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Jun She

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Jun She
e-mail: js@dmi.dk

Danish Meteorological Institute, Copenhagen, Denmark

Contents

Abstract

An operational numerical weather model HIRLAM (HIgh Resolution Limited Area Model) and an operational third generation WAve Model (WAM) have been validated over the North Sea for a 14-month period during January 1999 - March 2000. The forecasted 10m wind speed and significant wave height are compared with hourly buoy observations in the North Sea. Results show that the average bias is 0.64m/s for the HIRLAM 10m wind speed and -0.75cm for the WAM significant wave height. Averaged RMSE is 2.3m/s for the 10m wind speed and 0.45m for the significant wave height. The averaged scatter index is 0.30 for the 10m wind speed and 0.25 for the significant wave height. WAM is better correlated with observations (R=0.90) than HIRLAM (R=0.85). Error mechanism analysis shows that the positive bias of HIRLAM wind (0.64m/s) leads to a positive WAM bias of 12.6%, which is almost balanced by bias caused by WAM set-up (-8%) and WAM physics (-5%). Significant annual variations of error statistics are found for both HIRLAM and WAM. The bias is under (or near) the averaged bias during March - October and above it during the rest of the months for both HIRLAM and WAM. There is negative bias in summer and positive bias in winter. WAM error statistics is coherent with that of the HIRLAM. The correlation coefficient of the 10 wind speed between the HIRLAM and the wind observations is a good indicator for that of the significant wave height. The validation results in this report suggest that 1) 10m wind error from HIRLAM is a major error source in the temporal variation of the WAM error; 2) to obtain a WAM significant wave height with no bias, a half meter per second positive wind bias is required, i.e., the best WAM calibration does not assume the best HIRLAM wind quality and vis-a-vis; 3)Long-term model validation is necessary (at least a year) for the HIRLAM-WAM model optimization.

1 Introduction

In ocean models for storm surge, ocean circulation, wave, ice and oil drift prediction, surface stress and heat flux parameterizations are based on winds at 10m height (hereafter referred as 10m wind). This is partly due to the fact that the 10m wind is a variable which can be measured conveniently. Therefore 10m wind is an important forcing input to the ocean models. However, 10m wind is usually a diagnostic component in weather models (as is in HIRLAM): the 10m wind is calculated from winds in the lowest model layer and Monion-Obukhov similarity theory in the surface layer. Furthermore, the 10m wind is not used to determine the surface fluxes in the turbulence closure models in HIRLAM. In a view of operational ocean modeling, the quality of the 10m wind is essential for producing high quality ocean forecasts. It is important to know how good the 10m wind is in the weather model. This knowledge can be helpful in validating the operational weather and ocean models, analyzing the model error mechanisms and improving the models.

Calibration of the 10m wind in the North Sea has not been well documented for the DMI HIRLAM model, partly due to lack of confidence on the amount and quality of in-situ wind measurements and the calibration results which can be distorted by the existence of waves. In the following we look into the issues in details.

1.1 Data availability in the North Sea

In the North Sea there are over 370 in-situ surface wind measurements in average each day, which includes a large amount of high quality measurements from buoys, rigs and platforms. These data can be obtained via GTS (Global Transfer System). This is a valuable database for long-term model calibration of the 10m sea surface wind.

1.2 Quality of 10m wind corrections

Since the sea surface winds are measured in different heights, the data need to be corrected to 10m height before the model validation. For buoy measurements, this is usually done before they are sent to GTS. However, the correction normally assumes a neutral stability and no wave effects on the sea surface roughness are involved. This, of course, will introduce a certain amount of error to the corrected 10m winds because the correction should be related to the real stability and wave-induced surface roughness. It is important to analyze the error introduced and its influence on the model calibration.

In a neutral stability, a correction from an normal buoy anemometer level of 4.5m to 10m leads to 6-13% increasing of the measured wind speed for wind speed up to 30m/s, according to Monion-Obukhov theory. The stability effects add another ±15% of the corrected part [Komen, et al., 1994], which means $\pm(0.9 - 1.95)\%$ of the wind speed. However the bias of error can be very much smaller than the $(0.9 - 1.95)\%$ of the wind speed since stable and unstable cases diminish each other.

