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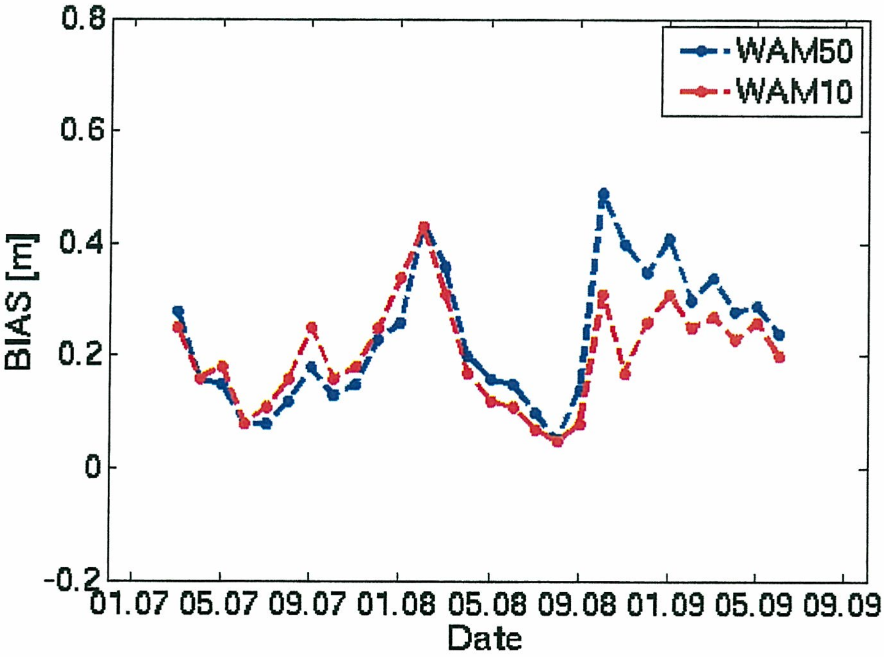

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Title

Validation of the Operational Wave Model WAM - February 1999 through June 2009

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Abstract

The aim is to study the skill of the operational wave forecast at the Norwegian Meteorological Institute. First we validate the Significant wave height (SWH) predicted from the wave model WAM. To this end we use observations from six sites in the Norwegian and the North Sea covering the period February 1999 through June 2009. WAM is the operational wave model at the Norwegian Meteorological Institute. It is forced with 10m surface winds from the numerical weather prediction model Hirlam to produce a 66 hour forecast four times a day. During the validation period, one of the major changes is the introduction of a medium-resolution (10km) model WAM10 in March 2007. We find that by increasing the resolution of the model a more accurate forecast is produced. Different changes has also been implemented in the 10m forcing with a positive impact on the operational forecast due to improved wind fields. However, around 2003 WAM systematically starts to overestimate the wave height. This may be associated with an upgrade in the mesh size of Hirlam from 50km to 20km in March 2003. The higher resolution wind field leads to stronger winds which in turn gives higher waves. The physics in WAM is not tuned due to these changes. Second, we replace the source of observation used in the assimilation of SWH. When providing ENVISAT data as input, we find that the data has a positive impact on the forecast. Since March 25th 2009, both ENVISAT and ERS-2 are providing input data for assimilation.

Keywords

WAM, Significant wave height,Validation, Assimilation

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Lars Petter Røed	Øystein Hov

1 Introduction

The object is to study the skill of the significant wave height (SWH) forecast at the Norwegian Meteorological Institute. The study is two folded. First we perform a validation of the wave model WAM, covering the period February 1999 through June 2009. The major change in the wave model for this period, is the increased resolution from 50km to 10km. In addition, different changes is implemented in the weather prediction model[1]. As a result, we get improved wind fields, used as wind forcing in the wave model.
Second, we explore the forecast skill when replacing the satellite providing input data for assimilation. Traditionally, the wave height in WAM is initialized with observations from ESA's (European Space Agency) Remote Sensing Satellite ERS-2[2]. In this study, the input data is replaced with observations from ESA's earth observation spacecraft ENVISAT[3]. We find that it has a positive impact on the wave forecast. On March 25th 2009, the ENVISAT data is introduced in the WAM assimilation system together with the ERS-2 data.
The report is organized as follows. Section 2 gives an introduction of the wave model, the observations and the methods used in the validation. In section 3 we go through the results from the validation study, while in section 4 results from the assimilation study is discussed. Finally, in section 5 we have the summery and the conclusions.

