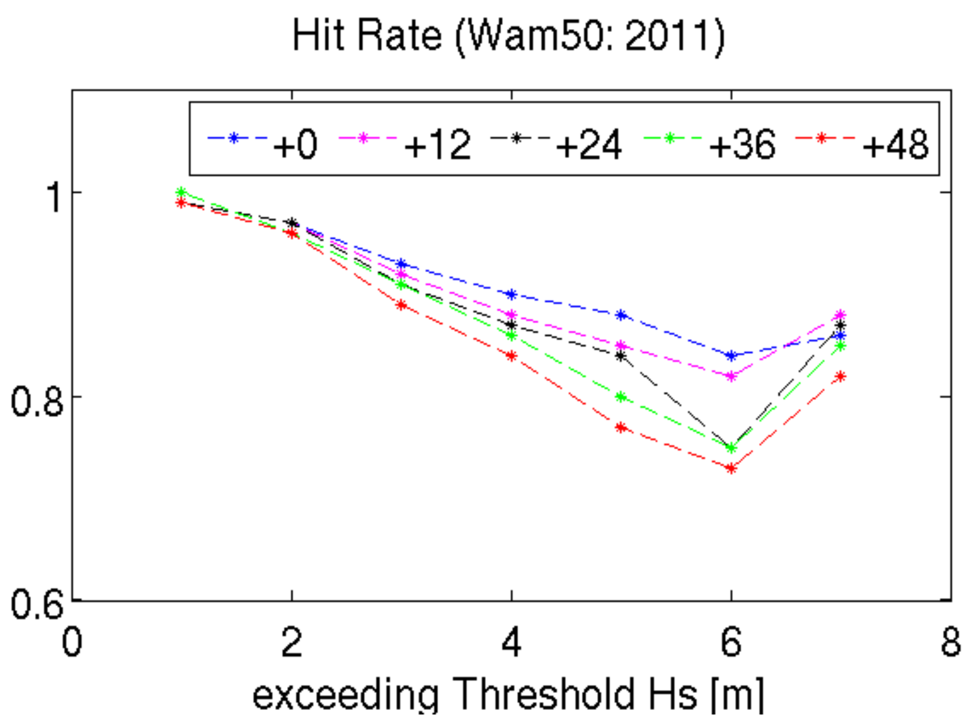
Norwegian Meteorological Institute
met.no

met.no report

Report no. 23/2012
Oceanography
ISSN: 1503-8025
Oslo, December 21, 2012

Validation of the Operational Wave Models - Report 2011

Yvonne Gusdal and Ana Carrasco



Norwegian
Meteorological Institute
met.no

report

Number	**Subject**	**Date**	**Classification**	**ISSN**
23/2012	Oceanography	December 21, 2012	☒ Open ☐ Restricted ☐ Confidential	1503-8025

Title

Validation of the Operational Wave Models - Report 2011

Authors

Yvonne Gusdal and Ana Carrasco

Client(s)	**Client reference**

Abstract

The significant wave height (Hs) from the operational wave model WAM and SWAN at met.no, is validated against EnviSat Radar Altimeter (RA-2) and in-situ observations. 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. The nearshore wave model SWAN is run at 500m resolution, forced with UM wind. We find that the forecast skill of Hs at met.no has improved over the period 1999 to 2011. Mostly due to changes implemented in the 10m forcing. However, due to the continually upgrade of the mesh size in HIRLAM, a systematically overestimation can be observed for Hs. The physics in WAM are not tuned due to these changes, and since 1998 an artificial enhancement of the wind has been used in the wave model. From November 1, 2011 this was removed. When comparing WAM50, WAM10 and WAM4 for 2011, the behavior of the models are quite similar. This may be due to the fact that altimeter data and available buoys are located offshore where the advantage of higher resolution models can't be seen. For one buoy located close to the coast, we can see how the wave model SWAN performs better than WAM10 and WAM4 as expectied since SWAN has better physics for shallow water than WAM. However, for the same location, the improvements of running WAM4 over WAM10 are small. The model that shows the highest score in this report compared to all WAM models at met.no, is the limited area wave model from ECMWF, run at 11km resolution (WAMECMWF). The reason for WAMECMWF to give better results than met.no WAM, may be due to the different atmospheric models forcing the wave models and the different set-ups. The WAMECMWF is a coupling between the atmospheric and wave model, while for the WAM models at met.no there is no coupling, and parts of the dynamics are therefore lost.

Keywords

WAM, SWAN, WAMECMWF, Significant wave height, Validation

Disiplinary signature	Responsible signature
Lars Andres Breivik	Øystein Hov

Postal address PO Box 43 Blindern N-0313 Oslo Norway
Office Niels Henrik Abels vei 40
Telephone +47 2296 3000
Telefax +47 2296 3050
e-mail: met.inst@met.no **Web:** met.no
Bank account 7695 05 00601
Swift code DNBANOKK

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). 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 winds 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 together with the model domains for WAM are shown in Fig.(1). The only wave parameter validated in this study is

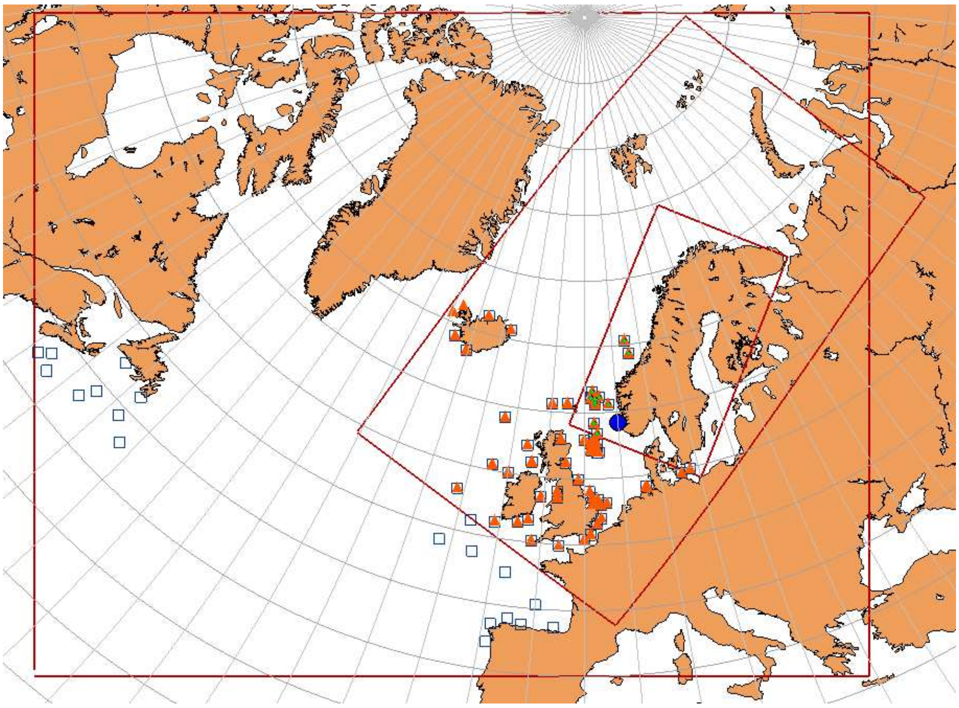


Figure 1: Buoys and domains of WAM50, WAM10 and WAM4. The large domain corresponds to WAM50 the middle to WAM10 and the smallest to WAM4. The blue dot corresponds to the Hywind station where results of three models; SWAN, WAM4 and WAM10, are compared with observations.

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.

The report is organized as follows. Chapter 2-4 gives an introduction of the wave models, the observations and the methods applied. Results from a long term validation of WAM since 1999 is presented in Chapter 5.1, while the forecast skill of the wave models for 2011 is shown in Chapter 5.2, 5.3 and 5.4. Finally, in Chapter 6 we have the summery and conclusions.

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.(1). The forecast period for each model is 66 hours. Wave measurements from ERS-2[4] and ENVISAT[4] satellites have been used to correct the initial state of the WAM model. However, on July 5, 2011 the ERS-2 satellite was retired after 16 years of successful operations and on April 8, 2012 communication with ENVISAT was lost. As a consequence, there is no assimilation of significant wave height in WAM from April 8, 2012. In table 3 in Appendix A, there is an overview of all main changes effecting the wave model set-up/code since 2003.