Existence of waves usually enhance the sea surface roughness in comparison with a smooth sea, which is assumed in a normal wind correction procedure. A larger sea surface roughness means a larger correction to the 10m wind speed. For an average wind speed of 8m/s, 0.5-1% of the observed wind speed should be added to the corrected 10m wind speed. For a 30m/s wind, however, this added part could be as high as 5% of the observed wind speed. Previous studies [Talor et al., 1999, Zeng and Brown, 1998] also suggested that buoy measurements may under-estimate the wind speed in the high winds. For example, the friction velocity measurements suggested the wind error in the 20-25 m/s region was 3% to 5%. Considering that the wave correction is negligible small in the average case, it will not be included in our error analysis.

1.3 Objectives and organization of the report

The purpose of this study is to evaluate the quality of DMI HIRLAM 10m wind and related WAM products in order to provide comments for further HIRLAM-WAM improvements. The HIRLAM 10m wind will be validated by using hourly buoy winds in the North Sea for 14 months. Together with winds, WAM significant wave height will also be validated for the same period by using buoy measurements in the North Sea (in most cases, the waves and winds are measured at same locations). The inter-comparison of WAM and HIRLAM results can harmonize our conclusions. It is a common question in the weather and ocean model calibrations that, where does the error come from? and does the best forcing create best wave height? etc. Answers to these questions are essential in optimizing the existing weather-ocean models.

Another issue that we are going to look at is the time and space dependence of the error statistics, as well as the difference between different HIRLAM versions. WAM has been calibrated before its operationalization in the North Sea, inner Danish waters and the Baltic Sea [She and Nielsen, 1999]. At that time, however, HIRLAM was in a different version and the calibration period is only one month in the North Sea. It is not clear how the HIRLAM and WAM errors vary in different months, if any; and with different HIRLAM versions. The validation for the 14 months will give an assessment of the new HIRLAM model and wider spatial and temporal features in model errors for DMI HIRLAM and WAM.

The rest of the report is organized as follows: section 2 describes the operational DMI HIRLAM and WAM models and simulation strategy used in the model validation; section 3 describes data and validation method; section 4 analyzes the model-data comparison results and spatial and temporal error statistics of the HIRLAM 10m wind speed and WAM significant wave height; section 5 gives discussions and conclusions.

2 Operational models and simulation strategy

HIRLAM is an operational numerical weather model used in DMI and national meteorological agencies in several other European countries. DMI HIRLAM is a nested domain model with boundary conditions from ECMWF model outputs. HIRLAM E15 is one of the nested regions which covers part of North Atlantic, entire North Sea and Baltic Sea with a resolution of about 15km. The model has 31 vertical layers. The lowest model level is at about 35 meters above the sea. As described in section 1, the 10m wind is calculated by using the lowest layer winds and similarity theory. A 6-hour forecast has been produced for the period of Jan. 1, 1999 - Mar. 1, 2000. Hourly 10m winds from the HIRLAM E15 are used in the WAM model as forcing data. A full description of the HIRLAM model physics can be found in Sass et al. [1999].

DMI WAM is based on WAM-cycle4, a third generational wave model. A full description of the WAM-cycle4 can be found in the technical report written by the WAM Group [Günther, 1992]. Here the model is set up in a limited domain [$48°N$-$68°N$, $30°W$-$30°E$, Fig. 1], which covers both the North Sea and Baltic Sea, and part of the North Atlantic. The northern boundary of the model is selected based on the model calibration results, which suggests that the current location of the boundary ($68°N$) can include most of the swell effects in the North Sea [She and Nielsen, 1999]. The model is discretized on a latitude-longitude grid with a resolution of $15' \times 15'$, which is about 27km in latitude and 16km in longitude. The bathymetry is based on ETOPO5, a global topography data set with 5 minutes resolution generated by National Geophysical Data Center (NGDC, USA). On the open boundaries, the wave spectrum is diagnosed from wind at 10m height by using a parameterized JONSWAP [Hasselmann et al., 1973] spectrum.

3 Data and validation methods

In the North Sea (south of $60°N$), there are 11 buoy stations that provide both wave and surface wind measurements in hourly interval during January 1, 1999 - March 1, 2000. The wind and wave measurements are obtained from GTS. Among the 11 stations, 2 of them have quality problems in wind measurements and another 2 of them in waves. Finally 9 stations are used for wind validation and 9 stations for wave validation. Locations and usages of the stations in model validation are described in Tab. 1. A quality control has been made for checking the time continuity in the time series records.