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[1] http://fou.oslo.dnmi.no/seksjoner/meteorologi/opr_log.html
[2] http://www.esa.int/esaEO/SEMGWH2VQUD_index_0_m.html
[3] http://www.esa.int/esaEO/SEMWYN2VQUD_index_0_m.html

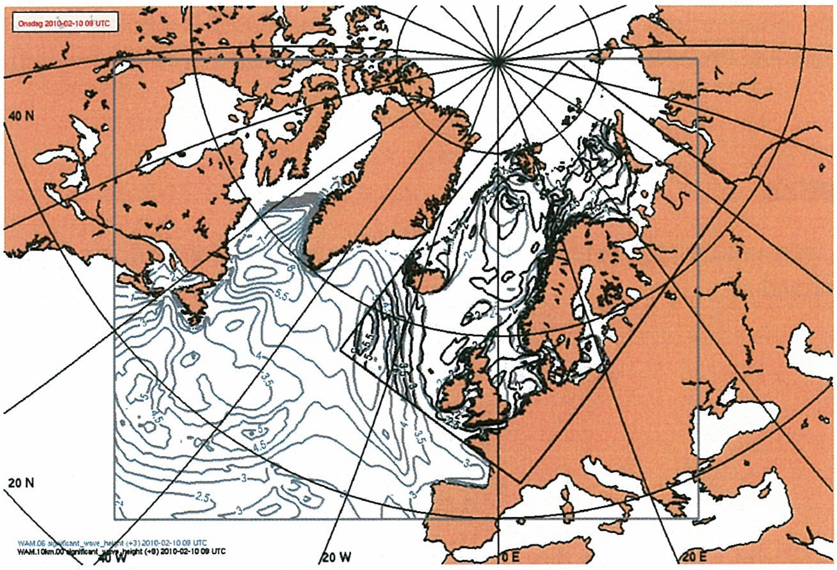

Figure 1: Displayed is the domain of WAM50 (Gray area) and WAM10 (Black area), covering the North-West Atlantic, Norwegian Sea, North Sea and the Barents Sea. The contour lines show the significant wave height.

2 Methods

2.1 The model

The wave model run operationally at the Norwegian Meteorological Institute is WAM (an acronym for WAve Model), see (Saetra et al., 2004; Komen et al., 1994). The model has a grid resolution of 50km (WAM50) covering among others, the North-West Atlantic, the Norwegian Sea, the North Sea and the Barents Sea as shown in Fig.(1). In March 2007, a higher resolution wave model was set up and run operationally. The model is a medium-resolution model with a mesh size of 10km (WAM10) nested in the coarse-resolution model WAM50. The model domain is shown in Fig.(1). WAM is forced with 10m winds from the numerical weather prediction model Hirlam, producing a 66 hour forecast four times a day. We have only validated the SWH for the analysis and for all lead times up to 48 hour. This is due to the validation period which starts in 1999. At this time, only a 48 hour forecast is produced two times a day.

2.2 The data

Observations from six sites in the Norwegian and the North Sea is applied. The observation sites can be seen in Fig.(2). At all stations, except Ekofisk, the wave height is carried out by the wave radar MIROS[4]. At Ekofisk observations are obtained from a waverider buoy. In situations where the capillary waves has wavelengths less then 2.5 cm, the MIROS radar has problem measuring the wave height. This occur in situations with low winds. To exclude this error from the observations, all situations where the wind speed is weaker than 4 m/s and the difference between observed and modeled wave height exceed 1m has been excluded.

2.3 Statistics

The skill is measured using standard statistics. These are the Mean Square Error (*MS Error*) and Bias, 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 as shown in Fig.(2) and H_i^{mod} and H_i^{obs} is the modeled and observed wave height respectively. The monthly Root Mean Square Error (*RMS Error*), Root Mean Square Error Normalized (*RMS Error Normalized*) and Bias are then defined as

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[4] http://www.miros.no/doc/wave_radar_principles_of_operation.pdf

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

$$RMS\ Error\ Normalized = \frac{RMS\ Error}{Std(H^{obs})} \tag{4}$$

$$Bias = \frac{1}{N_T}\sum_{j=1}^{N_d} Bias_j \cdot N_j \tag{5}$$

where N_j is the number of existing observations for day j, $Std(H^{obs})$ is the monthly standard deviation of the observed wave height, while N_T is the number of observations in a month given as

