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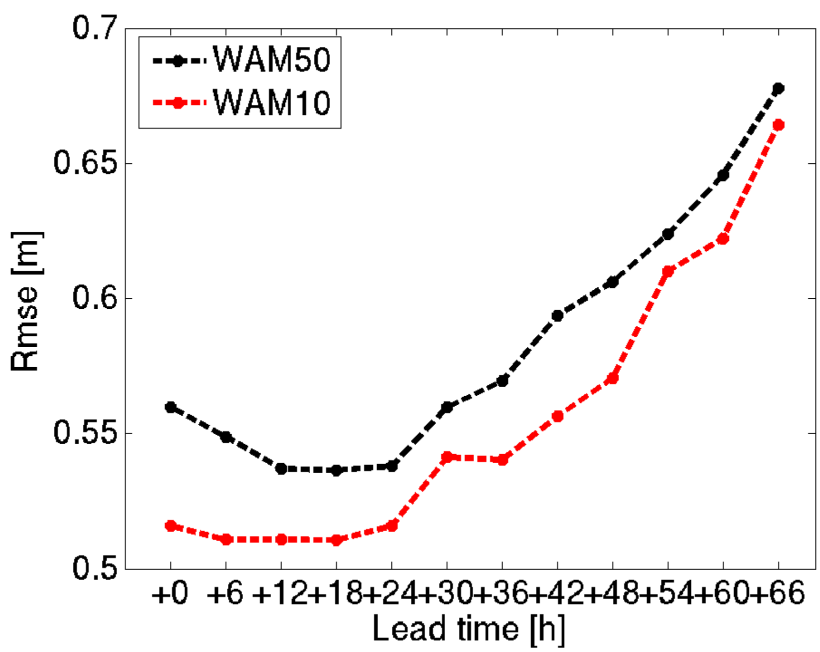

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Title

Validation of the Operational Wave Model WAM and SWAN - 2009

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Abstract

The significant wave height (Hs) from the operational wave models at met.no WAM and SWAN, is validated against EnviSat Radar Altimeter (RA-2) and in-situ buoy observations for the year 2009. WAM is run at 50km, 10km and 4km resolution (WAM50, WAM10 and WAM4) and is forced with 10m surface winds from the numerical weather prediction model Hirlam to produce a 66 hour forecast. SWAN is a wave model employed at met.no to forecast waves in coastal regions and is run operationally for Trondheimsleia and Karmøy. It is forced with 10m winds from UM to produce a 36 hour forecast with a grid spacing of 500m. We find that the agreement between observed and modeled Hs is very good for all WAM models with a correlation exceeding 0.95. However, for higher waves, Hs is overestimated in WAM. When comparing WAM10 and WAM50 we find that the behavior of the two models are quite similar, but WAM10 performs better than WAM50. When increasing the resolution from 10km to 4km, small improvements are shown. This may be due to the fact that the available buoys are located offshore where the advantage of WAM4 can not be seen. When comparing WAM4 and SWAN for the coastal areas at one observation site at Karmøy, we find that SWAN performs better than WAM4. SWAN is run on a finer resolution than WAM4 and have better physics to solve waves in shallow waters. Secondly, three cases during January and October, with high winds and high sea state has been evaluated for WAM50 and WAM10. We find that the storms are well predicted in both models, but often with an over- or undershoot in Hs, depending on the observation site.

Keywords

WAM, SWAN, Significant wave height,Validation

Disiplinary signature	Responsible signature

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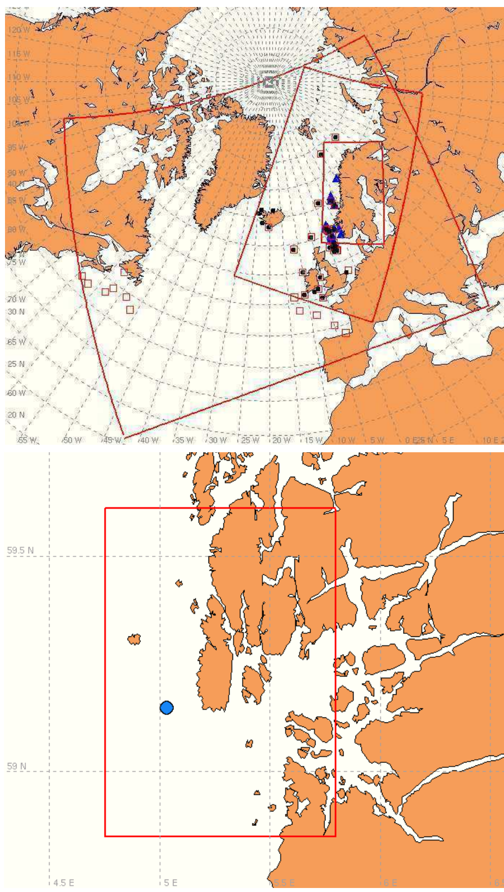
1 Introduction

The aim of the validation is to estimate the forecast skill of the operational wave models at the Norwegian Meteorological Institute (met.no) for the year 2009. The wave models run operationally at met.no are the regional wave model WAM at 50km, 10km and 4km resolution, and the nearshore wave model SWAN at 500m resolution. All models are run with 10m wind from Hirlam, except SWAN which is forced with UM wind. Both in-situ buoy and EnviSat Radar Altimeter (RA-2) data are applied to validate the wave models. The buoy sites are shown in Fig.(1), together with the model domains. The only wave parameter validated in this study is the significant wave height (Hs). To give a better estimate of the model skill, wave period, wave direction and the 10m wind should be studied in future work.



a) b)

Figure 1: a) Buoys and domains of WAM50, WAM10 and WAM4. The large domain corresponds to WAM50 the middle to WAM10 and the smallest to WAM4. b) The domain of SWAN for the Karmøy area, with the one and only buoy, Hywind.

2 Model

2.1 WAM

The operational wave prediction model at met.no is the third generation spectral wave model, WAM, initially developed by an international group of scientists [Saetra et al. (2004); Komen et al. (1994)]. At met.no, WAM50 is run four times a day at 50km resolution, with wind from HIRLAM12[1] as input data. Additionally, a WAM model with 10 km and 4 km resolution (WAM10 and WAM4) is run twice a day, forced with wind data from HIRLAM8[2] and HIRLAM4[3] respectively. WAM10 is nested into the 50km model while WAM4 is nested into WAM10. The higher resolution model WAM4 primarily covers the Norwegian coastal waters as shown in Fig.(1a). The forecast period for each model is 66 hours. Wave measurements from ERS-2[4] and ENVISAT[4] satellites are use to correct the initial state of the WAM model. The WAM model computes two-dimensional wave spectra. From the two-dimensional spectra, several parameters are computed, e.g. significant wave height, peak wave period, mean wave period, peak wave direction and mean wave direction. The wave parameters are computed for total sea, and for wind sea and swell.

2.2 SWAN

The wave model SWAN (Simulating Waves Nearshore) developed by The Technical University of Delft, The Nederlands [Booij et al. (1999)], was employed at met.no in 2005 for the forecasting and study of waves in coastal regions of Norway. It is a spectral wave model developed from the WAM model, optimized for shallow water and high spatial resolution. It propagates waves through a domain while including effects of refraction, shoaling, blocking and reflection due to variations in bottom and currents. Waves are generated by wind and dissipated (decaying) due to breaking and bottom friction. Wave-wave interaction (quadruplets and triads) account for the transport of energy between the frequencies. On the oceanic scales, SWAN is likely less efficient than WAM. The reason to use it in Norwegian coastal regions is that it runs on high spatial resolution, has better physics for shallow water and it is able to include variable currents. SWAN is run operationally for Trondheimsleia and Karmøy (shown in Fig.(1b) for the Karmøy area only) coastal regions twice a day, 36 hours ahead with a grid spacing of approximately 500m in each direction. SWAN receives two-dimensional wave spectra on the boundaries from WAM4km, and waves inside the domain are generated by hourly winds from the non-hydrostatic atmosphere model UM4[5]. Only SWAN Karmøy is validated here, since there is no buoys covering Trondheimsleia.

[1] HIRLAM12 = Atmospheric model with 12km resolution,[Unden (2002)]
[2] HIRLAM8 = Atmospheric model with 8km resolution,[Unden (2002)]
[3] HIRLAM4 = Atmospheric model with 4km resolution,[Unden (2002)]
[4] http://www.esa.int/esaEO/SEMGWH2VQUD_index_0_m.html
[5] UM4 = Atmospheric model with 4km resolution,[Davies et al. (2005)]

3 Data

3.1 EnviSat RA-2

The EnviSat RA-2 instrument operates on both Ku- and S-band. Former work [Abdalla (2005)] shows that the Ku-band Hs is of higher quality than the S-band Hs. Therefore, in this study we only apply the Ku-band Hs. Before collocating the observations and the model results, the altimeter data is quality controlled. Close to the coast and the ice edge some bad quality data occurs. These observations are removed from the data set. It is important to note that from experience with EnviSat and buoy observations, it is determined that the EnviSat wave height is slightly overestimated by 3-4 %, [Abdalla (2005)]. Further, to perform a proper validation, the scale of the observations must match the scale of the model. For our purpose, the resolution of the EnviSat RA-2 measurements (8km) are much higher than the model resolution of WAM50. Also the model resolution of WAM10 has a slightly higher mesh size then the observed wave height. An along track averaging of the observations are therefore performed. Before the altimeter data are averaged, the data are collocated against the model results. Due to the high resolution of the altimeter data, the model result in a grid-box may be collocated against more than one observation. This group of observations are then averaged. The maximum time span between model and observation is set to +/- 30 min. The coverage of the collocated altimeter data for the year 2009 is displayed in Fig.(2). The blue contours