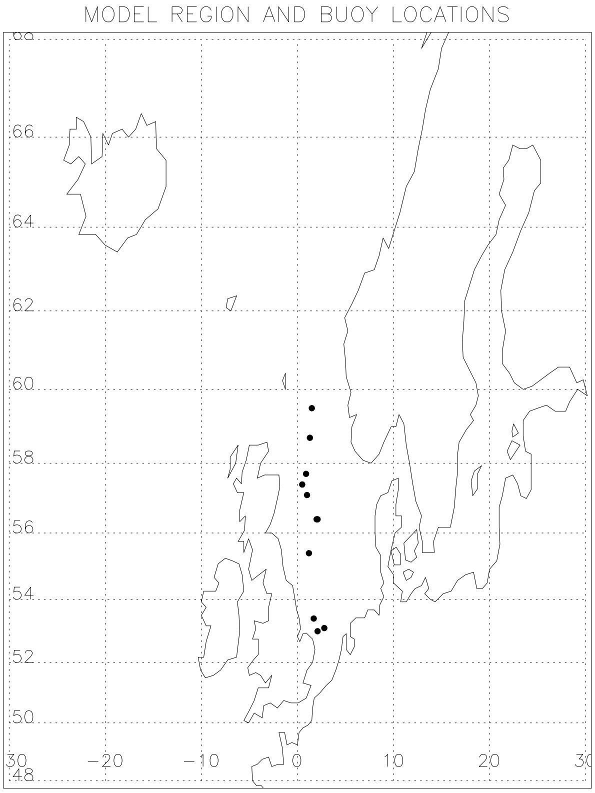

Figure 1: Model domain and Buoy locations for calibration

Table 1. Buoy locations and usage information

Latitude	Longitude	Winds used	Waves used
59.5	1.5	yes	yes
58.7	1.3	no	yes
57.7	0.9	yes	yes
57.4	0.5	yes	yes
57.1	1.0	yes	no
56.4	2.1	no	yes
56.4	2.0	yes	no
55.4	1.2	yes	yes
53.4	1.7	yes	yes
53.1	2.8	yes	yes
53.0	2.1	yes	yes

All the wind data used in this report have been corrected to 10m height from their measured elevation by using certain kinds of correction methods, e.g., Monion-Obukhov similarity theory assuming a neutral stability (private communication with Martin Holt).

Error parameters used here are: mean error (ME) or bias; Root-Mean-Square Error (RMSE); Scatter Index (SI) defined as the ratio of RMSE to the mean observed value of the parameter and linear correlation coefficient (R) between model and observations. The spatial and temporal distribution of the error statistics will be analyzed in the next section.

4 Results analysis

4.1 Error statistics in average

For the 12 months in 1999, HIRLAM has a mean positive bias of 0.64m/s for the 10m wind speed and WAM has a negative bias of 0.75cm for the significant wave height. Averaged RMSE is 2.3m/s for the 10m wind speeds and 0.45m for the significant wave height. WAM shows a better model-data correlation (0.90) than the HIRLAM (0.85). The averaged scatter index is 0.30 for the 10m wind speed and 0.25 for the significant wave height.

Bias in WAM is mainly caused by 3 factors: wind forcing error, model set-up error and model physics error, i.e.,

$$\epsilon = \epsilon_1 + \epsilon_2 + \epsilon_3 \tag{1}$$

where ϵ is the WAM bias, ϵ_1 is WAM bias caused by wind forcing, ϵ_2 is WAM bias caused by model set-up error and ϵ_3 is WAM bias caused by model physics error.

It is known that ϵ=-0.0075m, mean wind speed at the 9 locations is $\overline{u} = 7.7m/s$, mean significant wave height is $\overline{H}_s = 1.8m$. Now we can estimated ϵ_1, ϵ_2 and ϵ_3. ϵ_1 can be estimated from an empirical wave height-wind speed relation (Kinsman, 1965, p.391):

$$h(u) = 0.015u^2 \tag{2}$$

where h is mean wave height and u the 10m wind speed. This equals to:

$$H_s(u) = 0.023u^2 \tag{3a}$$

or

$$\overline{H}_s = 0.023 * (1+ < \frac{u'}{\overline{u}} >^2) * \overline{u}^2 \tag{3b}$$

where <> represents expectation and u' is bias from the mean wind speed. Based on the observed 10m mean wind speed and the significant wave height, we have $\overline{H}_s = 0.030\overline{u}^2$ in the North Sea, which is rather consistent with eq. (3b).

From eq. (3a) we have

$$\delta H_s(u) = 0.046u\delta u \tag{4}$$

For $\delta u = 0.64$m/s and the average wind speed of 7.7m/s, we have $\epsilon_1 = \delta H_s = 0.226$m, which is about 12.6% of the average significant wave height.