$$N_T = \sum_{j=1}^{N_d} N_j \tag{6}$$

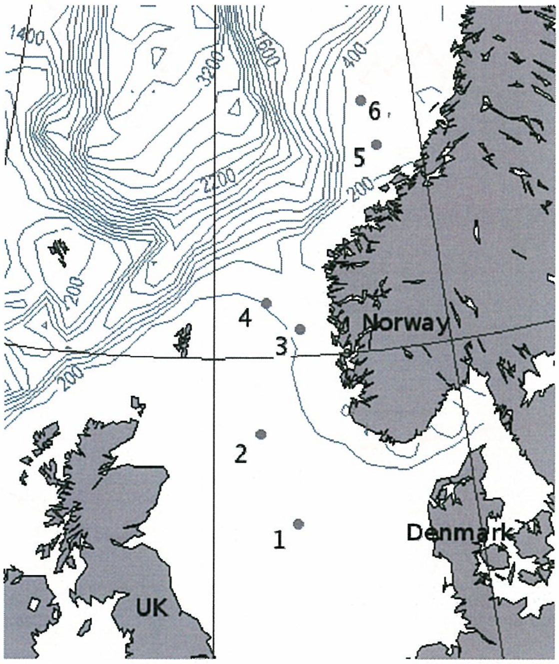

Figure 2: Displayed is the observation sites located in the Norwegian and the North Sea. The sites are named 1: Ekofisk, 2: Sleipner, 3: Troll A, 4: Gullfaks C, 5: Draugen and 6: Heidrun. At all stations except Ekofisk, a MIROS radar is used to measure the wave height. At Ekofisk a waverider buoy is applied.

3 Results

3.1 WAM50 vs WAM10

Shown in Fig.(3) is a statistical comparison of SWH from the coarse-resolution model WAM50 and the medium-resolution model WAM10 for the period March 2007 through June 2009. Fig.(3a)-Fig.(3b) show Bias and RMS Error for the analysis hour and reveals how WAM10, before March 2008, contributes to a higher Bias and RMS Error than WAM50. For this period, WAM50 is forced with winds from Hirlam20 while WAM10 uses wind fields from Hirlam10. In February 2008 the resolution in Hirlam increases from 20km and 10km to 12km and 8km respectively. The model is further upgraded to a new version in March 2008 [5]. As a result, WAM10 starts to obtain a lower Bias and RMS Error than WAM50. We may conclude that the change in the wind fields has a larger impact on WAM10 than WAM50. This may be due to

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[5] http://fou.oslo.dnmi.no/seksjoner/meteorologi/opr_log.html

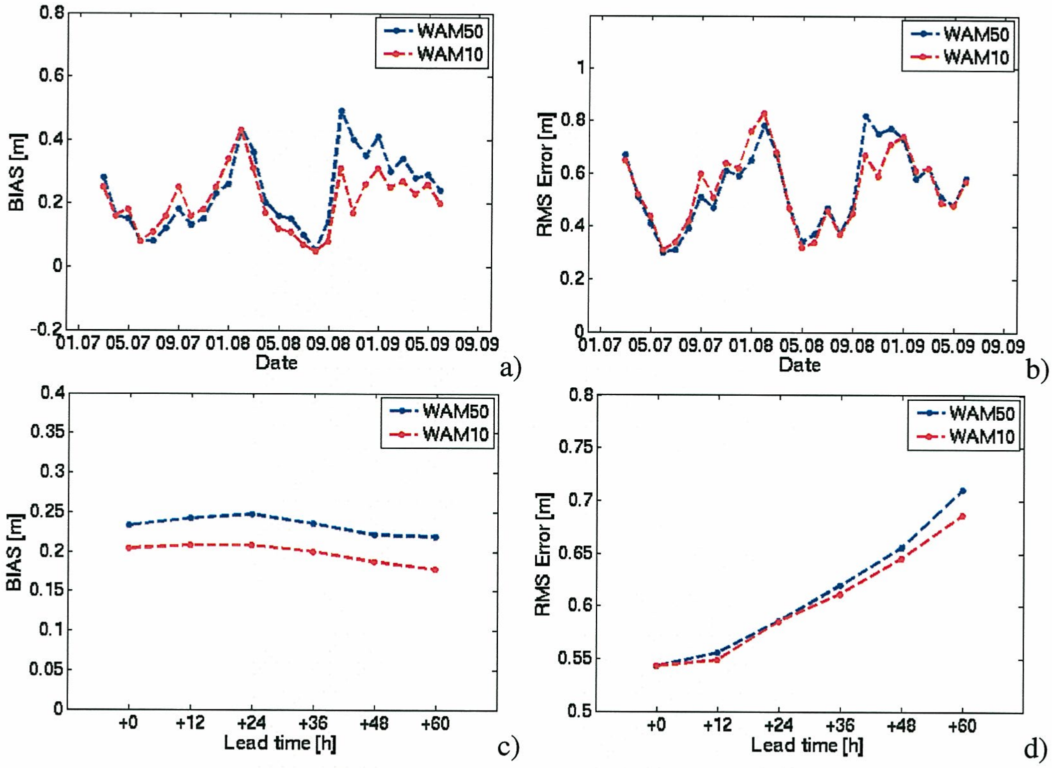

Figure 3: Displayed is a comparison of the wave height from WAM50 and WAM10 for the period March 2007 through June 2009. Figure a): shows the Bias (model minus observation) for the analysis, while figure b): shows the RMS Error. Figure c): shows the mean Bias for each lead time, while figure d): shows the mean RMS Error for each lead time.