The WAM model computes two-dimensional wave spectra, with 25 frequencies and 24 directions. 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. WAM at ECMWF

Met.no has access to the wave forecast from the WAM of ECMWF. The WAM model at ECMWF is a different version to the one run at met.no but essentially has the same source code. The WAM model at ECMWF is coupled to their atmospheric model TL799L91, producing 10 days forecast every 12 hrs. The output data from their Limited Area model (LAW) were used in this report. The LAW, which covers the area from 5N to 90N and 98W to 56E, has a 11 km resolution and it is forced with 10 m neutral wind fields from the global system. The wave energy spectra is discretized into 36 frequencies and 36 directions. The model assimilates data from altimeter wave heights (ENVISAT and Jason 2).

2.3. SWAN

The wave model SWAN (Simulating Waves Nearshore) developed by The Technical University of Delft, The Netherlands [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

[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

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 Karmoy 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 Karmoy is validated here, since there is no buoys covering Trondheimsleia.

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 than the observed wave height. An along track averaging of the observations is 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 is displayed in Fig.(2). The blue contours 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 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

[5] UM4 = Atmospheric model with 4km resolution,[Davies et al. (2005)]

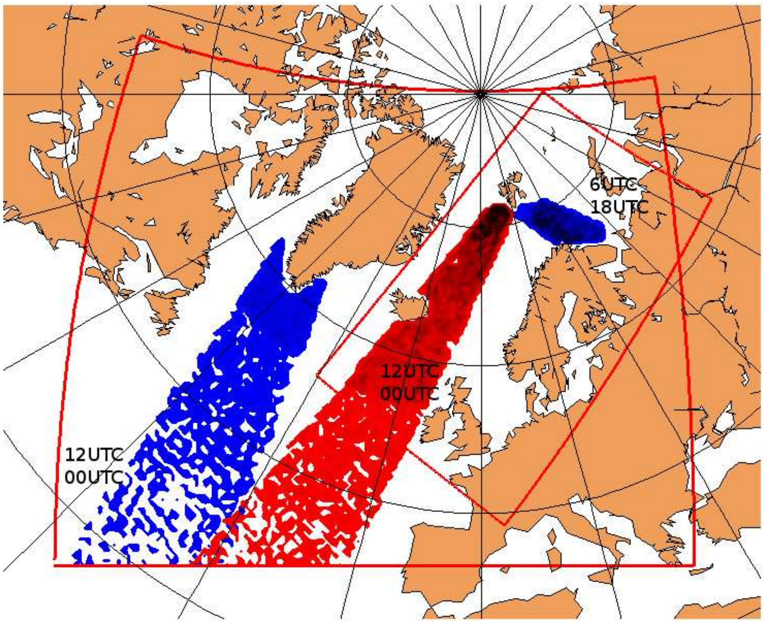


Figure 2: Displayed is the density of the collocated EnviSat RA-2 observations. Red contours shows the coverage when the satellite is descending, while the blue contours shows the coverage when the satellite is ascending. The hours are the approximate time for the given paths, with a time span of +/-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

observation coverage in Fig.(2). EnviSat RA-2 data are used to validate WAM50 and WAM10. For a reasonable comparison between the two models, only observations inside the WAM10 domain is applied (the inner red area shown in Fig.(2)).

3.2. Buoys and Wave Radar observations

3.2.1. Observations from ECMWF

The applied buoy observations in Chapter 5.4, 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. 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). A summary of the data used can be seen in Table 1. The locations of the buoys are shown in Fig.(1). For this report we have access to more buoys observations than in the previous reports. The observations used to validate WAM50 come from 87 buoys with approximately 46233 observations at analysis time, while the observations used to validate WAM10 come from 74 buoys with approximately 37163 observations. For WAM4, there are 24 buoys with 7081 observations. To validate SWAN we have only one buoy, HYWIND,

Models	WAM50	WAM10	WAM4	SWAN	WAMECMWF
total obs	46233	37163	7081	111	
buoys used	87	74	24	1	79
Models to compare	WAM50	WAM10			
obs	34600	34600			
buoys	59	59			
Models to compare		WAM10	WAM4		
obs		7100	7100		
buoys		13	13		
Models to compare		WAM10	WAM4	SWAN	
obs		90	90	90	
buoys		1	1	1	
Models to compare	WAM50				WAMEC
obs	33764				33764
buoys	79				79
Models to compare		WAM10			WAMEC
obs		27026			27026
buoys		63			63
Models to compare			WAM4		WAMEC
obs			5270		5270
buoys			12		12

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

which is also in the WAM10 and WAM4 domains.

3.2.2. Observations from met.no

The six sites in the Norwegian and North sea used to validate WAM in Chapter 5.1 and 5.2 are shown in Fig.(3). These in-situ observations are quality controlled at met.no, but have not been averaged in a window of 4 hours as for the observations processed at ECMWF. They have been averaged over each hour, and the resulting time series have a 1 hour time interval. This is the same method used in previous work on validating WAM, see Gusdal (2010). Since the results in Chapter 5.1, are extended time series from former study, we apply the same method in this study.

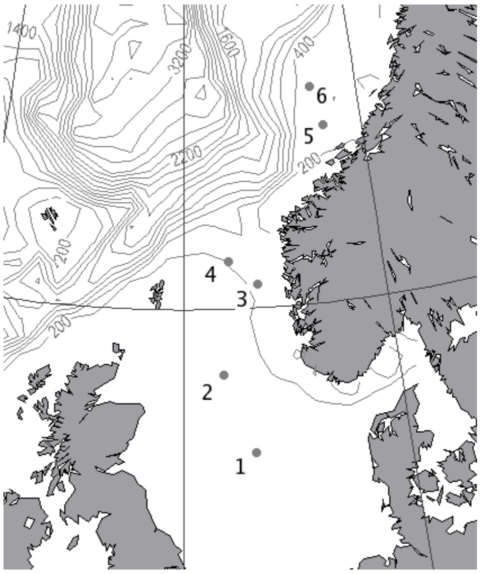


Figure 3: Displayed is the observation sites located in the Norwegian and the North Sea applied in Chapter 5.1. The sites are 1: Ekofisk, 2: Sleipner, 3: Troll A, 4: Gullfaks C, 5: Draugen and 6: Heidrun.

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.

4.2. Categorical Statistics

Table 2: Contigency table, showing the frequency of "yes" and "no" forecasts and occurrences.

		Observed		
		yes	no	Total
	yes	hits	false alarm	forecast yes
Forecast	no	misses	correct negatives	forecast no
	Total	observed yes	observed no	total

hits - event forecast to occur, and did occur

misses - event forecast not to occur, but did occur

false alarm - event forecast to occur, but did not occur

correct negative - event forecast not to occur, and did not occur.

Categorical statistics are computed from the contigency table to describe particular aspects of the forecast performance. For example, the forecast skill for wave heights exceeding 7m. A large variety of categorical statistics can be computed from the table, in this study the following have been computed:

Hit Rate - measures the fraction of the observed yes events that were correctly forecasted!

$$\frac{hits}{hits + misses} \tag{6}$$

False alarm ratio - measures the fraction of the predicted yes events that did not occur

$$\frac{falsealarm}{hits + falsealarms} \tag{7}$$

Frequency bias - measures the ratio of the frequency of forecast events to the frequency of the observed events.

$$\frac{hits + falsealarm}{hits + misses} \tag{8}$$

5. Results

5.1. WAM - 1999 to 2011

In this study, observations from six sites in the Norwegian and the North Sea are applied, Ekofisk, Sleipner, Troll A, Gullfaks C, Draugen and Heidrun as shown in Fig.(3). The rmse and bias (model minus observations) for different lead times are displayed in Fig.(4), covering the period February 1999 through 2011. In the first period, the forecast skill of WAM50 (50km resolution) is shown. In March 2007, the higher resolution model WAM10 (10km resolution) was employed at met.no, and the forecast skill of WAM10 is therefore represented in the latest period. In WAM at met.no, an artificial enhancement of the wind has been used since 1998, where the enhancement is 4% for winds between 15m/s and 25m/s. However, there has been many upgrades in the mesh size of HIRLAM from 50km, to 20km and to 12km. The higher resolution wind field leads to stronger winds and the WAM model have never been tuned due to these changes. This may be the reason for the systematically overestimation in Hs as shown by the bias in Fig.(4b). This artificial intensification of the wind was removed from the model November 1, 2011.
By looking at the rmse results in Fig.(4a), no decreasing trend in the rmse can be seen for the model analysis since 1999. However, the forecast skill has improved, illustrated by the decreasing deviation in rmse between the model analysis and the different lead times. This is due to the continuously improvements implemented in the 10m forcing over this time period.