There are two major parts in ϵ_2, which are errors caused by using 12 rather than 24 directions in WAM and the excluded swell at the model boundary. The former leads to a bias up to -3% [She and Nielsen, 1999; Komen et al. 1994]. The latter, was estimated as up to -10% of the significant wave height in the northern North Sea with open sea boundaries along 68°N and 8°W [She and Nielsen, 1999]. In this study, the west boundary has been extended to 30°W and the entire North Sea are concerned, a rough estimate of swell error in the current set-up could be up to -5% of the significant wave height. This gives a total WAM bias of -8% (ϵ_2), which is caused by the current model set-up.

From eq. (1) we have

$$\epsilon_3 = \epsilon - \epsilon_1 - \epsilon_2 \tag{5}$$

Hence we can estimate the WAM bias component ϵ_3 for the North Sea, which is -5%. Please note that WAM set-up error of -8% is on the high end of the estimation and physics error of -5% is at the lower end of the estimation. Error fluctuation of 1-2% of the significant wave height can be expected for both ϵ_2 and ϵ_3.

4.2 Temporal features of error statistics in spatial average

Figure 2 shows time-dependent error statistics for the 10m wind speed. Mean values of error indexes are also shown in the figure in thick horizontal lines. Figure 3 gives the similar error statistics for the significant wave height. The error statistics is calculated for each month and buoy station and then averaged for all buoy stations. An annual variation of error statistics is clearly shown in bias, RMSE and correlation coefficient for both the 10m wind speed and the significant wave height. It is shown that December 1999 is a month with the worst model performance. Other remarkable features are discussed in the following:

4.2.1 Bias

For the 10m wind speed (Fig. 2), the annual variation of bias is significant. The amplitude of the bias is almost 4 times as high as the mean bias. In summer months bias goes lower and even becomes negative in August and September. The bias is below the average during

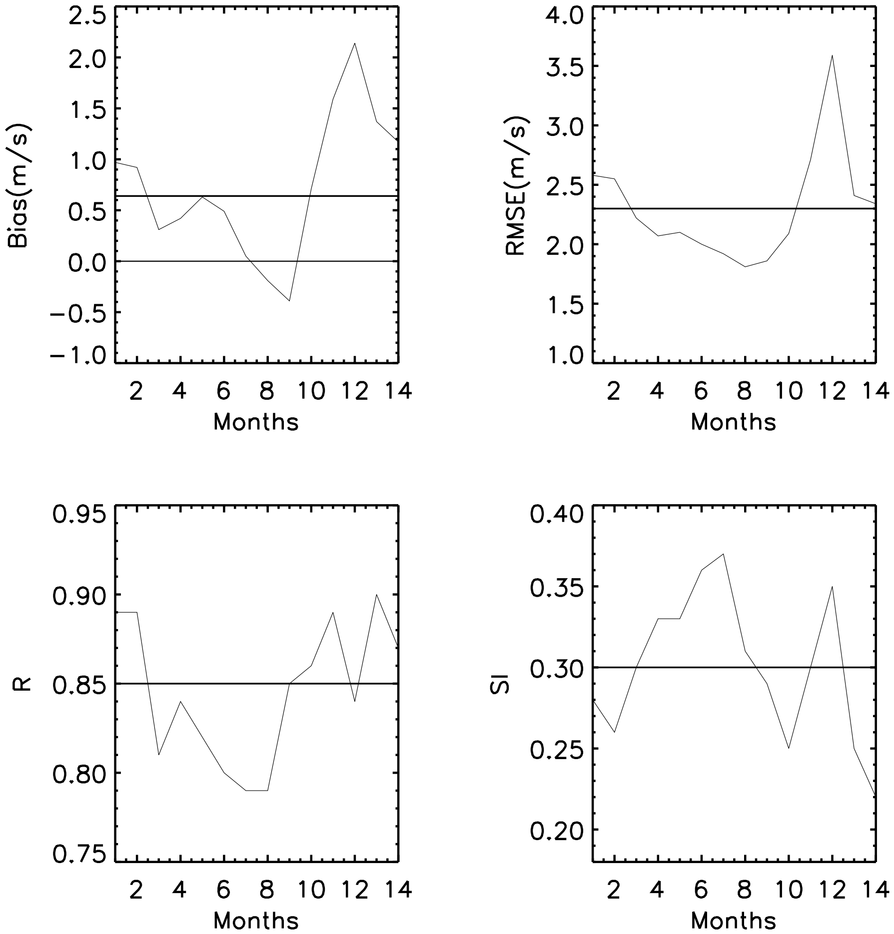

Figure 2: Error statistics of 10m wind speed for 14 months. Mean values are shown in horizontal lines