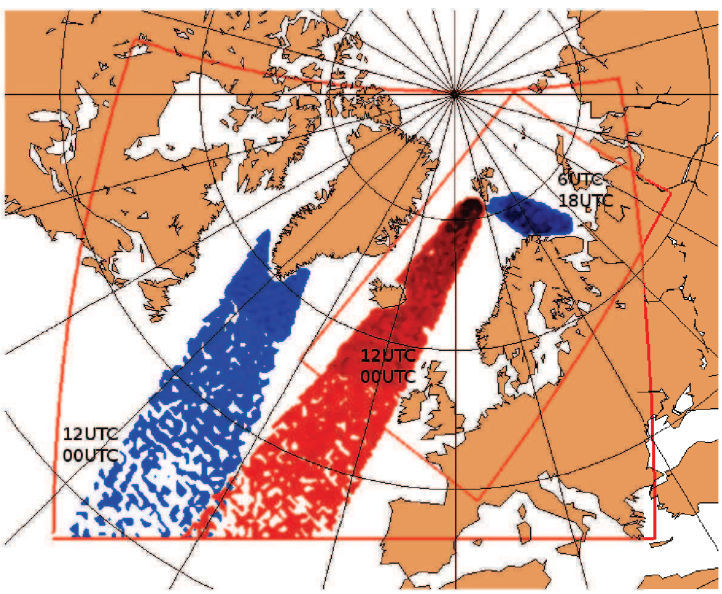


Figure 2: Displayed is the density of the collocated ENVISAT RA-2 observations during 2009. Red contours shows the coverage when the satellite is descending, while the blue contours shows the coverage when the satellite is ascending. The hours are the approximate time for the given paths, with a time span of +/- 30 min. The outer red area is the domain of WAM50, while the inner red area is the domain of WAM10.

represent the coverage when the satellite is ascending (from south to north), while the red contours represent the coverage when the satellite is descending (from north to south). The Figure shows a repeating pattern for the different satellite paths, which is due to the cyclic pattern of the satellite. The EnviSat RA-2 is continuously providing measurements around the whole orbit with a 35 day repeating cycle. At the same time, WAM is producing a 66 hour forecast four times a day (6UTC, 12UTC, 18UTC and 00UTC), where only results from the 12UTC and 00UTC runs are stored, and therefore validated in this study. Additionally, we have only validated the model results every 6 hour. The fixed model hours together with the cyclic observation pattern gives the limited observation coverage in Fig.(2). EnviSat RA-2 data are used to validate WAM50 and WAM10.

3.2 Buoys

The applied buoy observations is processed and quality controlled by the ECMWF. Since Buoys exhibit high-frequency variability not captured by the model results, the hourly observations are averaged in a window of 4 hours centered around the verification time, see Bidlot et al. (2002). The resulting time series have a 4 hour time interval. An example of this procedure can be seen in Fig.(3) where the raw and processed data from the station Draugen are plotted. Not averaging the data can result in a scatter between the models and observations [Janssen et al. (1997)]. For a more detailed description of the data treatment, see Bidlot et al. (2002) and Saetra et al. (2004). Unfortunately, not all observations are used. For example, in the English channel, the wave observations are not reliable due to uncalibrated instruments.

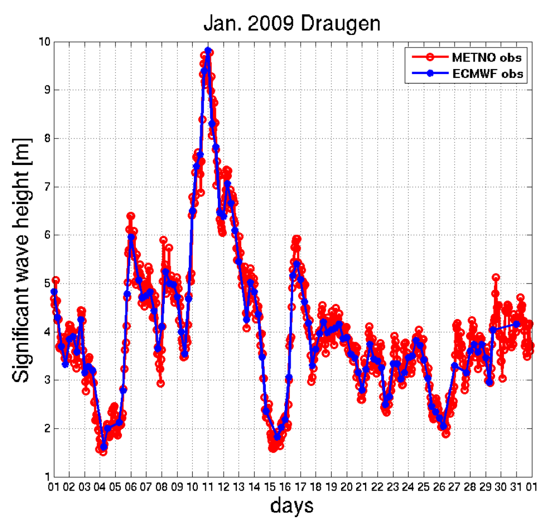


Figure 3: Time series of raw 20min (red line) and processed 4hr mean (blue line) observations for the month of January 2009 at station Draugen. The raw data are from met.no and the processed data from ECMWF.

Models	WAM50	WAM10	WAM4	SWAN
total obs	19478	15625	4538	80
total buoys	39	33	24	1
Models to compare	WAM50	WAM10		
obs	11800	11800		
buoys	27	27		
Models to compare		WAM10	WAM4	
obs		1700	1700	
buoys		10	10	
Models to compare			WAM4	SWAN
obs			76	76
buoys			1	1

Table 1: Numbers of buoys and observations used to validate the models. Observations refers to the number of observations at each forecast time. Also presented is the number of buoys and observations used when comparing two models.

A summary of the data used can be seen in Table (1). The locations of the buoys are shown in Fig (1). The observations used to validate WAM50 come from 39 buoys with approximately 19478 observations at analysis time, while the observations used to validate WAM10 come from 33 buoys with approximately 15625 observations. For WAM4, there are 24 buoys with 4538 observations, while SWAN is only validated against one buoy HYWIND, with 80 observations. For comparisons between the models, only observations similar for both models are applied.

4 Methods

4.1 Statistics

The skill is measured using standard statistics. The Mean Square Error ($MS\ Error$) and BIAS, is defined as

$$MS\ Error_j = \frac{1}{n}\sum_{i=1}^{n}(H_i^{mod} - H_i^{obs})^2 \tag{1}$$

$$BIAS_j = \frac{1}{n}\sum_{i=1}^{n}(H_i^{mod} - H_i^{obs}) \tag{2}$$

where the subscript j denote the day number in a month, i represent the observation number and H_i^{mod} and H_i^{obs} is the modeled and observed wave height respectively. The monthly Root

Mean Square Error (RMSE) and BIAS are then defined as

$$RMSE = \sqrt{\frac{1}{N_T}\sum_{j=1}^{N_d} MS\,Error_j \cdot N_j} \tag{3}$$

$$BIAS = \frac{1}{N_T}\sum_{j=1}^{N_d} BIAS_j \cdot N_j \tag{4}$$

$$N_T = \sum_{j=1}^{N_d} N_j \tag{5}$$

where N_j is the number of existing observations for day j and N_T is the number of observations in a month.

5 Results

5.1 ENVISAT-RA2

5.1.1 Each model

The collocated Hs of altimeter data and model analysis for both WAM10 and WAM50 are plotted as scatter diagrams and quantile-quantile plots (Q-Q plot) in Fig.(4) for the year 2009. A Q-Q plot is a graphical method for comparing two probability distributions by plotting their quantiles against each other. If the two distributions are similar, the points in the Q-Q plot will approximately lie on the 1:1 line. As the scatter plot shows, the agreement between the observed and the modeled Hs is very good for both models with a correlation of 0.96. However, the Q-Q plots shows an overestimation of Hs by WAM at the tail of the distribution, when the wave height exceed 6m. Otherwise, the model results fit the observed distribution well. It is worth noting that when we validate the analysis (12UTC and 00UTC), the observations covering the Barents Sea is not included, see Fig.(2). Additionally, due to the domain of WAM50 which covers a larger area than WAM10, observations south of Greenland and in the Atlantic outside Spain and Portugal are included when the WAM50 wave height is validated but not for WAM10.

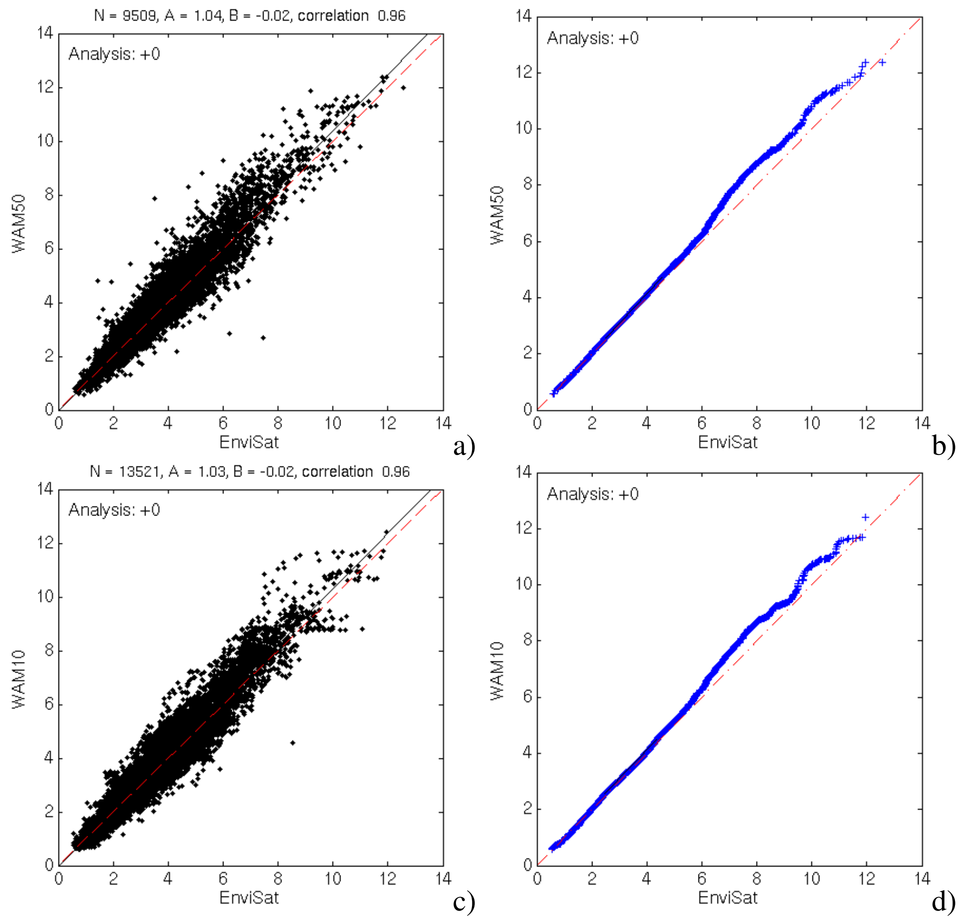


Figure 4: Shown are scatter and Q-Q plots between observed and modeled wave height for WAM10 and WAM50. The plots includes model results and observations from ENVISAT for the year 2009. The black line is the linear regression while the red dashed line represents the perfect fit between the two data sets.