the coarse resolution in WAM50, not able to resolve the waves no matter how well the winds are described. From the validation study of the weather prediction model, the improvements achieved in Hirlam8 are not more distinct than the improvements achieved in Hirlam12. Further, we find that the increasing resolution leads to improvements in the forecast. This is illustrated by the drop in Bias and RMS Error in Fig.(3c)-Fig.(3d). However, one systematic error observed in both WAM50 and WAM10 is the overestimation of SWH, illustrated by the positive Bias in Fig.(3a).

3.2 Long term statistics

Shown in Fig.(4) are scatter diagrams illustrating the correlation between modeled and observed wave height for the period February 1999 through June 2009. The model results from WAM50 are accounted for in the validation before March 2007, while results from WAM10 are included in the later period. We find a correlation between 0.91 and 0.95, with the highest

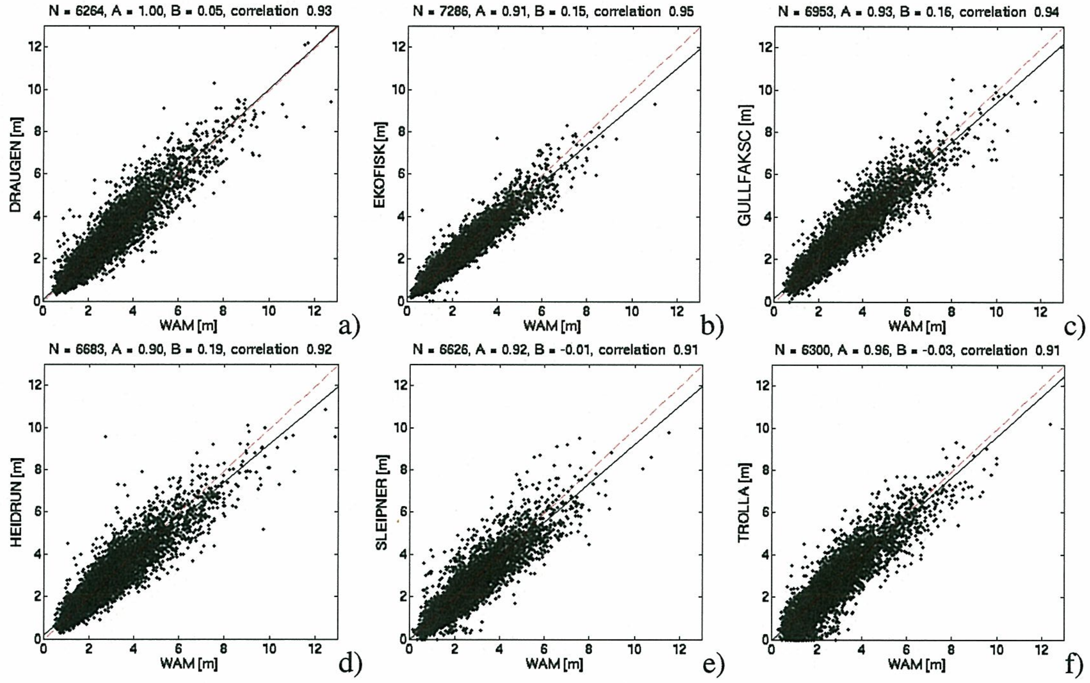

Figure 4: Shown are scatter plots between observed and modeled wave height at each observation site. a): Draugen, b): Ekofisk, c): Gullfaks C, d): Heidrun, e): Sleipner and f): Troll A. The plots includes model results and observations for the period February 1999 through June 2009. The black line is the linear regression while the red dashed line is the 1:1 line (The line represent the best fit between the model and observations). Note that results from WAM50 are included for the period before March 2007, while results from WAM10 are included for the later period.