March - October and above it in the remaining months. For the wave height (Fig. 3), the least bias occurs in spring (March - May, almost no bias). In summer months (June - October), the wave height is under-predicted with a maximum negative bias of about 30cm in August. Similar to the HIRLAM bias (Fig. 2), the WAM bias is under (or near) average bias during March - October. In winter months (November - February), the wave height is over-predicted with a maximum bias of 40cm in February 2000. Considering that the WAM set-up errors and WAM physics errors diminish the wind forcing errors (section 4.1) in average, the temporal variation of the bias in Fig. 3 suggests that the major bias in the WAM is dominated by the wind bias.

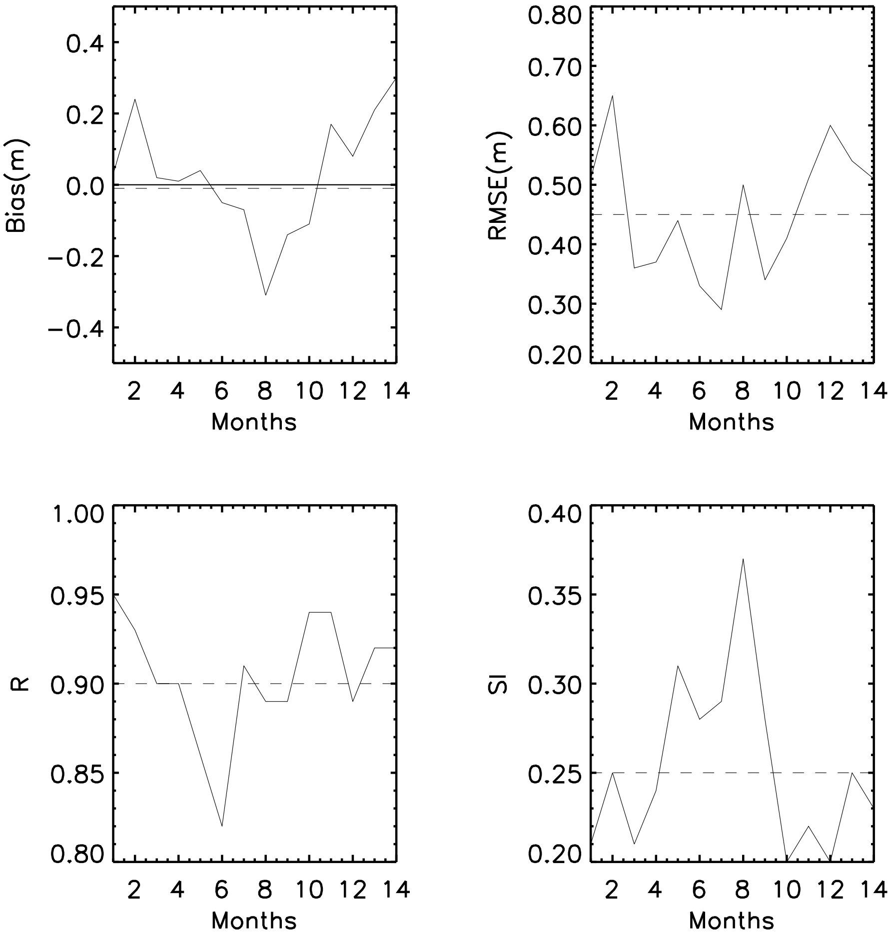

Figure 3: Error statistics of significant wave height for 14 months. Mean values are shown in horizontal lines

4.2.2 RMSE, correlation and scatter index

Both the HIRLAM and WAM have a lower RMSE in the summer months and higher RMSE in the winter months. The correlation coefficients (R) between model data and observations are lower in the summer months and higher in the winter months. In all the months the wave height correlation is higher than the wind speed correlation. The wind correlation is a good indicator of the wave correlation. The scatter indexes (SI) in May - September are higher than the other months. This is mainly caused by lower mean wind speed and wave height in the summer.