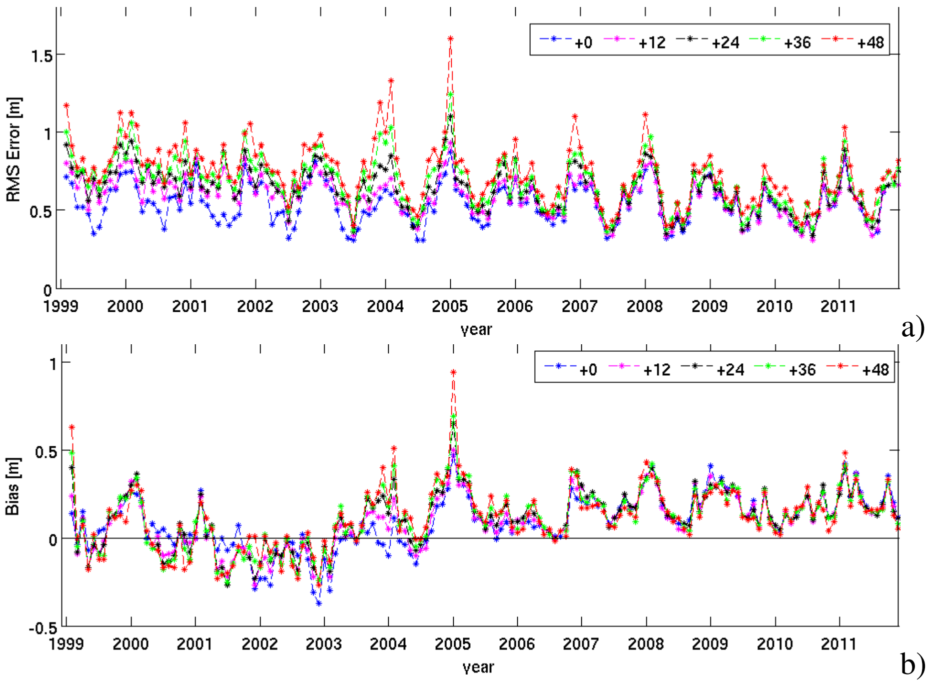


Figure 4: Time series of the rmse and bias for the forecast of Hs for the period 1999 to 2011. Note that model results from WAM50 are included for the period before March 2007, while model results from WAM10 are included for the later period.

5.2. Categorical statistics

Results from the categorical statistics are displayed in Fig.(5) for the year 2011, the left column shows results from WAM50 while the right column shows results from WAM10. The results from the two models are very similar. There are just small differences between the two models for the highest waves. However, for these waves we have few cases. For wave heights exceeding 7m, there were only observed 50 cases in 2011.
Fig.(5a and b), shows the hit rate. The hit rate is high, but as expected it decreases with wave height. For instance, 90% of the observed wave heights over 3m are predicted by the 24 hour forecast in WAM10, while 80% of the observed wave heights over 6m are predicted.
Fig.(5c and d), shows the False Alarm Ratio, to see the fraction of forecasted events that did not happen. For the 36 hour forecast from WAM10, 50% of the predicted cases with wave heights over 6m, did not occur. However, the false alarm ratio is not telling us anything about the size of the error between the forecasted and the observed wave heights.
Fig.(5e and f) shows the frequency bias, telling us the ratio between frequency of forecasted events to the frequency of observed events. There are 25% more occurrences of wave heights exceeding 3m in the model analysis of WAM10 than what has been observed, while there is twize as many occurrences of wave heights exceeding 7m in WAM10 than observed. This indicates that WAM overestimates the wave height, as shown by the bias in Fig.(4b).

5.3. ENVISAT-RA2

Due to the limited observation coverage from EnviSat RA-2, the altimeter data is only applied to validate WAM50 and WAM10. To get a reasonable comparison between the two models, observations found solely inside the WAM10 domain is applied (the inner red area shown in Fig.(2)). Since the location of the altimeter data is more offshore than for buoys and wave radar observation, the nearshore Hs is not validated with these data.
Fig.(6) shows scatter plots between observed ENVISAT-RA2 data and modeled significant wave height for WAM50 and WAM10 for the year 2011. As the scatter plot shows in Fig.(6a and b), there is a good agreement between the collocated Hs of altimeter data and the analysis from both models with a correlation of 0.96. For the analysis time, EnviSat RA-2 data is only covering the Norwegian Sea as shown in Fig.(2). The high correlation is also seen for lead time +6 in Fig.(6c and d), with a correlation of 0.95 for WAM10 and 0.96 for WAM50. For this lead time, EnviSat data is only covering the Barents Sea.
Fig.(7) is showing quantile-quantile plots (Q-Q plot) between models and the collocated EnviSat data. 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. The agreement between the modeled and the observed distribution is good for wave heights less than 8m in both models. However, the model analysis for both models have a higher distribution of waves over 8m than observed with altimeterdata. For forecast hour 48 as shown in Fig.(7e and f) there is a better agreement between the modeled and the observed distribution than for the analysis. For lead time +6 in (Fig.(7) f and h), in the Barents Sea, there is only a small overestimation in the tail of the distribution. But, for the highest waves, there is few cases.

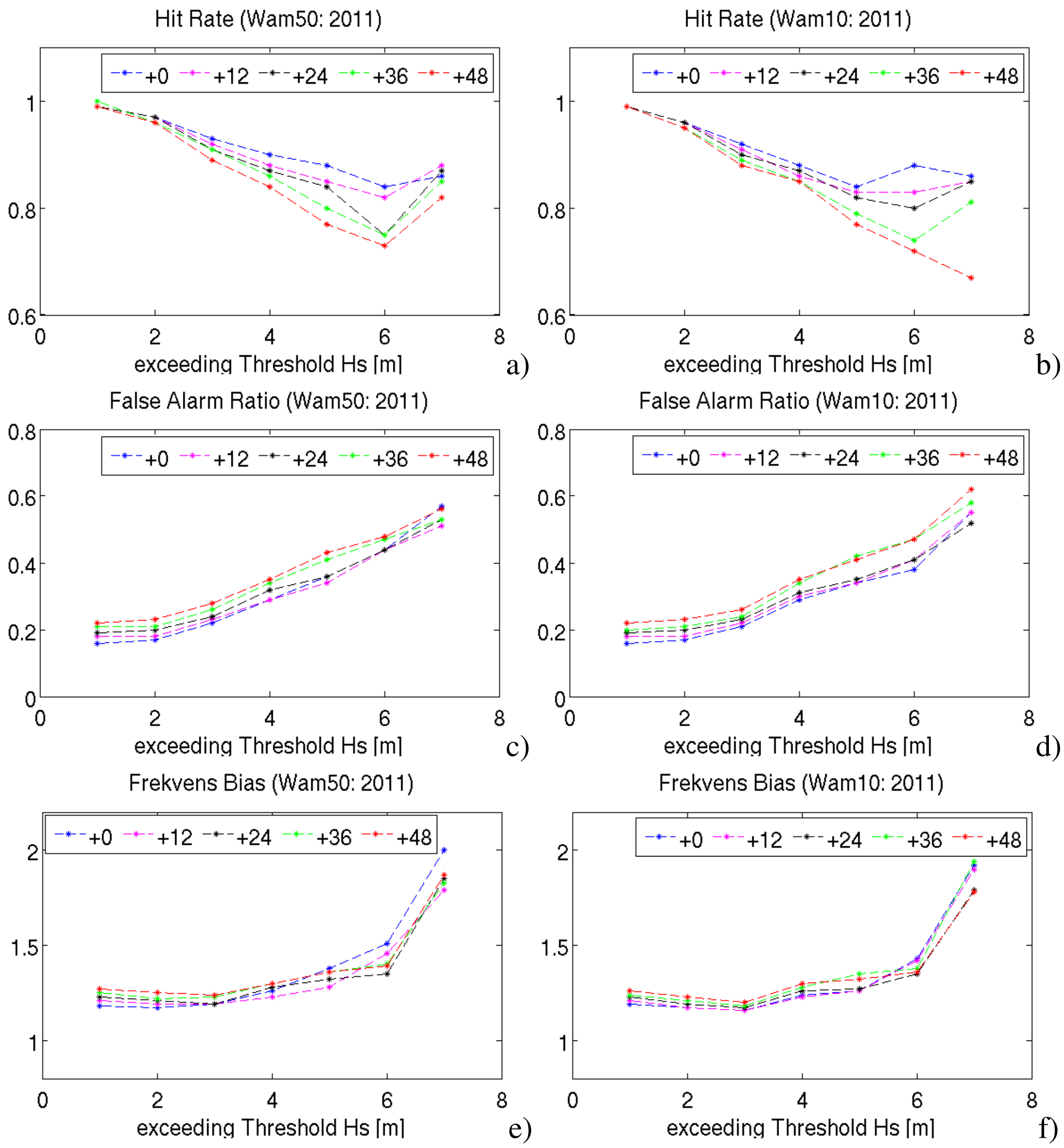


Figure 5: Shows the forecast skill of wave heights exceeding a threshold Hs. The statistics computed are Hit rate, False alarm ratio and Frequency bias. The left column shows results for WAM50, while the right column shows results forWAM10.