5.1.2 WAM50 vs WAM10

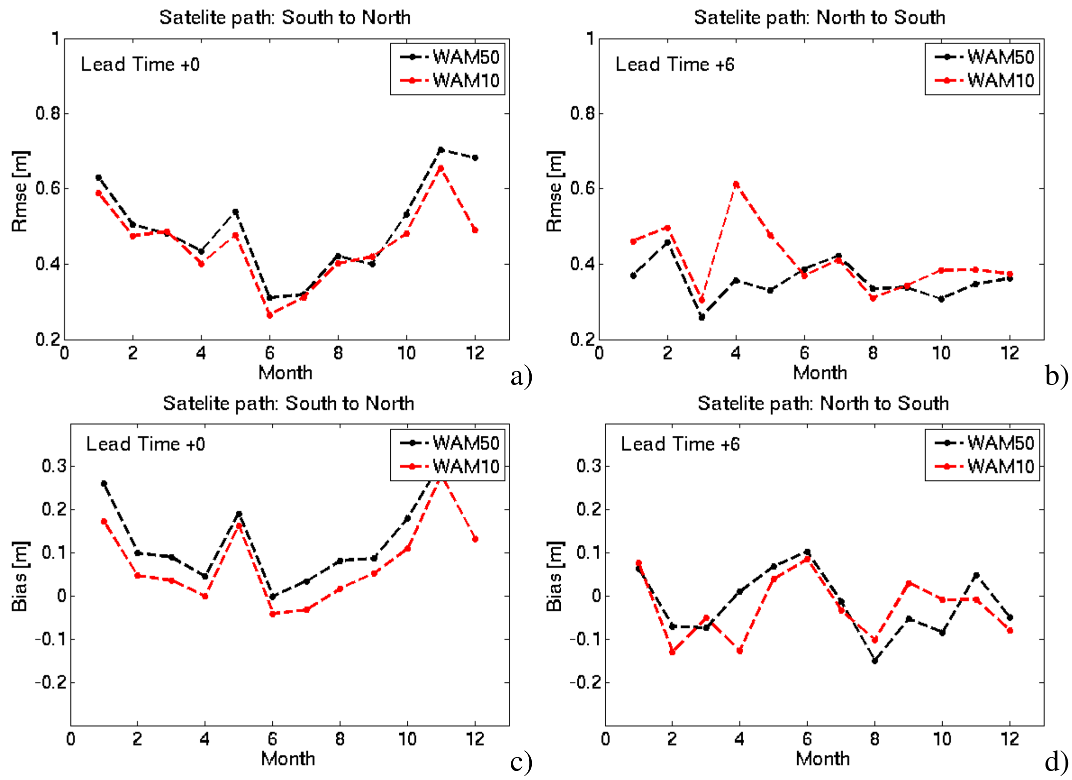


Figure 5: Displayed is a comparison of the wave height from WAM50 (black line) and WAM10 (red line) for each month in 2009. Figure a): shows the RMSE for the analysis, for the ascending path, figure b): shows the RMSE for the 6 hour forecast for the descending path. Figure c): shows the monthly BIAS (model minus observation) for the analysis for the ascending path and figure d): shows the BIAS for the 6 hour forecast for the descending path.

Shown in Fig.(5) is a monthly comparison between WAM50 and WAM10 for the year 2009. The plots show RMSE and BIAS between the modeled Hs and the collocated EnviSat Hs, where BIAS is model results minus observations. When comparing the two models for the analysis, only the observations from the ascending path (red area in Fig(2)) is applied. The observations south of Greenland which is included in the domain of WAM50 are therefore not included in this comparison. However, the satellite coverage west of Spain and Portugal is included in the WAM50 validation but not WAM10. The statistical comparison show how the models achieve approximately the same BIAS and RMSE for the analysis, however WAM10 has a slightly better agreement against the observations than WAM50, especially the BIAS. We can see how the different seasons effect the results with the lowest RMSE achieved around June. For the 6 hour lead time, as shown in Fig.(5b) and Fig.(5d), only the observations covering the Barents Sea is included in the comparison. For this area WAM50 has a better

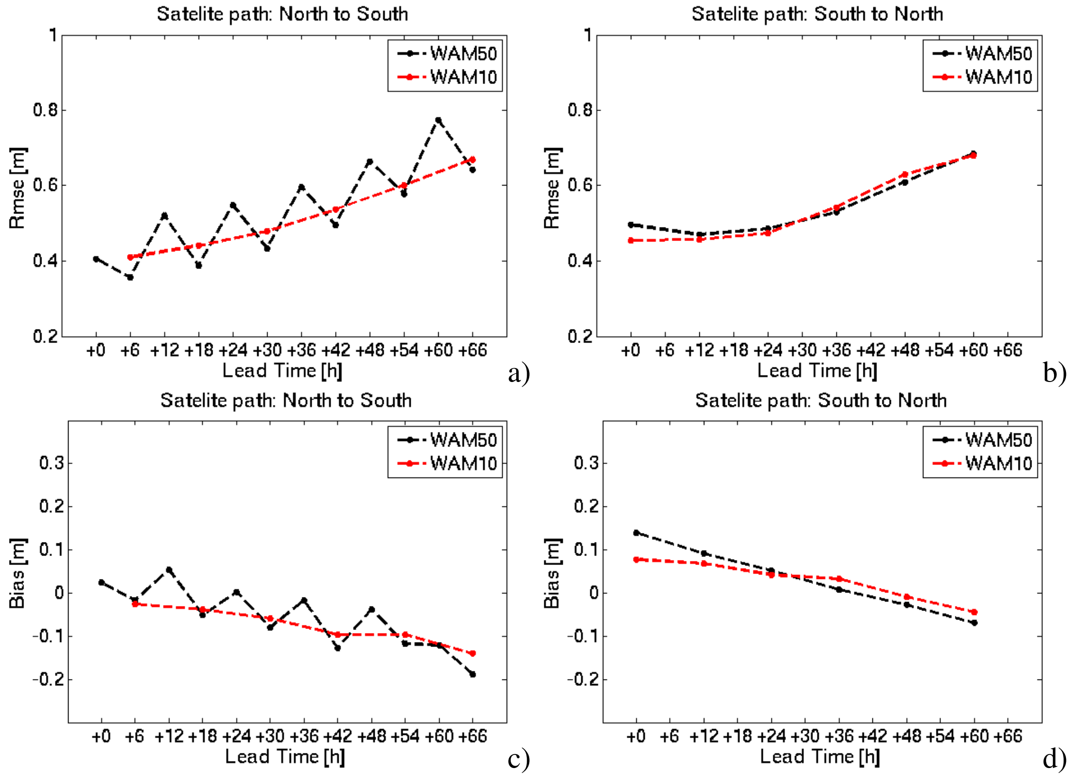


Figure 6: Displayed is the mean RMSE and BIAS (model minus observation) for each lead time for both WAM10 (red line) and WAM50 (black line). Figure a) shows the the RMSE for the descending path, while figure b) shows the RMSE for the ascending path. Figure c) shows the BIAS for the descending path, while figure d) shows the BIAS for the ascending path.

agreement against the observations than WAM10 when looking at the RMSE results, except in the summer period June to September. This may be due to the sea ice which occur during the winter months in the Barents Sea. The sea ice may lead to bad quality observations. Due to the along track averaging of the observations, WAM50 is validated against observation averaged over more data than WAM10. If bad quality data occur, this will have a larger effect in the WAM10 results. In Fig.(6), a comparison for each lead time for the two different paths are shown. As the results reveals, the RMSE increases with the lead time, while the BIAS (model minus observation) become more and more negative. For the ascending path in picture a) and d), WAM10 has a lower RMSE and BIAS for the analysis. However for the 30 hour lead time and onward WAM10 has a higher RMSE than WAM50. For the descending path we observe a saw tooth pattern in the WAM50 results. This is due to the path of the satellite. The peaks covers the area south of Greenland while the crests includes observations from the Barents sea. We can sea how the variable wave climate in the Atlantic gives a higher RMSE and BIAS. This reveals the difficulty of comparing the two models due to the different satellite coverage. Also in these results we can see how the validation of WAM50 gives better results in the Barents Sea (shown by the lower RMSE in the crests of the saw tooth pattern in Fig.(6a)).

5.2 Buoys

5.2.1 Each model

From the scatter and Q-Q plots at analysis time for the year 2009, shown in Figure (8), we can see that the three models WAM50, WAM10 and WAM4, behave quite well, but with a tendency towards overestimation. This is also seen in the validation against the EnviSat RA-2 data. However, the overestimation against buoy observations appears to be at lower Hs, around 3.75m, while for the satellite measurements the overestimation appears when the wave height exceeds 6m. The highest resolution model, WAM4, displays roughly the same behavior as the two coarse models.