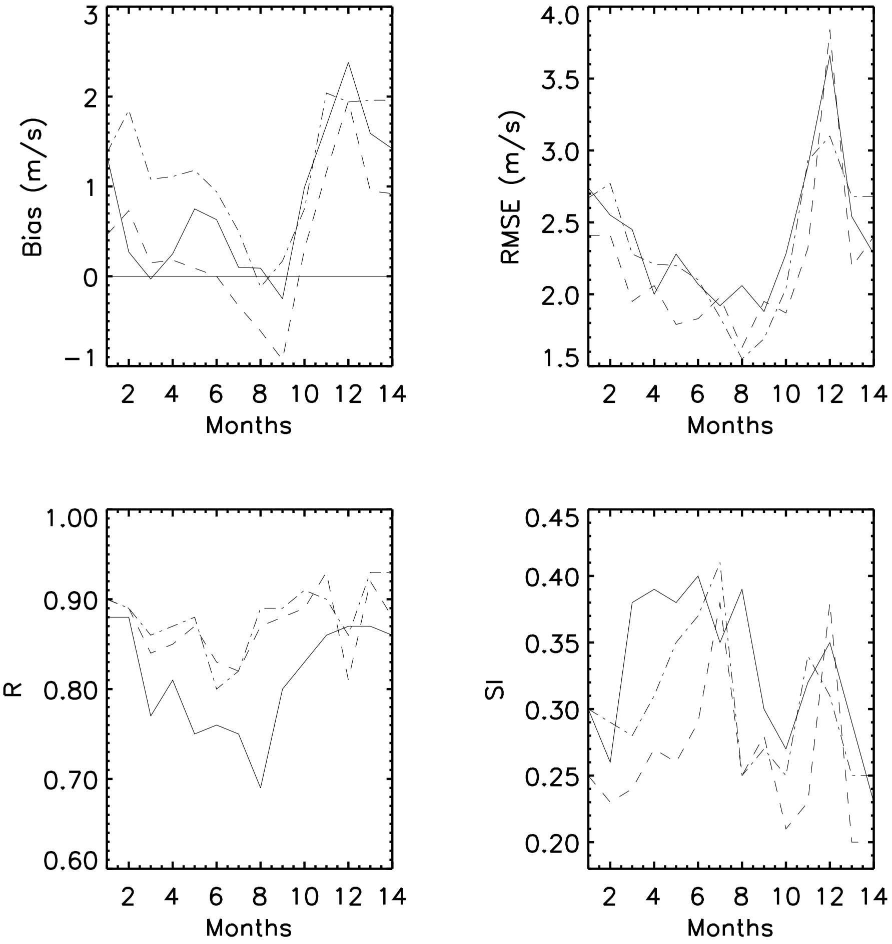

Figure 4: Error statistics of 10m wind speed in southern (solid lines), mid-(dashed lines) and northern (dot-dashed lines) North Sea for 14 months

4.3 Spatial features in error statistics

To investigate the spatial features of the error statistics, we divide the North Sea into 3 parts: northern North Sea (57.5°N-60.0°N), mid-North Sea (55.0 °N-57.5°N and southern North Sea (south of 55.0°N). Figure 4 shows the time-dependent error statistics for the 10m wind speed in the southern (solid lines), mid-(dashed lines) and northern (dot-dashed lines) North Sea. Figure 5 gives the similar error statistics as in Fig. 4 for the significant wave height. For the waves (Fig. 5), the northern North Sea has the largest bias, RMSE and scatter index and the lowest correlation coefficient in average. Another notable feature is that the negative bias coverage is the smallest in the northern North Sea (July - September) and the largest in the southern North Sea (March - October). For the 10m wind speed (Fig. 4), the major negative bias occurs in mid-North Sea. Since the waves response to not only local winds but also remote winds, the negative bias in the mid-North Sea inevitably influences the waves in the southern and northern North Sea. Here the response of waves to the remote winds is shown to be important in the summer months.