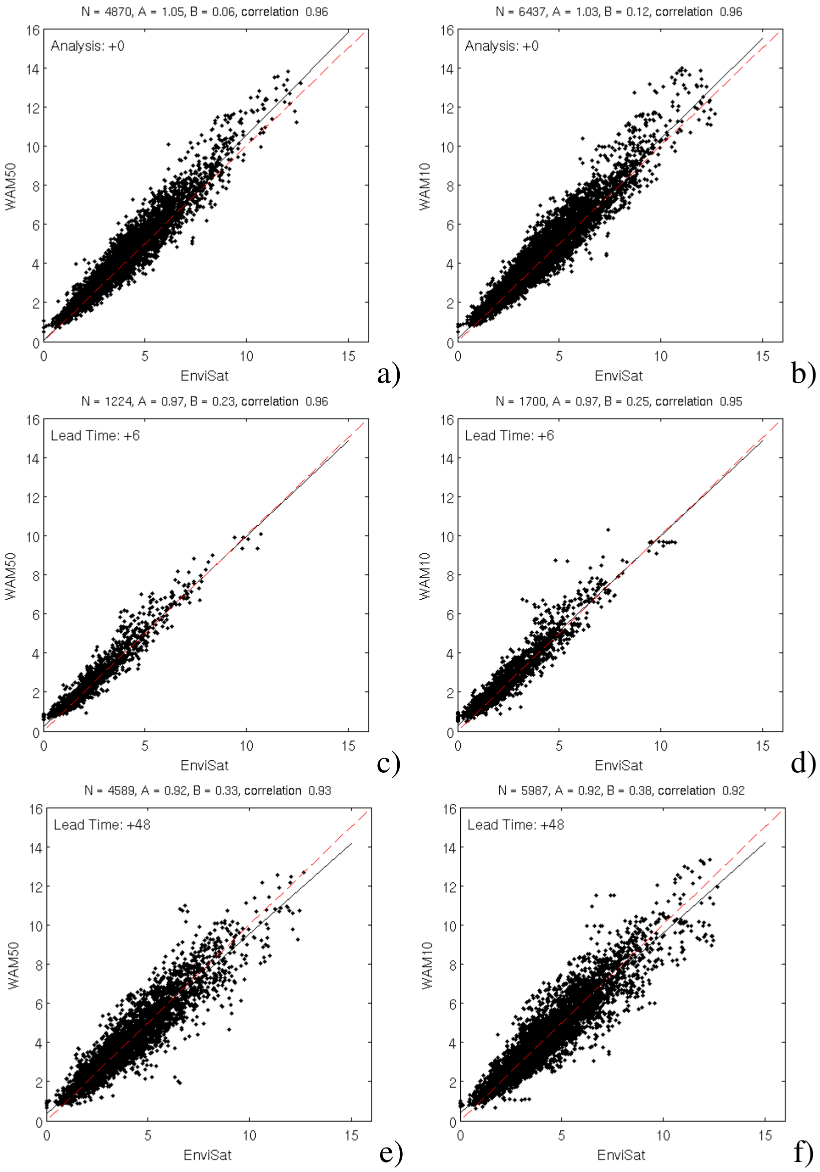


Figure 6: Scatter diagram between observed ENVISAT-RA2 data and modeled significant wave height for WAM50 and WAM10. The black line is the linear regression.

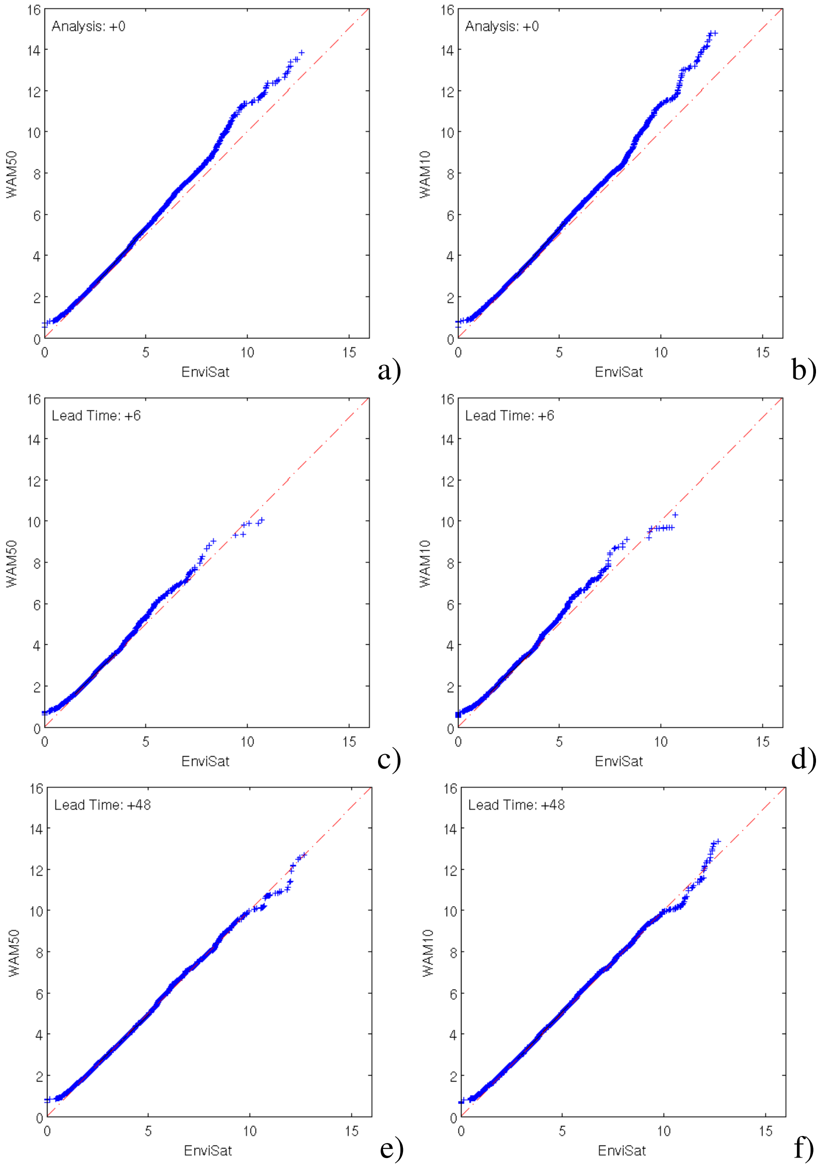


Figure 7: quantile-quantile plots (qq-plots) between observed ENVISAT-RA2 data and modeled significant wave height for WAM50 and WAM10. The red dashed line represents the perfect fit between the two data sets.