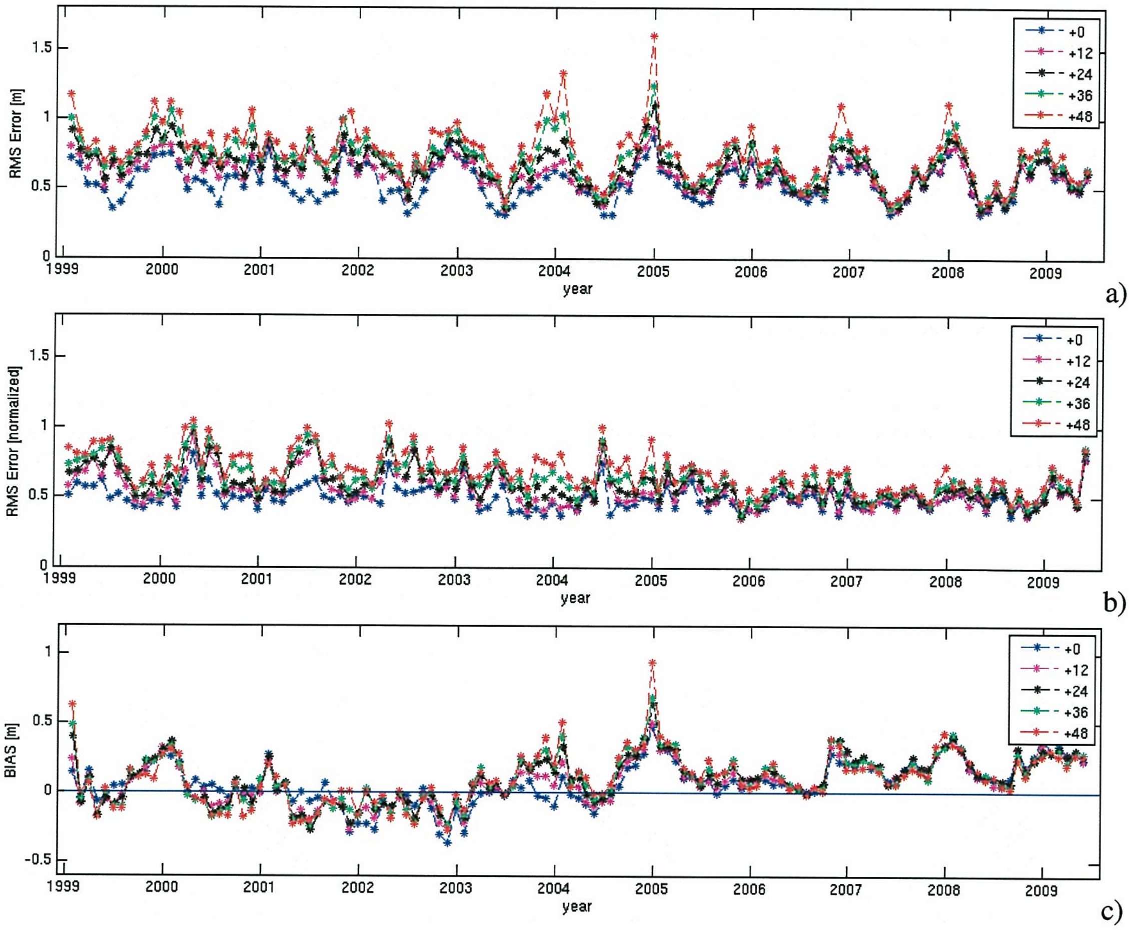

Figure 5: Shown are time series comparing modeled and observed wave height for the period February 1999 through June 2009 for all lead times. Figure a): show the RMS Error, b): the normalized RMS Error and c): the Bias (model minus observation). Note that model results from WAM50 are included for the period before March 2007, while model results from WAM10 are included for the later period.

value obtained at Ekofisk. The results illustrates how WAM on average overestimate the wave height, except at Draugen (Fig.(4a)).

The RMS Error, Normalized RMS Error and Bias for all lead times are displayed in Fig.(5), covering the period February 1999 through June 2009. The results reveal no decreasing trend in the RMS Error for the analysis hour. However, the forecast is improved, illustrated by the decreasing deviation between the RMS Error for the analysis and the different lead times. By normalizing the RMS Error in Fig.(5b), the wave climate is removed. During spring and summer there are weaker and smaller pressure systems making it more difficult to model the winds. This may lead to less accurate wave heights during this season of the year. However,

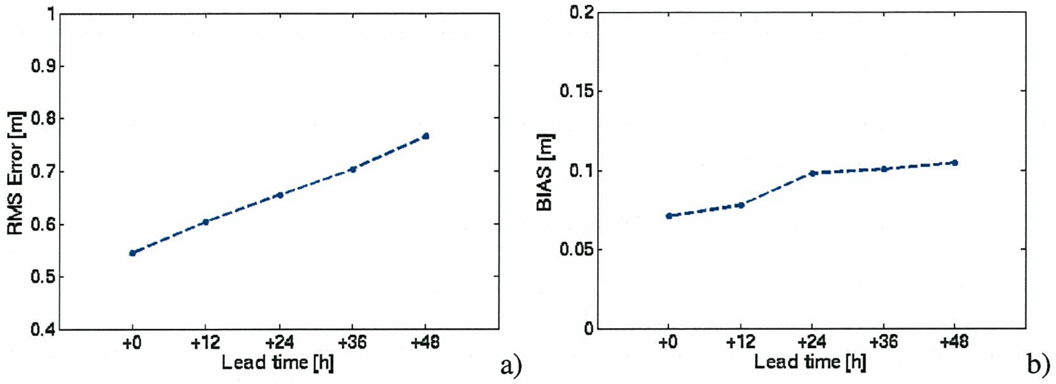

Figure 6: Shown are a): the mean RMS Error and b): the mean Bias (modeled wave height minus observed) from each observation site. The results covers the period February 1999 through June 2009. Note that results from WAM50 are included for the period before March 2007, while results from WAM10 are included for the later period.