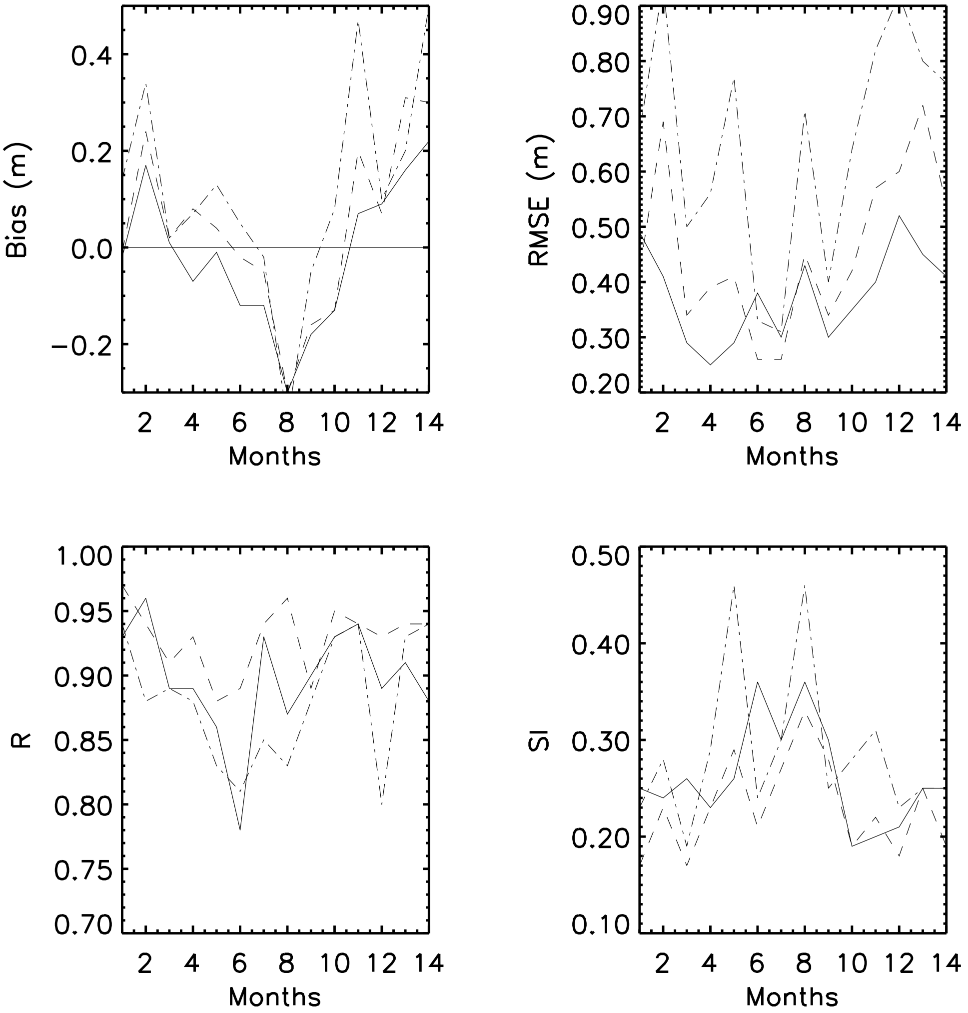

Figure 5: Error statistics of significant wave height in southern (solid lines), mid-(dashed lines) and northern (dot-dashed lines) North Sea for 14 months

4.4 Comparison of wave validation by using different HIRLAM versions

She and Nielsen [1999] calibrated the WAM model for March 1999. Since the HIRLAM version used in the 14-month run (hereafter referred as A55) is somewhat different from the operational version last spring (hereafter referred as OPR99), it is interesting to see if A55 has a better performance than OPR99 in forcing WAM. Table 2 shows the error statistics in southern and northern North Sea for the wave height forced by the two HIRLAM models. Here the domain is re-divided according to She and Nielsen [1999]: $55°N$ is the boundary of northern North Sea.

Table 2. Comparison of wave error statistics with different HIRLAM versions for March 1999

Area	Model	Bias	RMSE	Correlation	SI
		(m)	(m)		
S. North Sea	OPR99	-0.02	0.33	0.84	0.29
S. North Sea	A55	0.01	0.29	0.89	0.26
N. North Sea	OPR99	-0.23	0.40	0.92	0.19
N. North Sea	A55	0.02	0.40	0.90	0.18

Table 3. Wind error statistics from A55 in March 1999

Area	Bias	RMSE	Correlation	SI
	(m/s)	(m/s)		
S. North Sea	-0.03	2.45	0.77	0.38
N. North Sea	0.53	2.05	0.85	0.25

Table 2 shows that A55 is actually doing better in forcing WAM, both in the southern and northern North Sea. In the southern North Sea, A55 has a 1cm positive bias rather than 2cm negative bias in OPR99. The RMSE has reduced from 33cm to 29 cm and SI from 0.29 to 0.26, together with an increase of correlation coefficient from 0.84 to 0.89. In the northern North Sea, A55 has a 2cm positive bias instead of 23cm negative bias in OPR99 while other indexes remain similar to OPR99.