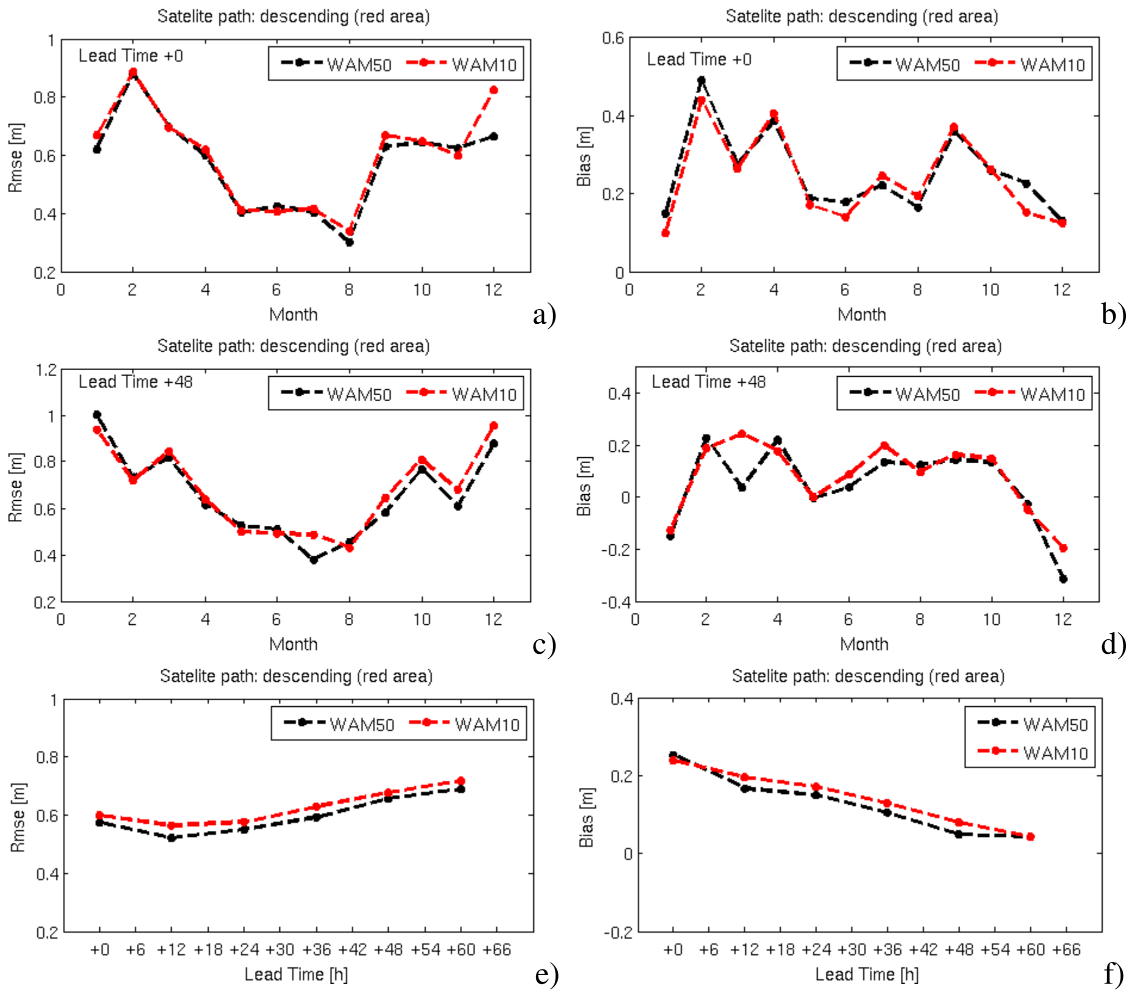


Figure 8: Displayed is a comparison of the wave height from WAM50 (black line) and WAM10 (red line) for the descending path. Fig.(a and b): shows the rmse and bias for the analysis, Fig.(c and d): shows the rmse and bias for the 48 hour forecast Fig.(e and f): shows the mean rmse and bias (model minus observation) for each lead time for both models.

Shown in Fig.(8) and Fig.(9) is a monthly comparison between WAM50 and WAM10 for the year 2011. The plots shows rmse and bias between the modeled Hs and the collocated EnviSat Hs, where bias is model results minus observations. In Fig.(8), validation results with observations from the descending path (red area in Fig.(2)) is applied, covering the offshore area of the Norwegian Sea, while in Fig.(9), observations from the ascending path is applied (blue area in Fig.(2)), covering the Barents Sea.
The statistical comparison in Fig.(8) shows approximately the same bias and rmse at analysis time for the two models. However, WAM50 has for all lead times a better score than WAM10 as displayed in Fig.(8e and f). For the Barents Sea area in Fig.(9), we can also see that WAM50 has a better agreement against the observations than WAM10. However, WAM50 is validated

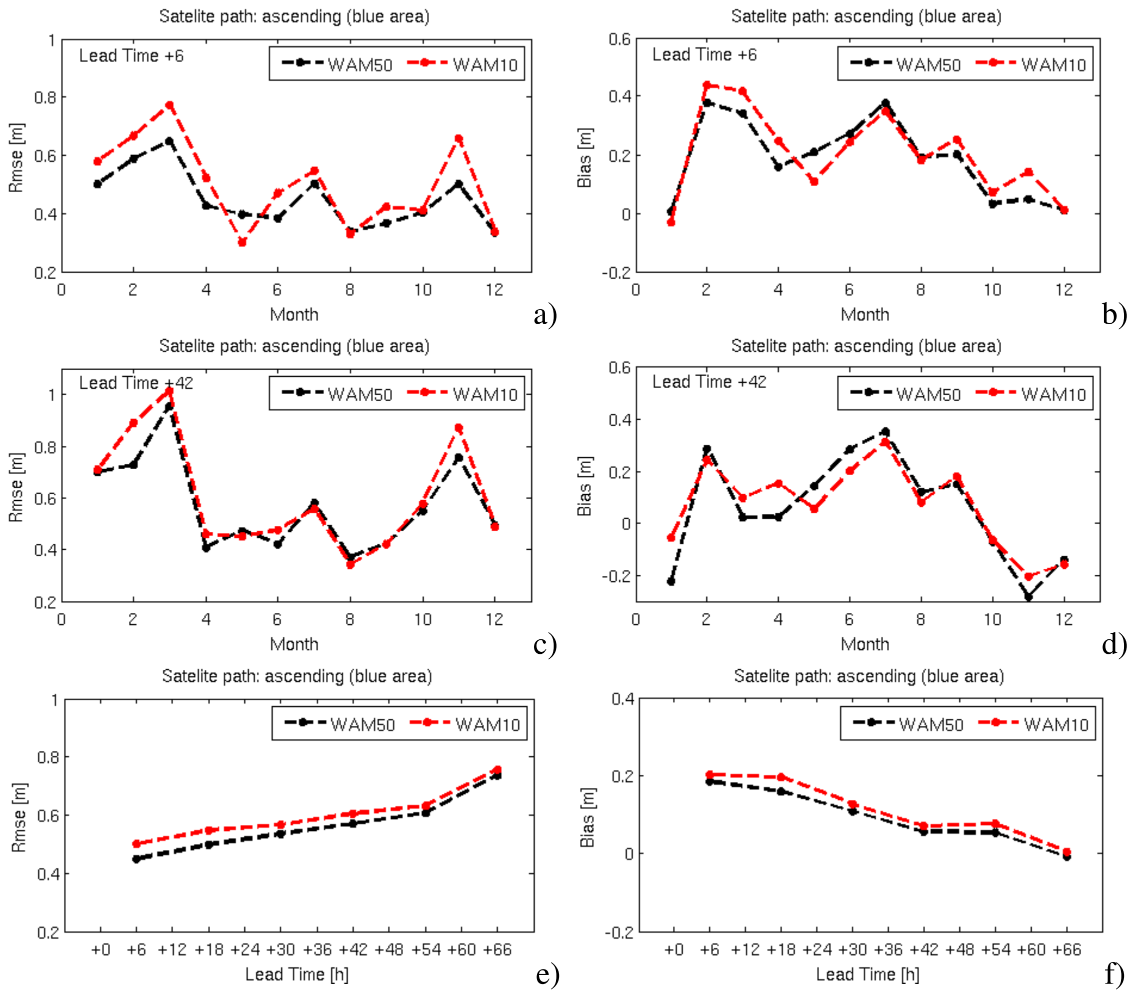


Figure 9: Displayed is a comparison of the wave height from WAM50 (black line) and WAM10 (red line) for the ascending path. Fig.(a and b): shows the rmse and bias for the 6 hour forecast, Fig.(c and d): shows the rmse and bias for the 30 hour forecast Fig.(e and f): shows the mean rmse and bias (model minus observation) for each lead time for both models.

against observation averaged over more data than WAM10. If bad quality data occur, this will have a larger effect in the WAM10 results. However, since the EnviSat data is located offshore, the improvements of running a higher resolution wave model with higher resolution atmospheric forcing will not be revealed.

5.4. Buoys in 2011

5.4.1. Each model

From the scatter and Q-Q plots at analysis time shown in Figure (10) during 2011, we can see that the three models: WAM50, WAM10 and WAM4, behave quite well, with an slightly tendency towards overestimation as the wave heights increase. The small overestimation can be seen even in the lower wave heights, $Hs = 2m$, and it increases rapidly after $Hs = 6m$.