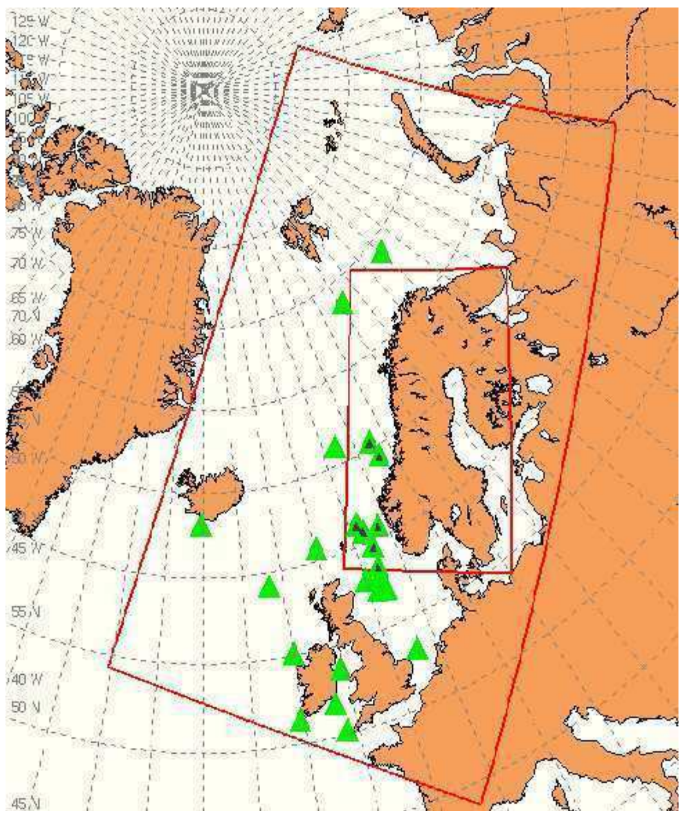


Figure 7: The green triangles are the buoys in common between WAM10 and WAM50. The small black triangles are the buoys in common between WAM10 and WAM4.

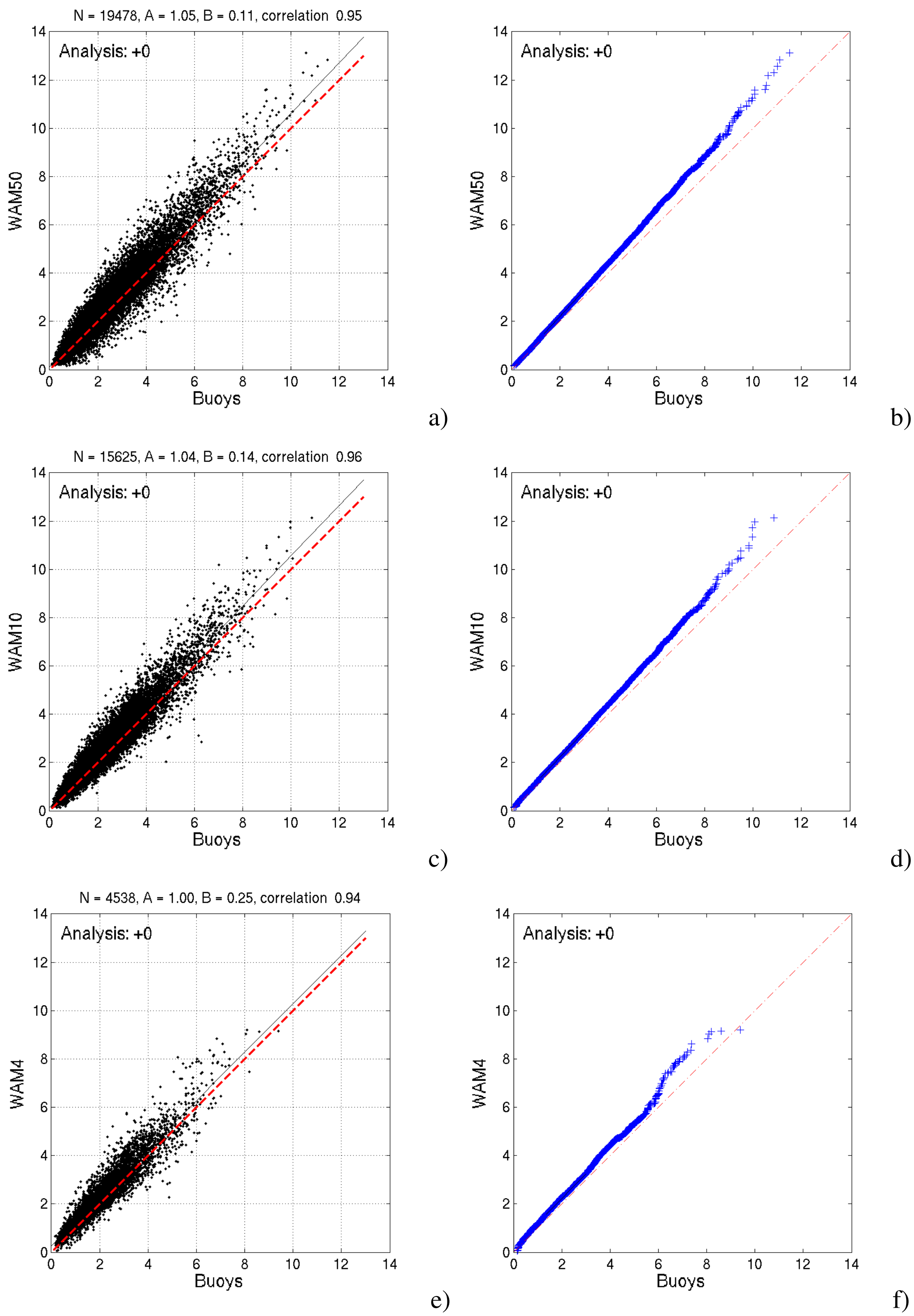


Figure 8: Scatter and quantile-quantile between observed and modeled significant wave height for WAM50 a) and b), for WAM10 c) and d) and for WAM4 e) and f).The black line is the linear regression line while the red line in the scatter plots refers to the perfect fit between the two data sets. The red line in the quantile-quantile plots indicates that the two sets come from a population with the same distribution.

5.2.2 WAM50 vs WAM10

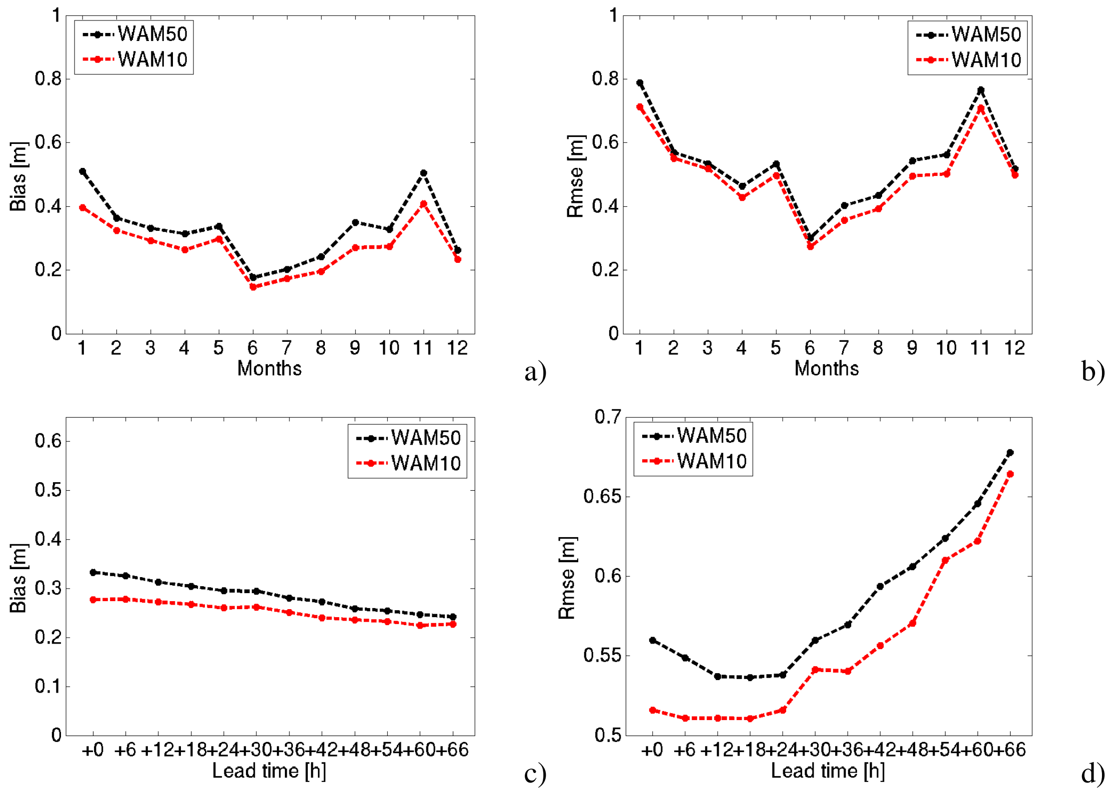


Figure 9: Comparison of the significant wave height from WAM50 and WAM10 during 2009. Figures a) and b) show the BIAS and the RMSE variation during the year for the analysis. Figures c) and d) show the BIAS ans RMSE with Lead time.