from the end of 2005, the normalized RMS error starts to get more consistent between the seasons. This may be due to improvements implemented in Hirlam[6] at this time.

However, in 2003 as displayed in Fig.(5c), we find a shift in the Bias where WAM starts to simulate higher waves than observed. In March 2003, Hirlam is upgraded to version 5.2 with a resolution of 20 km instead of 50 km (Bjørge et al., 2003). The higher resolution weather prediction model has a finer description of the pressure fields, which may lead to stronger winds which further gives higher wave heights in WAM. This change may be the reason for the systematicaly overestimation of the wave height in WAM. The physics in the wave model is not tuned due to the different changes implemented in Hirlam.

Shown in Fig.(6) is the mean RMS Error and mean Bias for each lead time, covering the period February 1999 through June 2009. We find that the difference between observed and modeled wave height increases as the forecast hour increases. However, the deviation between the mean RMS Error and mean Bias for the 48 hour forecast and the analysis is small. We obtain a RMS Error and Bias of respectively 0.53m and 0.07m for the analysis and 0.78m and 0.11m for the 48 hour forecast.

4 Assimilation in WAM

In this chapter, different experiments with assimilation of ENVISAT data [7] is tested. We have studied four different experiments covering the period March 3rd to March 5th 2009. The main difference between the experiments are how the model is initialized before the forecast run is started:

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[6] http://fou.oslo.dnmi.no/seksjoner/meteorologi/opr_log.html

[7] http://envisat.esa.int/handbooks/ra2-mwr/CNTR.htm

E1: Initialized with warm restart at t-6 hours using the previous 6 hour forecast as initial condition, with no assimilation.

E2: Initialized with warm restart at t-6 hours using the previous 6 hour forecast as initial condition, with assimilation.

E3: Initialized with cold start at t-48 with no assimilation.

E4: Initialized with cold start at t-48 with assimilation.

Shown in Fig.(7) is the RMS Error and Bias for each lead time for the period March 3rd to March 5th based on measurements from all observation sites. Even though the test period is short, the results illustrates how assimilation of ENVISAT data improves the modeled wave height for both the warm restart and cold start experiments. This is shown by the decreasing RMS Error and Bias compared to the experiments without assimilation. In this validation, E4 achieves the best results. This may be due to the t-48 hours initialization, which means that the model is adjusted against observations over a period of 48 hours before the forecast is run. However, also experiment E3 without assimilation gives lower RMS Error and Bias than E1 and E2. This may be due to the corrected winds over the 48 hour period, leading to more accurate wave heights. The experiments initialized with warm restart at t-6 hours with assimilation are only corrected against observations over a period of 6 hours. Only one forecast run has been simulated, where the restart file used in experiment E2 are from a previous simulation without assimilation. By setting up more forecast runs, we would obtain improved restart files with assimilation having a positive impact on the results from experiment E2.
The results in Fig.(7) illustrates how the impact of the assimilation decreases as the forecast hour increases. After roughly 30 hours, depending on location, all experiments obtain the same RMS Error and Bias. This is also illustrated in Fig.(8), which show the difference between simulation E1 and E4 for the analysis and the 12 hour lead time, where the assimilation has less impact on the wave height for the 12 hour forecast. The results are relative to simulation E1 (E4 minus E1). The difference in the Norwegian Sea and the North Sea reaches a value of 0m - 0.3m at the analysis hour, depending on location. The maximum difference is reached west of France with a value of 0.6m.
Shown in Fig.(9) is the significant wave height from run E1, E2 and E4 for the area west of France. The comparison show the 15 hour forecast together with observations from ENVISAT. The results from experiment E1 without assimilation gives higher waves and deviates more from the observed wave height compared to experiment E2 and E4. By assimilating ENVISAT data into WAM, the overestimation of the wave height decreases, improving the results at the analysis hour and the different forecast hours.