From the scatter plots we can see that the three models present a very high correlation coefficient, 0.95, 0.96 and 0.93, with a large number of data.

5.4.2. WAM50 vs WAM10

In order to compare the statistical performance of WAM50 and WAM10, only buoys covered by both model domains are included. This reduce the number of data, see Table (1). For the comparison between WAM50 and WAM10, data from 74 buoys, with 18300 observations at each forecast time are used. The bias and the rmse are plotted in Fig.(11). WAM10 performs better than WAM50 with lower bias and rmse. The behavior of these two models is quite similar. At analysis time we can see that both models perform better in the summer, where they coincide, than in the winter. The bias is always positive and decreases with forecast time while the rmse increases with forecast time.

5.4.3. WAM10 vs WAM4

The stations inside the smallest domain in Fig.(1) with 24 buoys, and aprox. 7200 observations, are used to compare WAM10 with WAM4. The bias and the rmse are plotted in Fig.(12). The striking feature, as in previous years, is that the two models perform equally well. For this report, WAM10 gives a slightly better rmse than WAM4. It does not seem to be an advantage of WAM4 over WAM10. This might be related to the fact that the buoys are located offshore, where the presumed advantage of running WAM4 is not noticeable. Except for the bias which is constant with lead time, Fig.(12)c), the variation of the bias and rmse in Fig.(12), have the same features as in Fig.(11).

5.4.4. WAM from ECMWF vs WAM from met.no

As it can be seen from Fig. (13) the limited area wave model from the ECMWF (WAMECMWF), presents lower values of Rmse than the WAM models at met.no. The amount of observations used for this comparison is indicated in Table (1). The maximum Rmse difference is of 0.225m for WAM50 and the minimum is of 0.09m for WAM10. Fig. (14) shows overestimation of our models in comparison to the one of 11km at ECMWF. The scatter plots look very similar to the ones in Fig. (10) but the correlation coefficients are always larger with the WAMECMWF model. The qq plots show that our models overestimate Hs in a larger range than the WAMECMWF model. That the WAM from ECMWF scores better can be due to several factors. One of them is the wind forcing that comes from different atmospheric models.

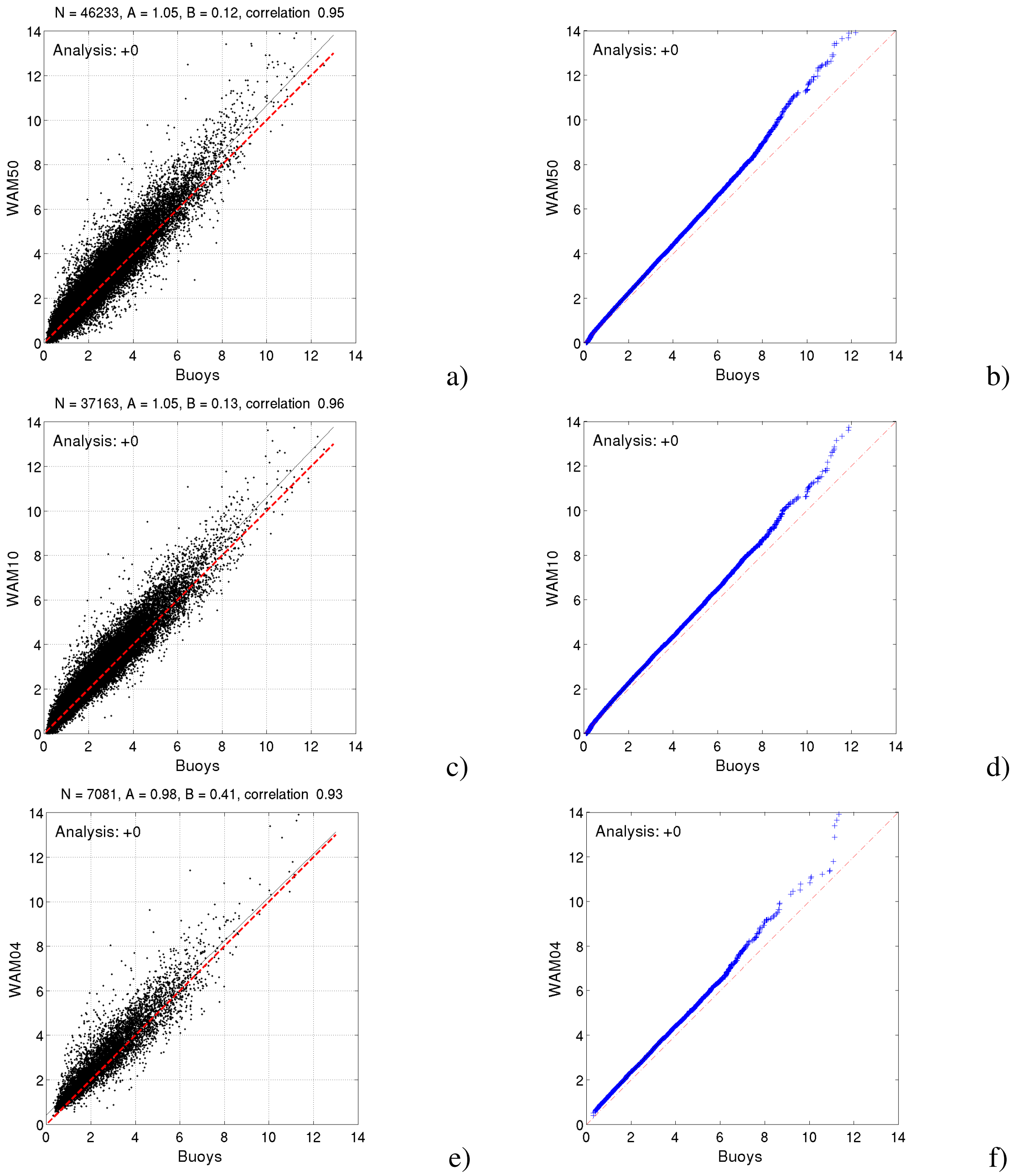


Figure 10: Scatter and quantile-quantile between observed and modeled significant wave height for WAM50 a) and b), for WAM10 c) and d) and for WAM4 e) and f). The black line is the linear regression while the red dashed line represents the perfect fit between the two data sets.

Another is the set-up. At met.no there is no coupling between the atmospheric model with the wave model and parts of the dynamics are lost.

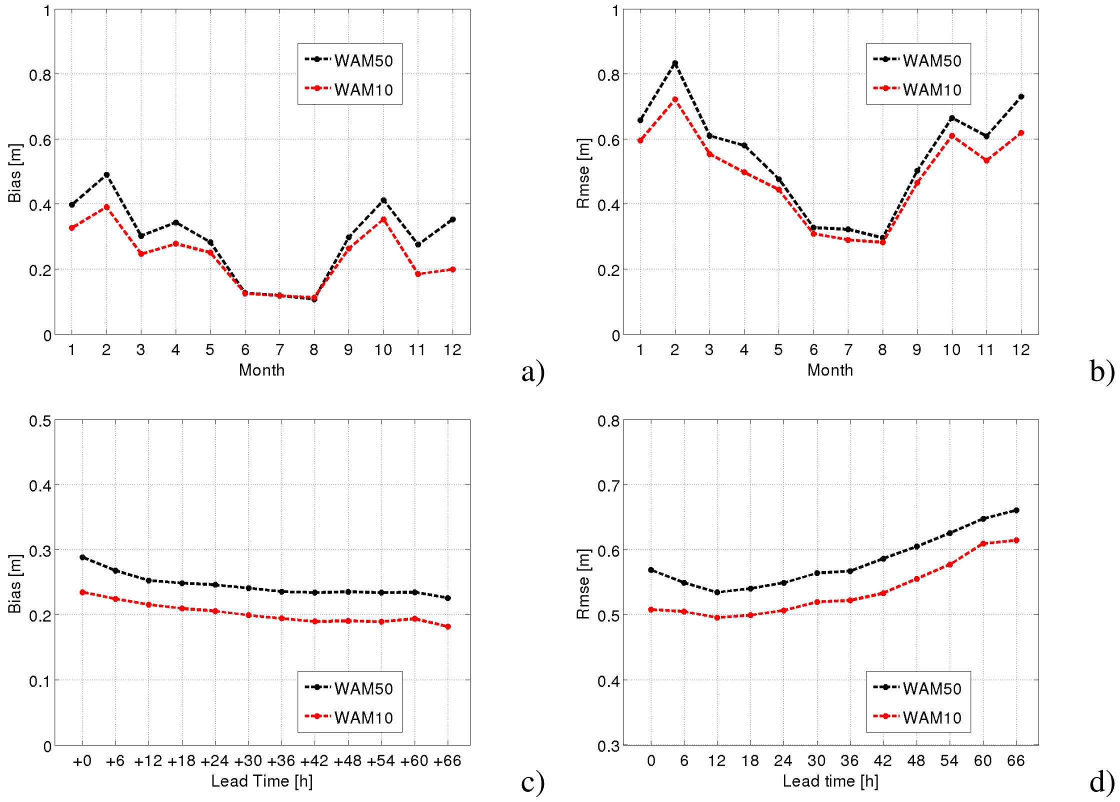


Figure 11: Comparison of the significant wave height from WAM50 and WAM10 during 2011. Figures a) and b) show the Bias and the Rmse variation during the year for the analysis. Figures c) and d) show the Bias ans Rmse with Lead time.