In order to make a statistical comparison between WAM50 and WAM10, only data of good quality and which are similar for both models are included. This collocation with two models reduced the number of data drastically, see Table (1). For the comparison between WAM50 and WAM10, only data from 27 buoys, with 11800 observations at each forecast time, marked with a green triangle in Fig.(7), are applied. The BIAS and the RMSE are plotted in Fig.(9). The behavior of these two models is quite similar, but WAM10 performs better than WAM50. At analysis time we can see how the models perform best during summer, specially in June, than during winter. This is expected due to the higher variability in the wave field during winter than summer. The BIAS is always positive and descreases with forecast time while the RMSE increases with forecast time. The difference in RMSE between the two models is larger than the one presented with the satellite data in Fig.(6). This may be due to the location of the buoys which are close to the coast while the satellite paths are more offshore. The finer resolution model may describing the wave field in a better manner nearshore than the coarse model, while offshore they are more similar.

5.2.3 WAM10 vs WAM4

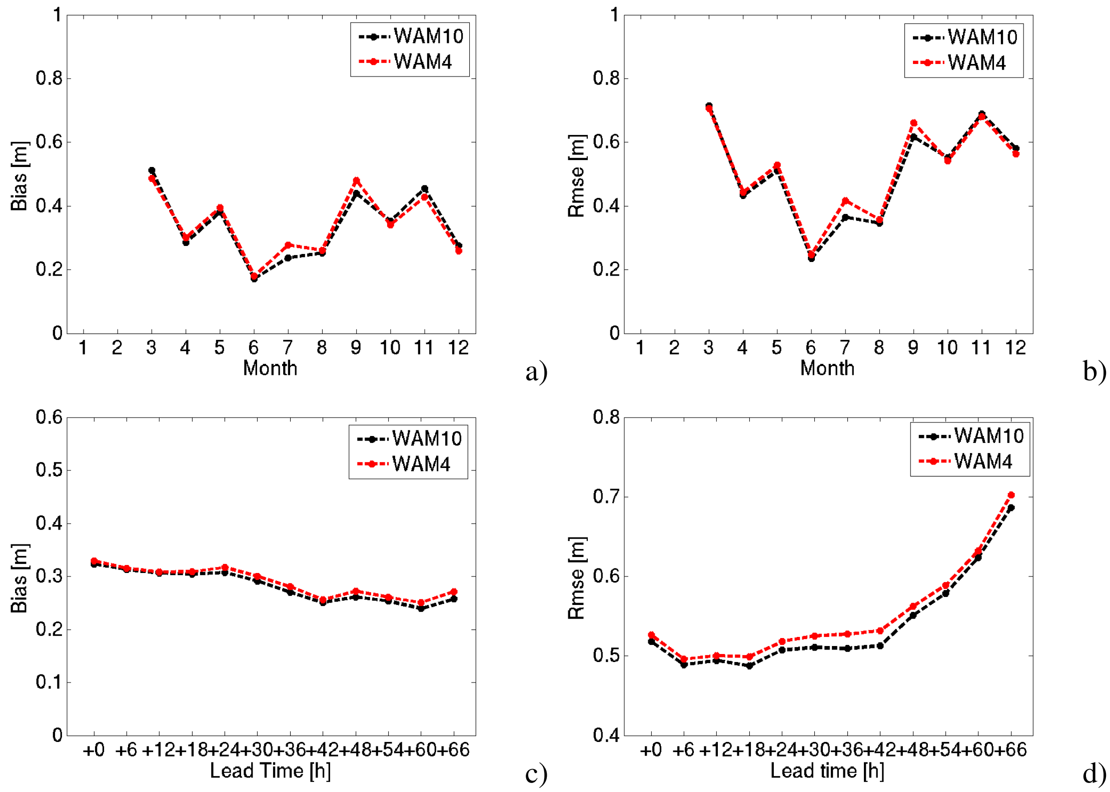
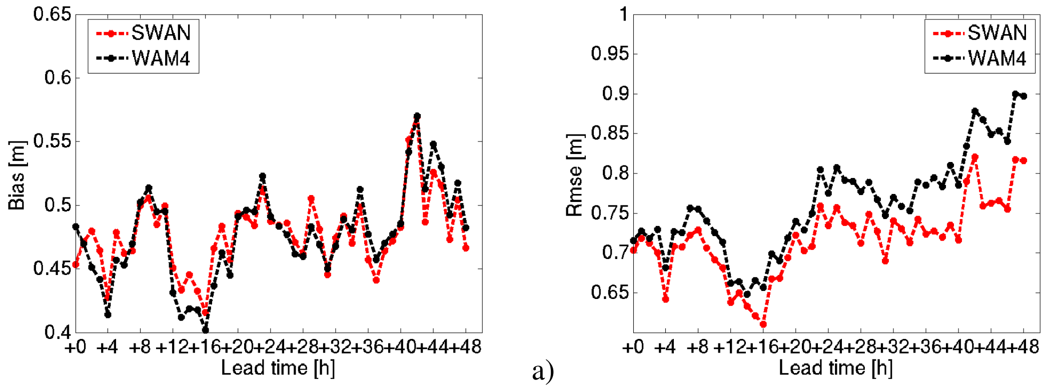


Figure 10: Comparison of the significant wave height from WAM10 and WAM4 during 2009. Figures a) and b) show the BIAS and the RMSE variation during the year for the analysis. Figures c) and d) show the BIAS and RMSE with Lead time.

The black triangles in Fig.(7) are the 10 buoys, with approximately 1700 observations, used to compare WAM10 with WAM4. The BIAS and the RMSE are plotted in Fig. (10). The striking feature is that the two models perform equally well, and it does not seem to be an apparent advantage of WAM4 over WAM10. This may be related to the fact that the buoys are located offshore, where the presumed advantage of running WAM4 is not in effect. The variation of the BIAS and RMSE in real time and in Lead time, Fig. (10), have the same features that was seen in Fig. (9).

5.2.4 WAM4 vs SWAN



a) b)

Figure 11: Comparison of the significant wave height from WAM4 and SWAN at the buoy HYWIND. Figure a) shows the BIAS while figure b) the RMSE.

For this comparison observations from only one buoy, Hywind, are used, see Fig. (1) b). After doing the the collocations with both models only 76 data points could be used. The BIAS and the RMSE plotted in Fig. (11) show that SWAN performs better than WAM4 in spite of the lack of data. The noisy curves are due to the lack of data as well.

5.3 Evaluation of three storm cases during 2009

2009 was a relatively calm year, but the following three cases with strong winds and high sea state were selected for a further study:

- Hs of 10m measured at Draugen and Heidrun 10-11 January 2009
- Hs of 10m at Gullfaks 16.-18. January 2009
- Hs of 8m at Ekofisk 3-4 October 2009.

Observations from oil rigs and a buoy operated by the Norwegian Coastal Authorities west of Skrova in Vestfjorden have been used for comparison. The locations of these are indicated on the map in Fig (12). Skrova and Ekofisk data originates from buoys, while the rest are MIROS-data (wave radar).

5.3.1 Case I: Draugen, Heidrun 10m Hs 10-11 January 2009

Two low pressures over Iceland moving towards Fram strait causes southwesterly 25-40knots winds in a long fetch from Shetland-Scotland towards Haltenbanken during January 9 and 10, shown in Fig(13) for January 10 at Draugen and Heidrun. The maximum in Hs of 10.16m occurs at Draugen at 22:40UTC on January 10 while the highest recorded Hs at Heidrun occur

Figure 12: Names and location of stations used in the comparison

much earlier, at 17:30 (11.09m), 17:40 (10.67m) and 18:00 (10.08m).
Fig(14) shows the observation of Hs together with prognoses from WAM50 and WAM10 for the period 9th - 13th of January 2009. Fig (14a) reveals how the storm in terms of Hs at Draugen, is well predicted. But there is an overshoot in Hs from both WAM10 and WAM50 of about 1m during the hours of the storm peak. At Heidrun, a larger overshoot of Hs is observed during the storm. WAM10 has the largest BIAS to the observations even for having the analysis closest to the storm peak (20090110 18UTC). This may be connected to the strength and direction of the tip jet at Stad, which has winds of 50knots in a region pointing northeast to the two platforms in HIRLAM8 (Fig (13)) during the hours 18-21UTC on January 10. If the wind is overestimated in HIRLAM8, it will effect the modeled wave field in WAM10 at Draugen and Heidrun. Fig(15) shows the differences in the forecasts from WAM50 and WAM10. The maximum in Hs in WAM50 lays North of Stad while in WAM10 it is closer to the shore. In this case it seems that WAM50 is most correct at both Draugen and Heidrun since waves measured at Heidrun (highest Hs in storm 11.09m) are higher than at Draugen (highest Hs in storm 10.16m). The high sea state passes into Vestfjord where we can compare the wave height with a wave buoy west of Skrova (see Fig (12)). Fig (14c) shows how WAM10 is over predicting the sea state at the buoy site and WAM50 is under predicting it. However, both models are forecasting the storm well in terms of Hs. This illustrates how a coarse model like WAM50 is able to predict Hs at Skrova when the wind is blowing from southwest into Vestfjord. WAM4 is not archived in this period and therefore not validated.