5 Summary and Conclusions

First in this report, a validation of the wave height forecast at the Norwegian Meteorological Institute has been carried out. Model results from the wave model WAM, and observations from buoy and platforms in the Norwegian and the North Sea are used for this purpose. The

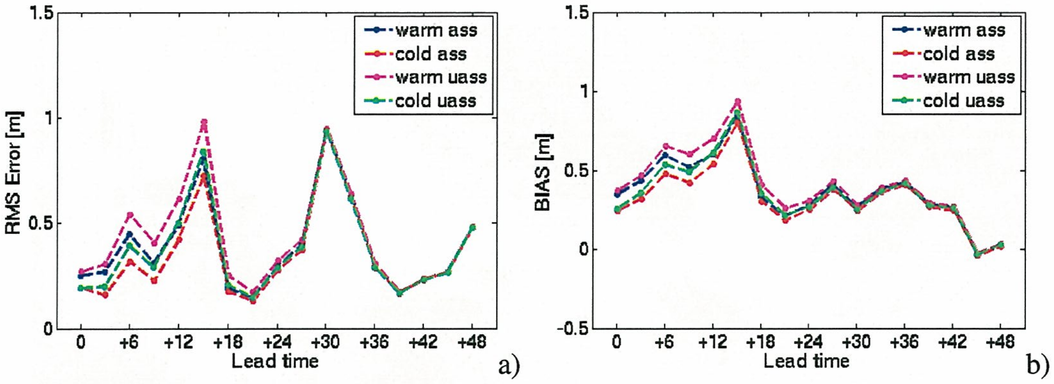

Figure 7: Shown is statistical results of each experiment for the period 3rd of March to 5th of March. The different colors indicate the different experiments: Pink curve: Experiment E1, Blue curve: Experiment E2, Green curve: Experiment E3 and Red curve: Experiment E4. Figure a): show the mean RMS Error for each lead time, while figure b): show the Bias (model minus observation) for each lead time.

validation covers the period February 1999 through June 2009. WAM is forced with winds from Hirlam, which during this period has experienced different upgrades. These embrace, among others an increased resolution from 50km to 20km in March 2003 and respectively from 20km and 10km to 12km and 8km in March 2008. The major change in WAM, is the introduction of a higher resolution model WAM10 (10km resolution) in March 2007, run additional to the coarser resolution model WAM50 (50km resolution). We find that the higher resolution model obtain a more accurate wave forecast. In addition, we can conclude that the upgraded wind resolution in March 2008, has a higher impact on WAM10 than WAM50, where WAM50, before the upgrade was forced with 20km winds and WAM10 forced with 10km winds. Further, as a result of the upgrade in Hirlam from 50km to 20km in 2003, WAM 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 is not tuned due to these changes which may explain the overestimation of the wave height.

Second in this report, an assimilation study has been carried out. In this study we explore the skill of the wave forecast when replacing the satellite providing the input for assimilation from ERS-2 to ENVISAT. Four different experiments has been carried out, with and without assimilation covering the period March 3rd to March 5th 2009. Even though the test period is short, we conclude that the assimilation of ENVISAT has a positive impact on the wave height. Since March 25th 2009, both ENVISAT and ERA-2 is used as observation sources in the assimilation system in WAM.

