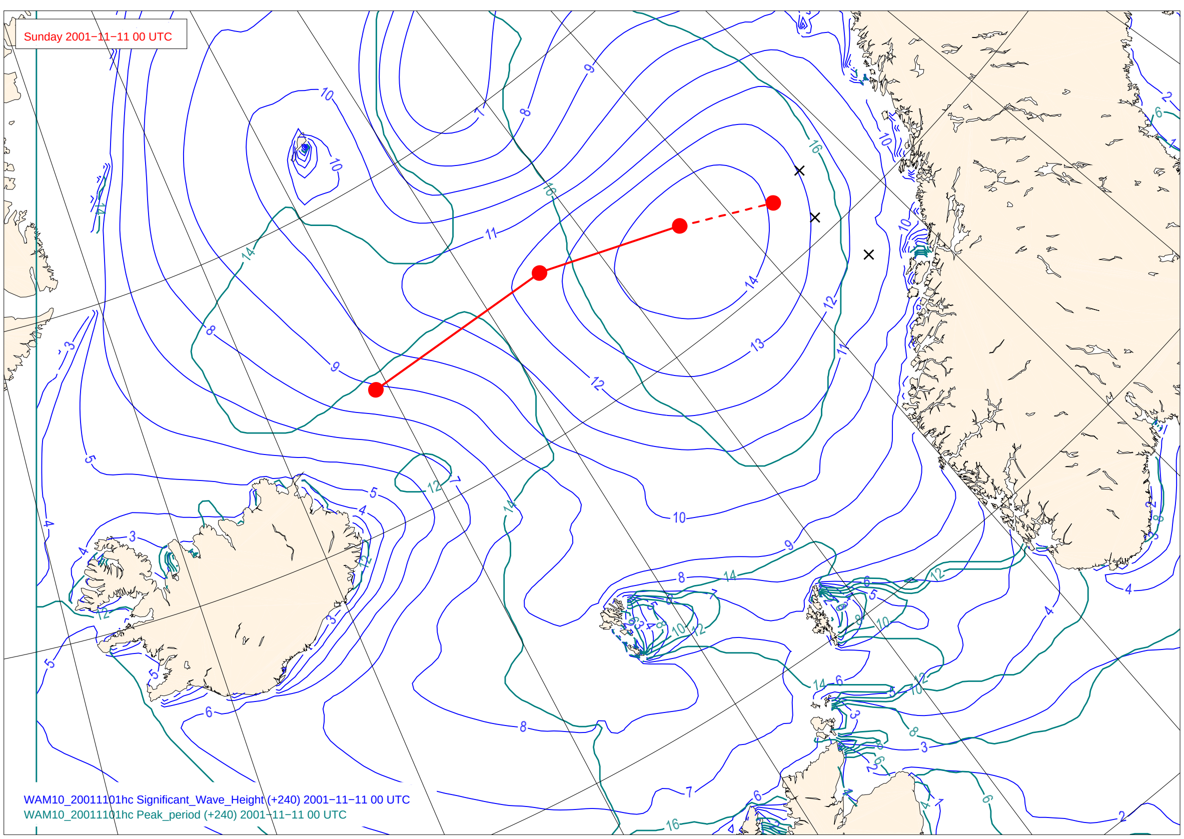


Figure 9 Peak period (cyan) *v* significant wave height (blue) near the peak of the storm at 2001-11-11T00UTC. The peak period is found to lie between 15 and 17s in the 12 hours of maximum intensity. This corresponds to a group speed of 11.5-13m/s, comparable to the average progression of 13m/s of the low pressure centre (position of maximum wind from 12UTC to 00UTC indicated by the red line, dashed towards location at 03UTC).

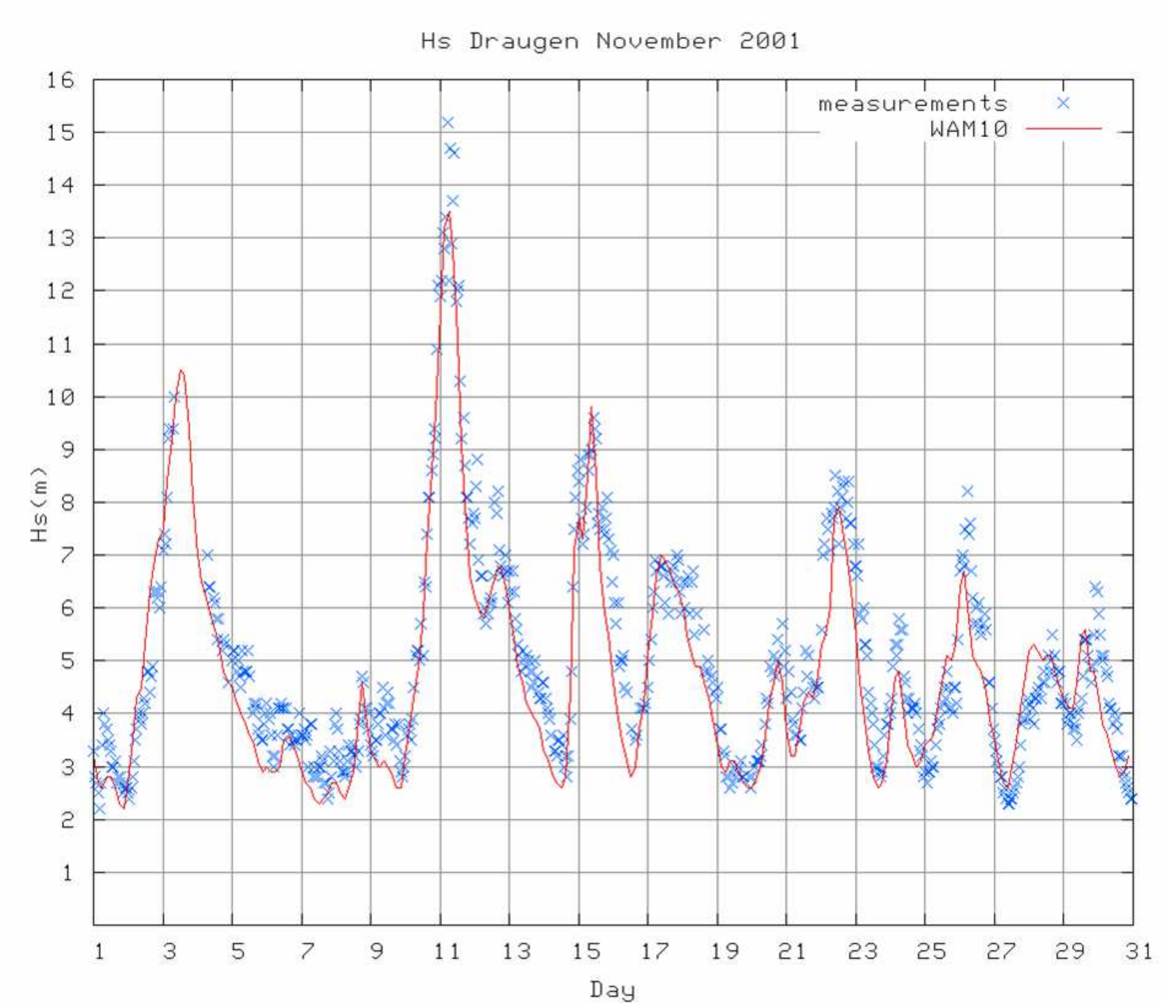


Figure 10 WAM10 *v* MIROS wave measurements at Draugen November 2001.

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