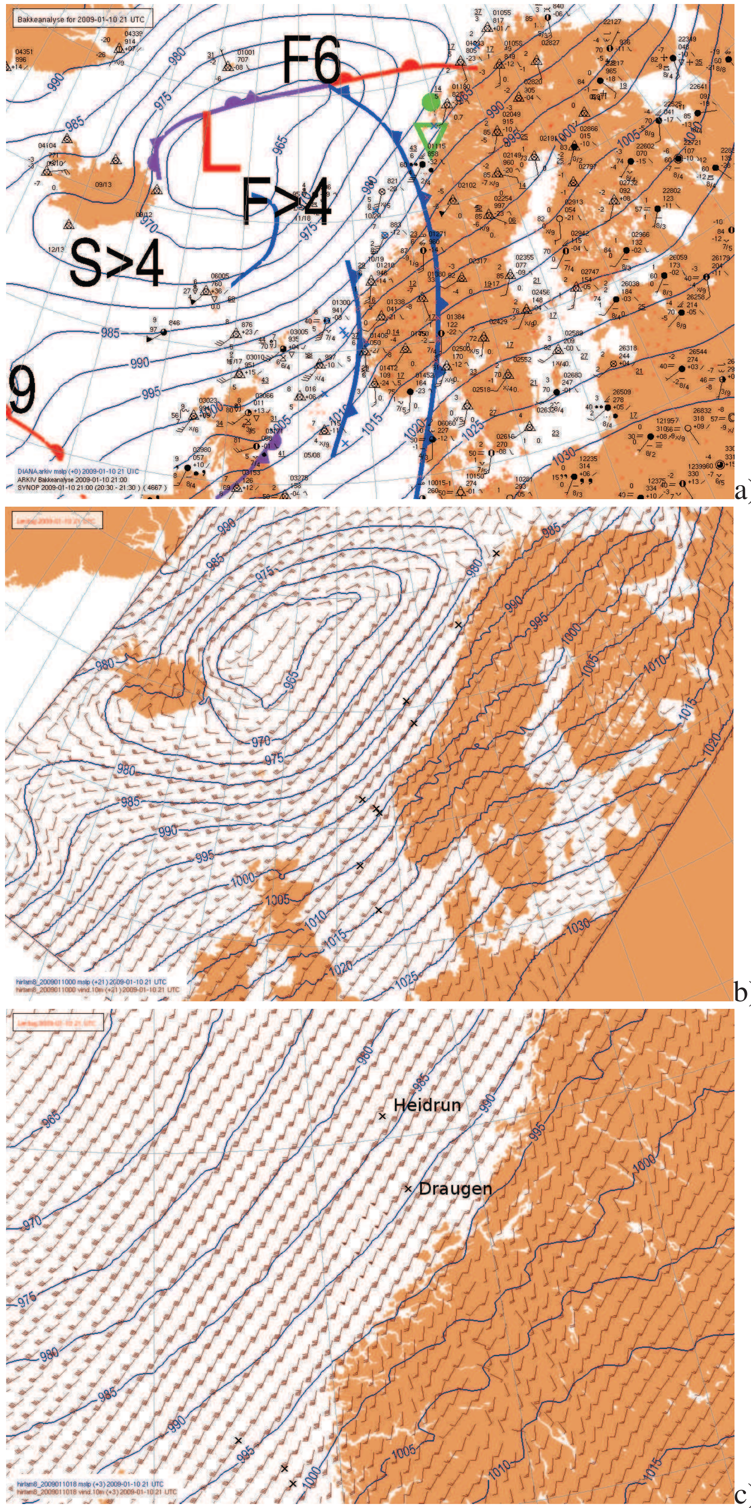


Figure 13: a) Analysis at 2009.01.10 21 UTC, b) HIRLAM8 forecast of MSLP (blue) and 10m wind vectors (red) for January 10, 2009 at 21UTC(+21), c) HIRLAM8 forecast of MSLP (blue) and 10m wind vectors (red) for January 10, 2009 at 21UTC(+21) for the observation sites of Heidrun and Draugen only.

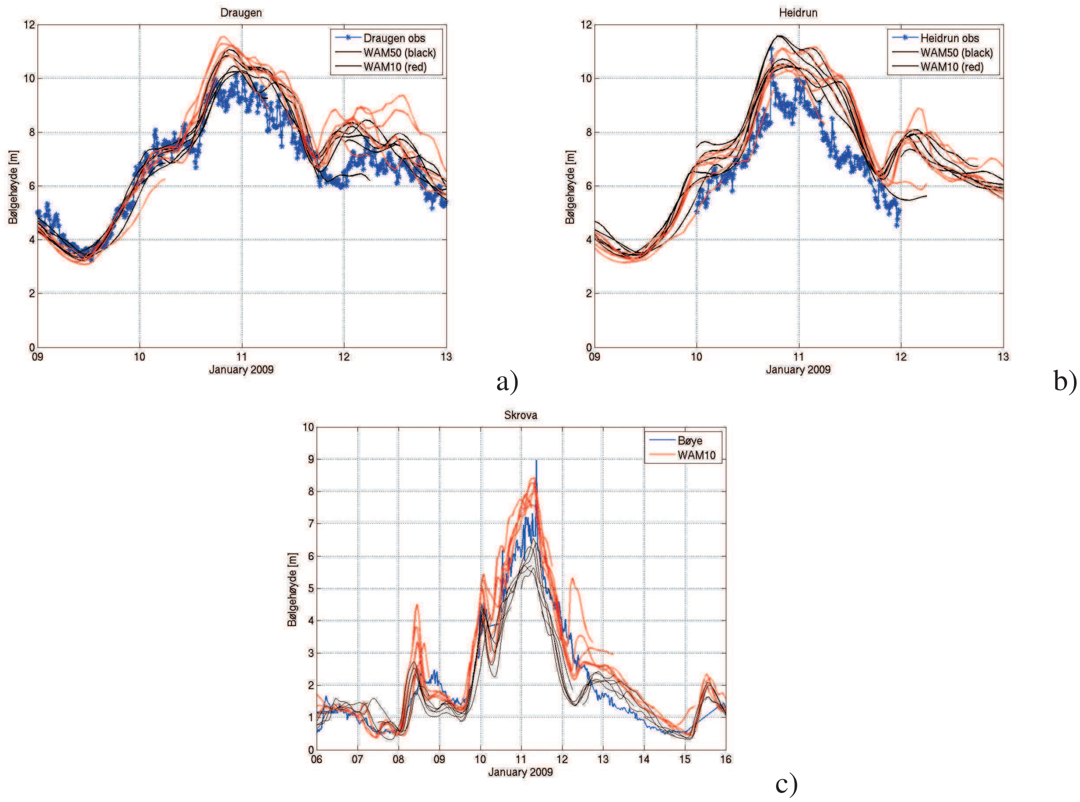


Figure 14: Observations of 10 min significant wave height at Draugen, Heidrun and Skrova (blue), and overlapping prognoses from WAM10 (red lines) and WAM50 (black lines). Figure a) and b) shows the results at Draugen and Heidrun for the period 9th - 13th of January 2009, and figure c) shows the results at Skrova for the period 6th - 16th of January 2009

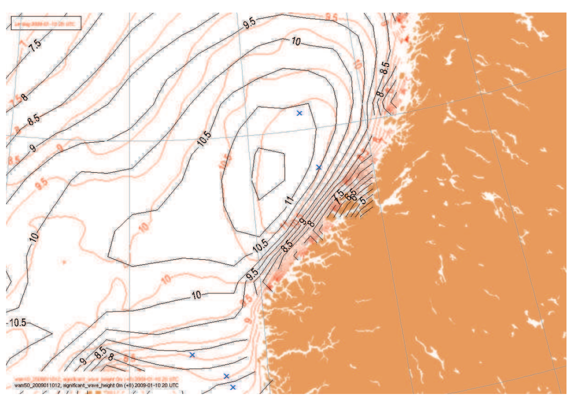
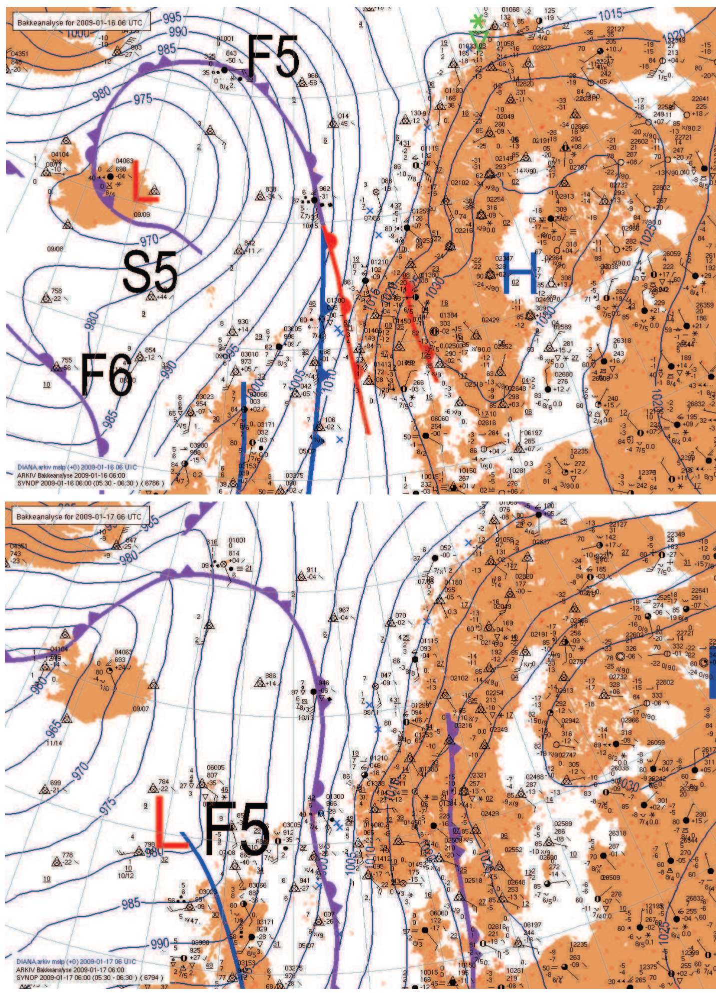