5.4.5. SWAN vs WAM10 and WAM4

For this comparison observations from only one buoy, Hywind, are used, see Fig. (1). After doing the collocations with the three models only 90 data points could by used. The bias and the rmse plotted in Fig. (15) show that SWAN performs better than WAM4 and WAM10 at almost all the lead times. Eventhough Hywind is located very close to shore, the difference between WAM4 and WAM10 is very small. The noisy curves are due to the lack of data.

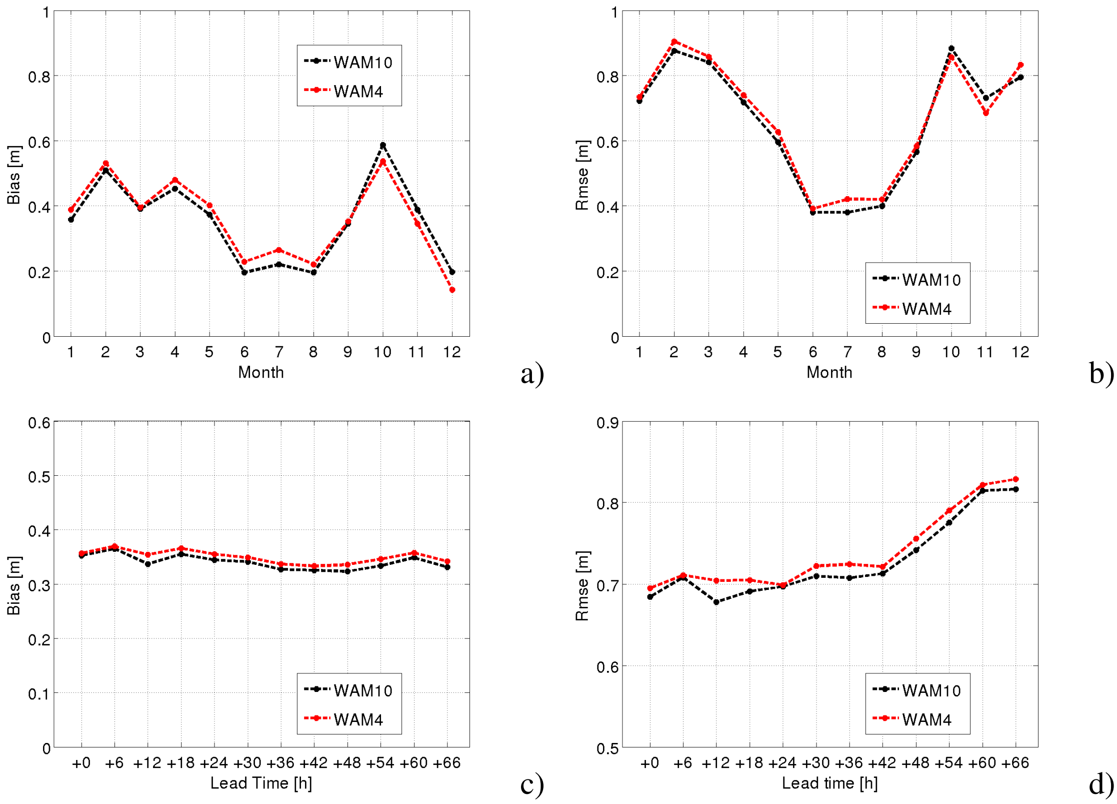
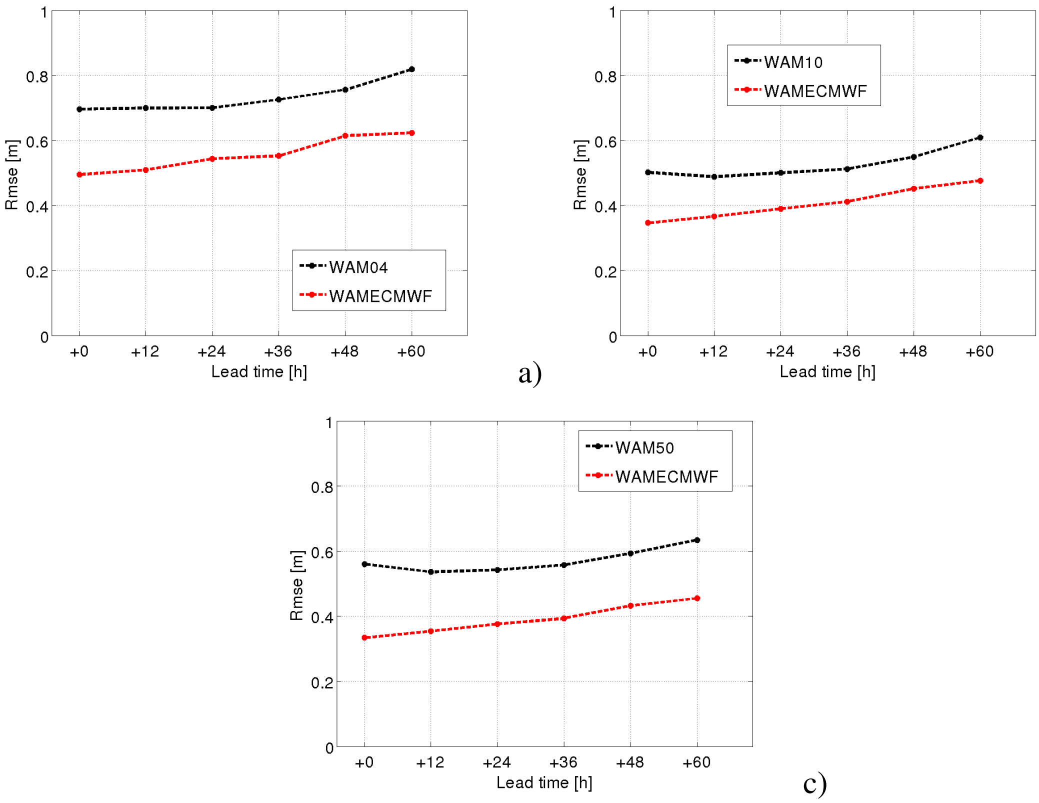


Figure 12: Comparison of the significant wave height from WAM10 and WAM4 during 2011. Figures a) and b) show the Bias and the Rmse variation during the year for the analysis. Figures c) and d) show the Bias and Rmse with Lead time.



a) b) c)

Figure 13: Rmse of significant wave height versus lead time of WAM ECMWF with WAM04 a), WAM10 b) and WAM50 c).