The above error features suggest that the forcing winds are increased in A55 during this month so that negative wave height bias in OPR99 is removed. Table 3 gives the wind errors for A55 in iMarch 1999. The wind speed in the northern North Sea has a positive bias of 0.53m/s. To overcome the negative WAM bias caused by the WAM set-up and physics, a half m/s positive wind bias is required. This is the similar to the results in the average case (section 4.1).

5 Conclusions and discussions

The current operational weather and wave models (HIRLAM and WAM) are validated for a 14-month period against hourly buoy measurements of the 10m wind speed and significant wave height. The buoys are located close to the Greenwich line from $53°N$ - $60\ °N$. Since most of the wind and wave measurements are taken at the same locations, WAM validation and HIRLAM validation can be examined against each other. The results show that the HIRLAM A55 has a 0.64m/s bias and the WAM has a -0.75cm bias in average. Error mechanism analysis indicates that the positive bias of HIRLAM A55 may cause a positive WAM bias of 12.6%, which is diminished by a WAM set-up bias of -8% and a WAM physics bias of -5% on the significant wave height. To obtain a non-bias WAM significant wave height in the North Sea, a half m/s positive wind bias is required. This is important in calibrating WAM-HIRLAM coupled models. Averaged RMSE is 2.3m/s for the 10m wind speed and 0.45m for the significant wave height. The averaged scatter index is 0.30 for the 10m wind speed and 0.25 for the significant wave height. WAM is better correlated with observations (R=0.90) than HIRLAM (R=0.85).

Annual variations of error statistics are found to be significant for both the HIRLAM 10m wind speed and the WAM significant wave height. The amplitude of the annual cycle of the bias is about 4 times as high as the average bias for the 10m wind speed. In the summer months, HIRLAM and WAM show negative bias, lower RMSE, lower correlation coefficient with observations and higher scatter index. It is opposite in the winter months. In spatial average, the wave error statistics is found to be consistent with the wind error statistics. Correlation coefficient of the 10 wind speed between HIRLAM and the wind observations is a good indicator for that of the significant wave height. The significant annual variation of the errors of HIRLAM and WAM indicates that the model calibration of HIRLAM and WAM shall be done for at least a year. Model calibration for HIRLAM and WAM with a shorter period could mislead the model optimization.

Spatial distribution of the 10m wind and wave error statistics is also studied. It is found that the wave responses to large scale wind rather than local wind.

In comparison with an old version of HIRLAM in early 1999, HIRLAM A55 shows an improvement in forcing the WAM in North Sea.

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7 Reference

Günther H., S. Hasselmann and P.A.E.M. Janssen, 1992: Wamodel Cycle4 (revised version). *Technical Report No. 4*, Deutsches KlimaRechnenZentrum.

Hasselmann, K., T.P. Barnett, E. Bouws, H. Carlson, D.E. Cartwright, K.Enke, J.A. Ewing, H. Gienapp, D.E. Hasselmann, P. Kruseman, A. Meerburg, P. Muller, D.J. Olbers, K. Richter, W. Sell and H. Walden, 1973: Measurements of wind-wave growth and swell decay during the Joint North Sea Wave Project (JONSWAP). (*Deut. Hydrogr. Z.*, **A8(12)**.

Janssen P.A.E.M, 1999: Wave modeling and altimeter wave height data. *ECMWF Technical Memorandum No. 269*, European Center for Medium Range Weather Forecasts.

Komen G.J., L. Cavaleri, M. Donelan, K. Hasselmann and S. Hasselmann, 1994: Dynamics and modelling of ocean waves. *Cambridge University Press.*

Kinsman B., 1965: Wind waves, *Prentice-Hall, Englewood Cliffs, N.J.*.

Sass B.H., N. W. Nielsen, J.U. Jørgensen and B. Amstrup, 1999: The operational DMI-HIRLAM system, 2nd rev. ed., *DMI Technical Report 99-21*, Danish Meteorological Institute

She J. and J. W. Nielsen, 1999: Operational wave forecasts over Baltic and North Sea, *Scientific Report No. 99-7*, Danish Meteorological Institute, pp25

Taylor, P. K., E. C. Kent, M. J. Yelland and B. I. Moat, 1999: The Accuracy Of Marine Surface Winds From Ships And Buoys. Pp59-68, *CLIMAR 99, WMO Workshop on Advances in Marine Climatology, Vancouver, Canada*

Zeng, L.X. and R.A. Brown, 1998: Scatterometer observations at high wind speeds. *J. Appl. Meteorol.*, **37(11)**, 1412-1420