Figure 15: 2009.01.10 12UTC prognoses WAM50 (black) and WAM10 (red) valid at 2009.01.10 20UTC (+8 hours)

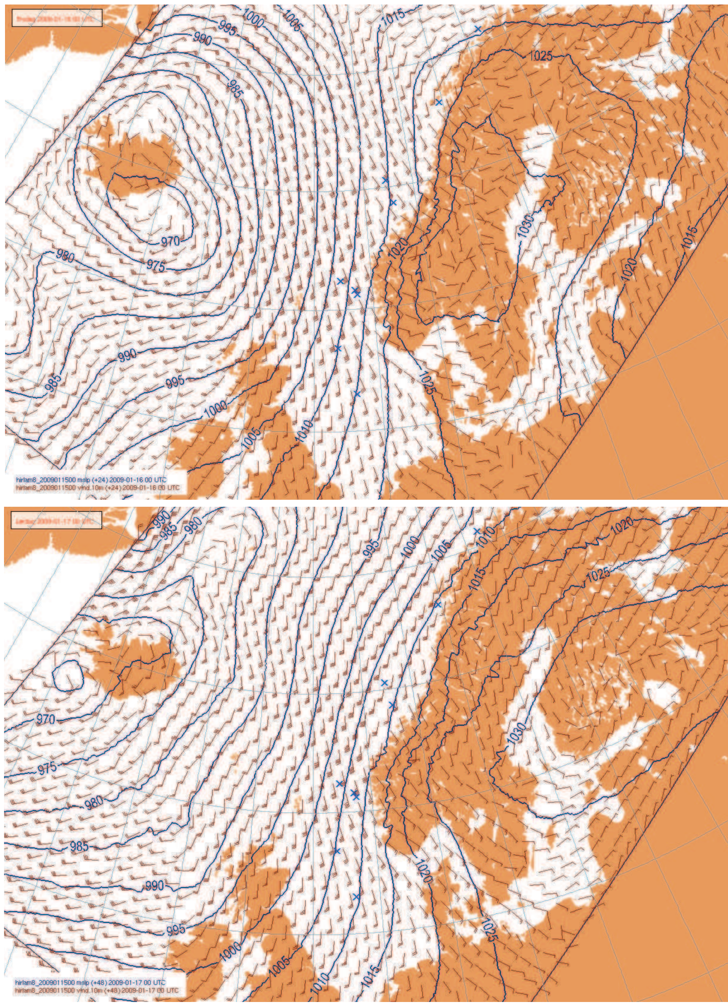
5.3.2 Case II: Gullfaks C Hs 10m 16.-18. January 2009

A week later, another series of low pressures are moving northeast over Iceland and together with high pressure over Finland, creating a southerly wind field in the North Sea, as shown in Fig.(16) and Fig.(17). The situation last for two days, with high sea state (Hs above 8m) recorded at Gullfaks C from the night between January 15 and 16 and until the morning of January 18, as displayed in Fig.(18).
From the time series compared to the observations at Heidrun, Gullfaks C, Troll A, Troll B and Sleipner we note that WAM10 and WAM50 have similar errors in this case. Both are overestimating the wave heights at Heidrun and underestimating at Gullfaks. Troll A and B are almost at the same location, so we may question the observations at Troll B, since the agreement at Troll A is good and the values at Troll A are more in the range observed at Gullfaks C and Sleipner, which lies North and South from Troll, respectively.



a)
b)

Figure 16: a) Analysis 2009.01.16 06UTC and b) 2009.01.17 06UTC.



a)

b)

Figure 17: HIRLAM8 MSLP (blue) and 10m wind vectors (red). 20090115 00UTC forecast for a) +24 hours, and b) +48 hours.

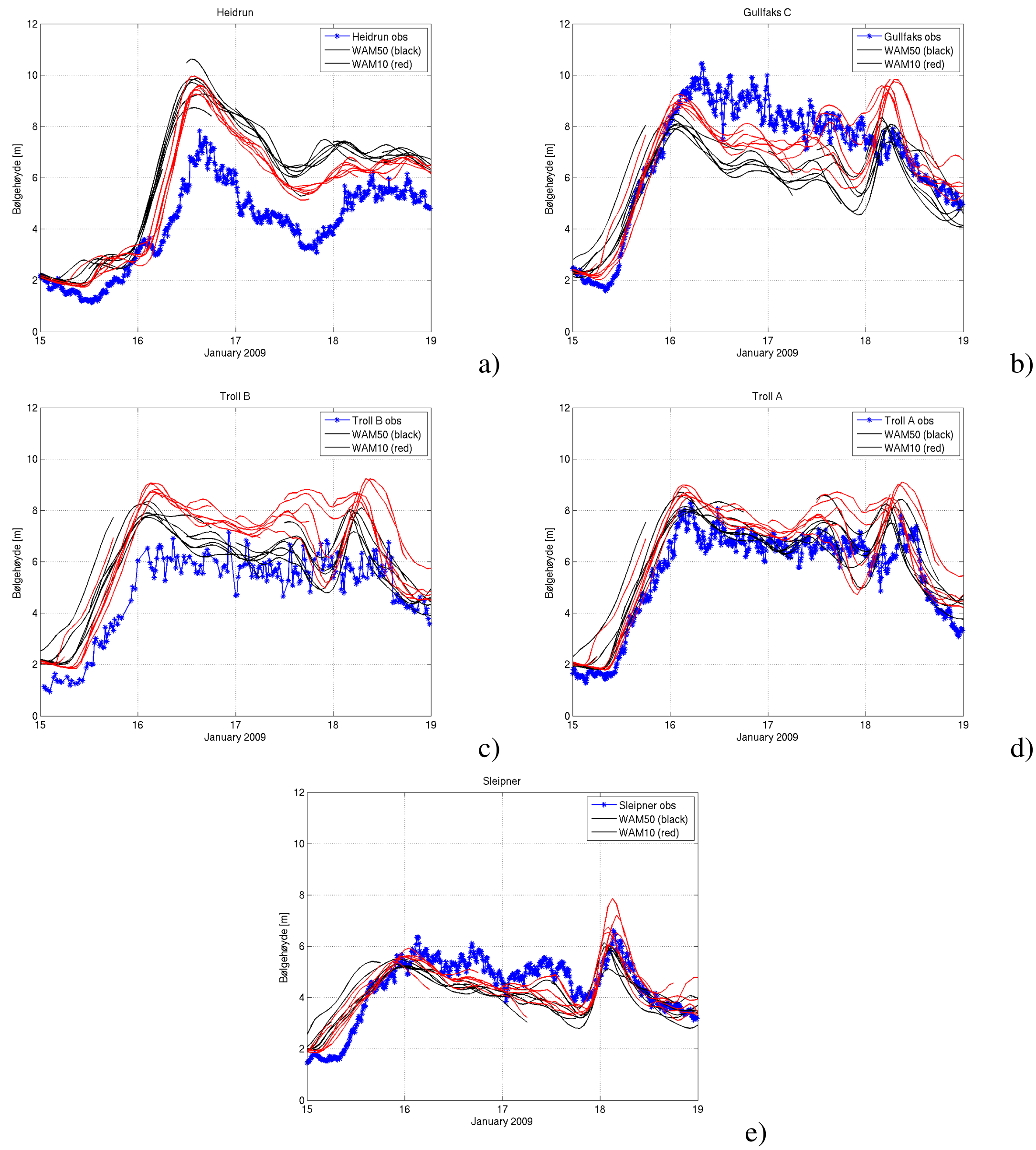


Figure 18: Timeseries from oilrigs in the order from North to South, Heidrun, Gullfaks C, Troll B, Troll A and Sleipner.