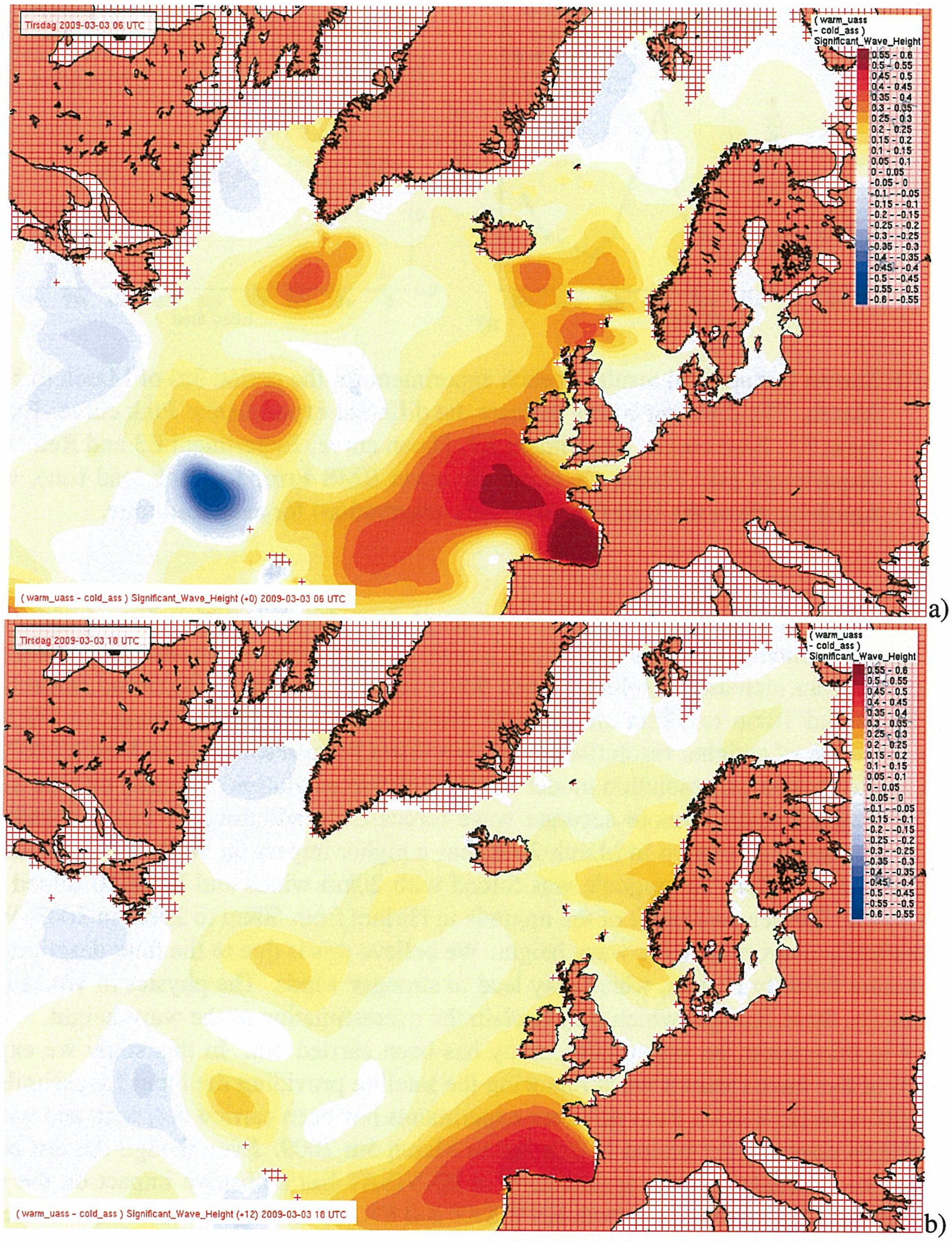

Figure 8: Shown is the difference between simulated wave height by warm start without assimilation (Experiment E1) and cold start with assimilation (Experiment E4). Figure a): show results for the analysis, while figure b): show results for the 12 hour lead time.

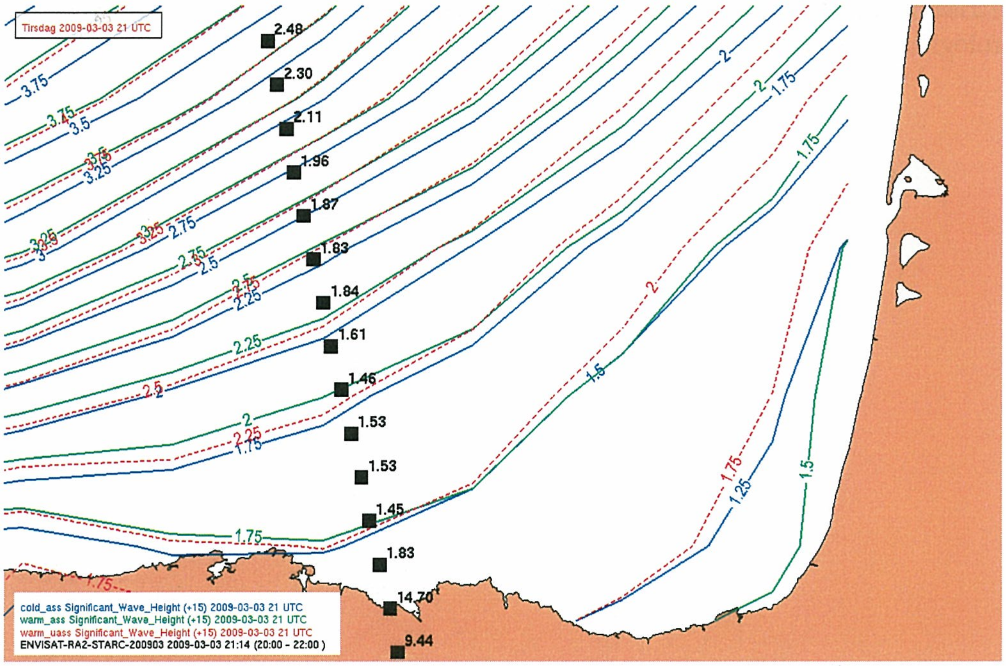

Figure 9: The curves shows the significant wave height from three different Experiments (E1, E2 and E4) together with ENVISAT observations (black dots). The different colors indicate the different experiments: Red curve: Experiment E1 , Green curve: Experiment E2 , and Blue curve: Experiment E4.

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