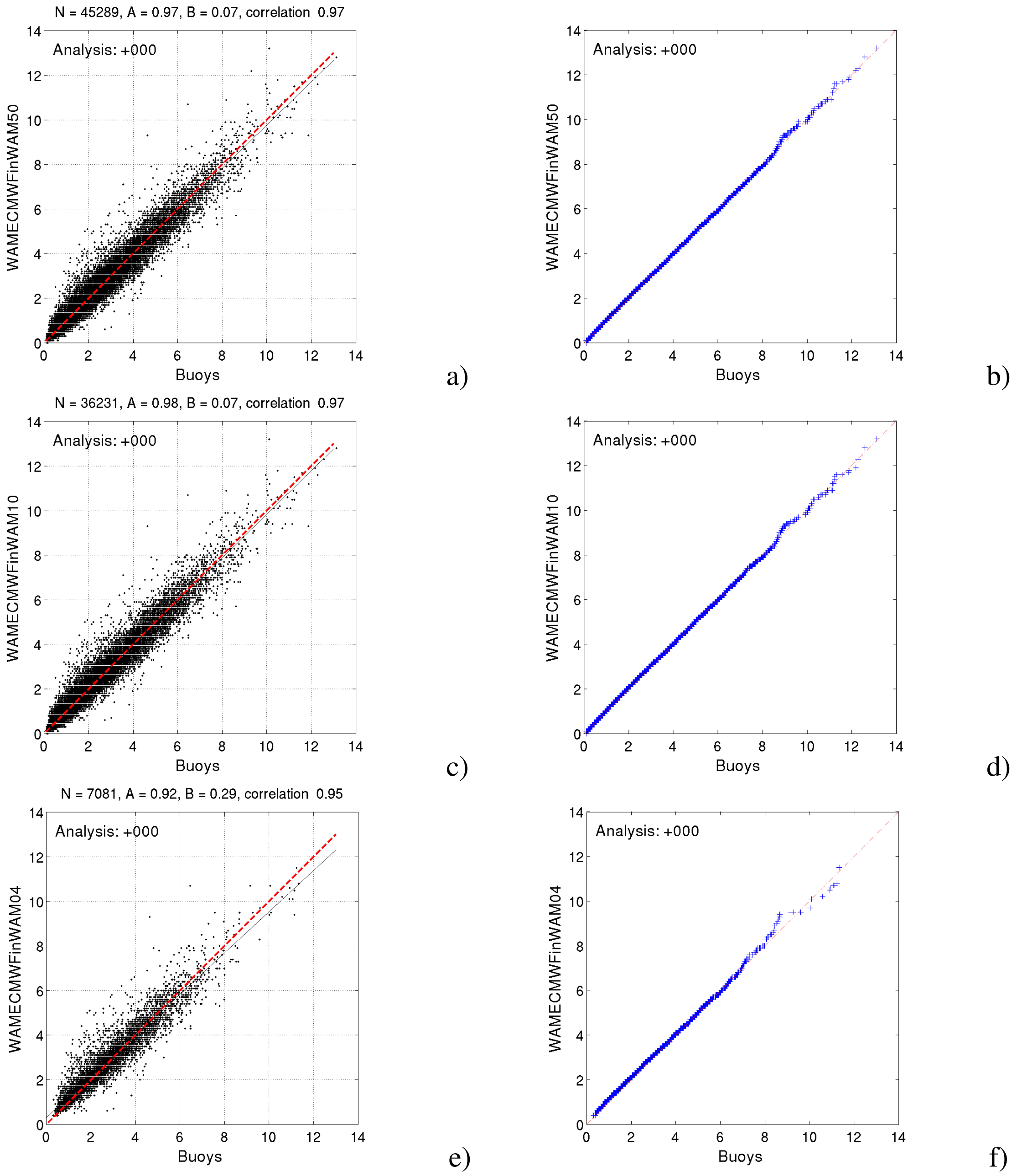
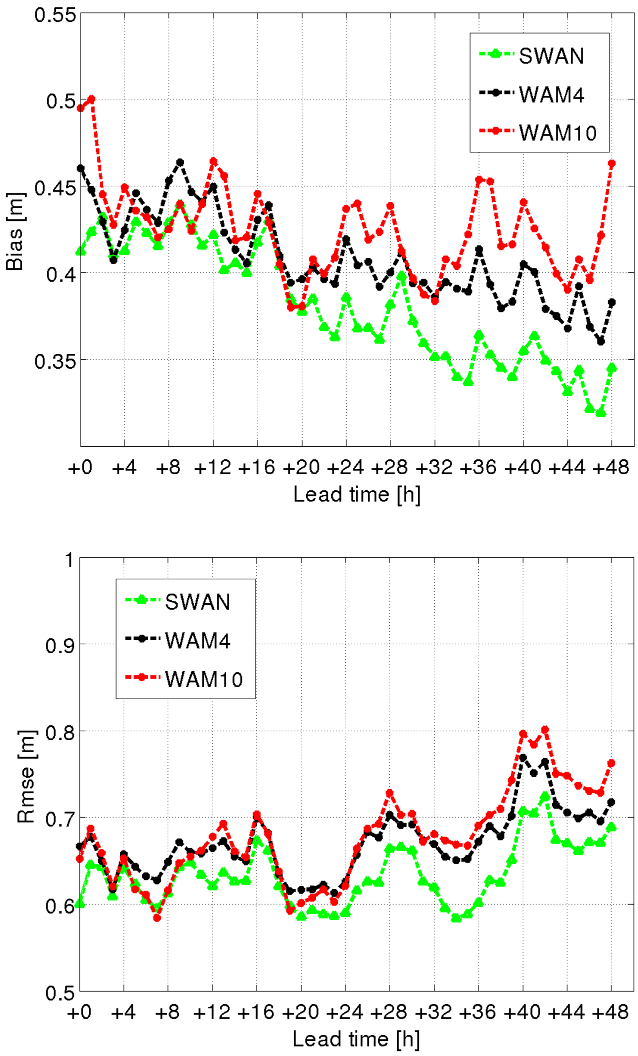


Figure 14: Scatter and quantile-quantile between observed and modeled significant wave height for the WAMECMF using the same data as WAM50 a) and b), as in WAM10 c) and d) as in WAM4 e) and f). The black line is the linear regression while the red dashed line represents the perfect fit between the two data sets.



a)

b)

Figure 15: Comparison of the significant wave height from SWAN, WAM4 and WAM50 at the buoy Hywind. Figure a) shows the bias while figure b) the rmse.

6. Summary and Conclusion

In this report, a validation of the wave height (Hs) forecast at the Norwegian Meteorological Institute has been carried out. Model results from the wave model WAM and SWAN, and observations from both in-situ buoy and EnviSat Radar Altimeter (RA-2) data are used for this purpose. WAM is forced with 10m surface winds from the numerical weather prediction model HIRLAM. Since HIRLAM is run operational at met.no, it is frequently upgraded with higher resolutions and improved set-ups/model codes. This has shown to have a positive impact on the wave model leading to improved forecast skills of Hs. However, as a result of the higher resolution atmospheric forcing, WAM has started to systematically overestimate the wave height. We believe this is due to the finer description of the pressure fields in HIRLAM, which may lead to stronger winds. The physics in WAM are not tuned due to these changes, however at November 1, 2011 an artificial enhancement on the wind, introduced in the wave model around 1998, was removed. This will hopefully improve the quality of the forecasted wave height in the future.

At met.no, WAM is run at 50km, 10km and 4km resolution, while SWAN is run at 500m resolution. When comparing the different WAM models for 2011, the behavior of the models are quite similar. The observations applied, like altimeter data and available buoys are all located offshore where the advantage of higher resolution models can't be seen. However, for one buoy located close to the coast, we can see how the wave model SWAN performs better than WAM10 and WAM4 as expected. SWAN has better physics for shallow water than WAM and is run with a higher resolution. For the same location, there is no clear advantage of the higher resolution model WAM4 over WAM10. One important finding in this report, is that the Limited area wave model from ECMWF run at 11km resolution (WAMECMWF), has a better score than all wave models at met.no. The WAMECMWF is a coupling between the atmospheric and wave model, while for WAM at met.no there is no coupling. The lack of wave-atmospheric coupling excludes important dynamics, and may be the reason for the higher score for the ECMWF model compared to wave models at met.no.

A. Appendix

Date	Description	Models effected
April 8, 2012	Communication with ENVISAT was lost	WAM50, WAM10
November, 1 2011	An artificial intensification of the wind were removed from the wave model. This enhancement has been applied since 1998, where the enhancement is 4% for winds between 15 m/s and 25m/s.	WAM50, WAM10, WAM4
July, 5 2011	The ERS-2 satellite was retired after 16 years of successful operations	WAM50, WAM10
March, 25 2009	Both ENVISAT and ERA-2 is used as observation sources in the Assimilation system in WAM	WAM50, WAM10
February, 13 2008	HIRLAM8 is upgraded with a resolution of 8km instead of 10km	WAM10
February, 13 2008	HIRLAM12 is upgraded with a resolution of 12km instead of 20km	WAM50
March, 1 2007	The higher resolution Wave model WAM10 is introduced at met.no	WAM10
March, 1 2003	HIRLAM20 is upgraded with a resolution of 20km instead of 50km	WAM50

Table 3: The table shows changes in the wave model since 2003.

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.

Gusdal, Y., Validation of the Operational Wave Model WAM - February 1999 through June 2009, 2010, met.no Rep. 3, Norwegian Meteorological Institute. 12 pp.

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