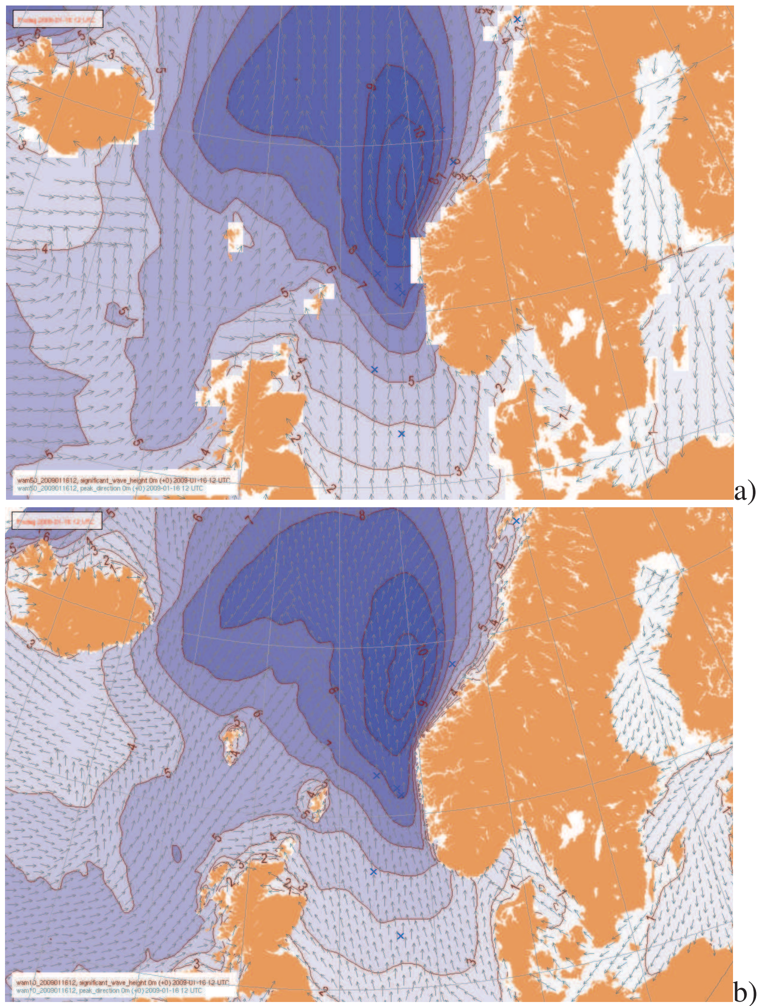
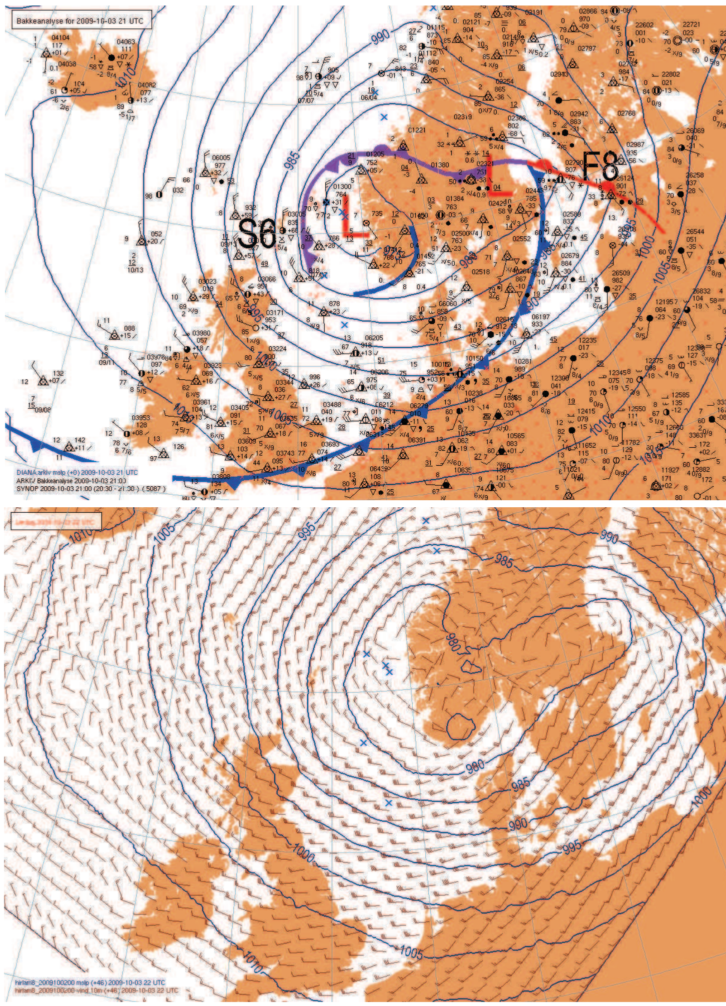


Figure 19: a)WAM50 and b) WAM10 Hs on 20090116 12UTC at +0hours.

5.3.3 Case III: Ekofisk Hs 8m 3-4 oktober 2009

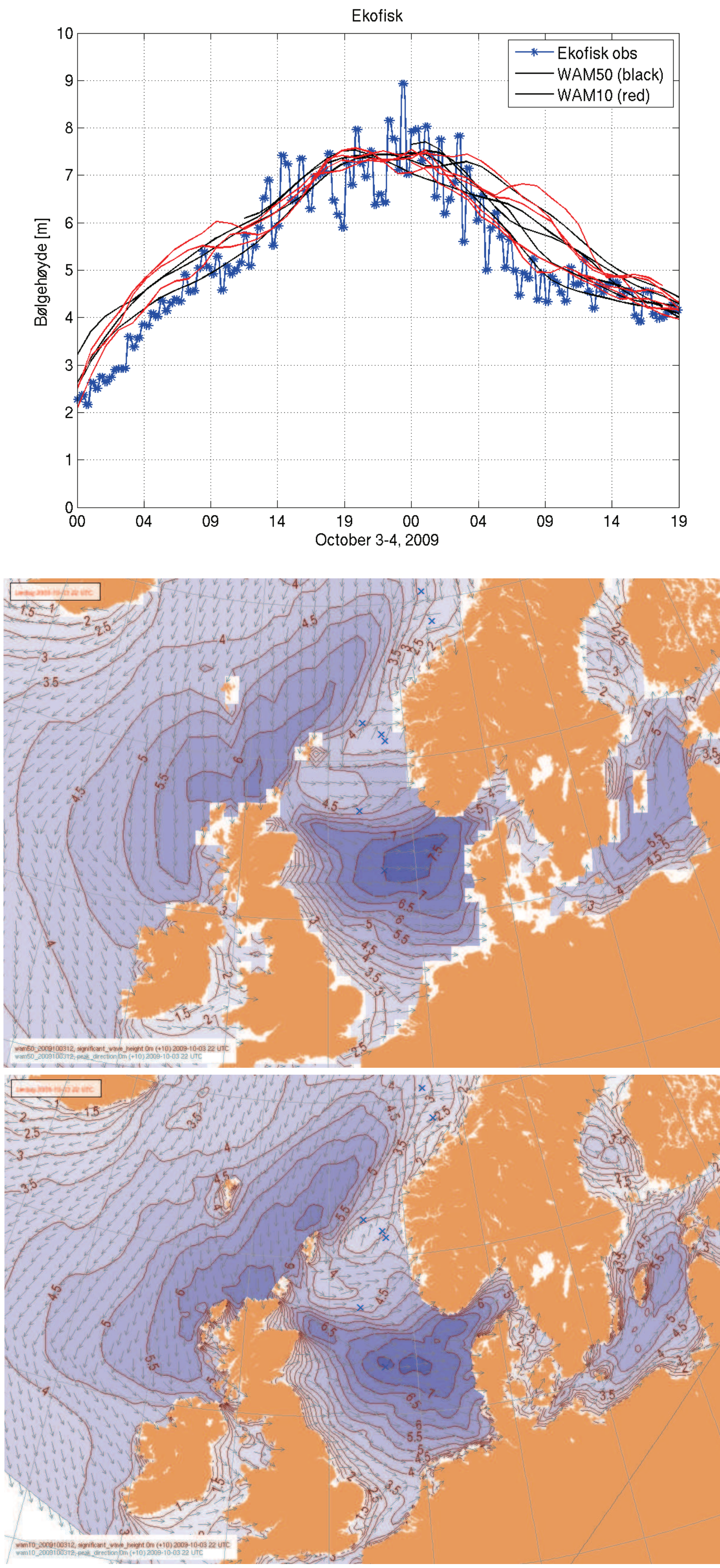
A low pressure (985hPa) over Iceland on October 2, deepens as it moves southeast and passes the North Sea on October 3 (Fig(20)). At Ekofisk in the southern North Sea the westerly winds were 40-45 knots with Hs about 7.5m during the evening and night of October 3-4. The highest Hs recorded was 8.93m at 23:20 UTC. The situation was well forecasted at Ekofisk by both WAM10 and WAM50 as seen from the time series in Fig(21a). Fig(21b and c) shows the wave forecasts valid at 2009.10.03 22UTC for both WAM10 and WAM50.



a)

b)

Figure 20: a) Analysis from 2009.10.03 21UTC and b) HIRLAM8 forecast 2009.10.02 00UTC at +46 hours.



a)

b)

c)

Figure 21: a) Shows wave height recorded at Ekofisk (blue), and forecast from WAM50 (black) and WAM10 (red). Figure b) and c) Shows Hs and peak direction from WAM50 and WAM10 forecast 2009.10.03 12UTC at +10 hours.

References

Abdalla, S., Global Validation of ENVISAT Wind, Wave and Water Vapour Products from RA-2, MWR, ASAR and MERIS, 2005, ESA report, Available at: http://www.ecmwf.int/publications/library/do/references/list/18

Bidlot, J. R., D. J. Holmes, P. A. Wittmann, R. L. Lalbeharry, & H. S. Chen, Intercomparison of the performance of operational ocean wave forecasting systems with buoy data, 2002, Wea. Forecasting, 17, 287-310.

Booij, N., R. Ris, & L. Holthuijsen, A third-generation wave model for coastal regions 1. Model description and validation, 1999, Journal of geophysical research 104(C4), 7649-7666.

Davies, T., M. J. P. Cullen, A. J. Malcolm, M. H. Mawson, A. Staniforth, A. A. Whilte, & N. Wood, A new dynamical core for the Met Offices global and regional modelling of the atmosphere, 2005, Q. J. R. Meteorol. Soc. 131. 1759-1782.

Janssen, P., B. Hansen, & J.-R. Bidlot, Verification of the ECMWF forecasting system against buoy and altimeter data, 1997, Wea. Forecasting, 12, 763-784.

Komen, G., J.L. Cavaleri, M. Donelan, K.Hasselmann, S.Hasselmann, and P.A.E.M. Jansen, Dynamics and Modelling of Ocean Waves, 1994, Cambridge University Press, 533 pp.

Saetra, Ø., and J.R. Bidlot, Potential Benefits of Using Probabilistic Forecast for Waves and Marine Winds Based on the ECMWF Ensemble Prediction System, 2004,American Meteorological Society, 673-689.

Unden, P., Hirlam-5 Scientific Documentation, (ed.) 2002, 1-144, Available at: http://www.hirlam.org