CHAPTER 27

AN EVALUATION OF TWO WAVE FORECAST MODELS FOR THE SOUTH AFRICAN REGION

by
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ABSTRACT
The forecasting of wave conditions in the oceans off Southern Africa is important for both offshore and coastal marine operations in the area. The accuracy of wave forecasts for the area from models operated in Europe has, however, not been high. One of the main reasons is that the local measurement of waves has not been taken into account. Since the necessary infrastructure for operational wave forecasting is locally available in South Africa, a decision has been taken to establish a local facility whereby a numerical wave forecast model will be implemented. This paper focuses on the comparison of two operational wave forecast models in order to assist in the selection of an appropriate model for the South African region.

1. INTRODUCTION
The South African ocean route is one of the major shipping routes in the world (approximately 120 million tonnes of oil were transported around the tip of Africa in 1991). In addition, the offshore activities such as oil exploration, diamond mining and also coastal construction operations are increasing.

The Southern African waters are renowned for their treacherous sea, especially during winter. The already established weather forecast service provided by the South African Weather Bureau (SAWB) has up till now depended largely on information obtained from the global forecast model data, especially for wave forecasts. However, the wave conditions are represented relatively poorly as the input data sources are sparse in the Southern Atlantic Ocean where most of the wave energy is generated which reaches the South African coast. Only a few weather data sources are available (a couple of islands and a number of weather buoys).

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The maritime activities need a reliable and accurate maritime weather forecast service which includes the prediction of the wave conditions. Local input data sources should be incorporated, including the local wave conditions. This information should result in a reduction in the risk of shipping accidents and could improve the planning for offshore exploration and operational activities.

Therefore, an appropriate wave forecast model should be implemented and operated in conjunction with the already established weather forecast service. This paper focuses on the comparison of two operational wave forecast models in order to assist in selecting an appropriate model for the South African region (CSIR, 1995).

2. DATA SOURCES

The data sources used for this exercise included the wave forecast data from the UKMO and WAM numerical wave models, wave data collected by wave recording buoys and also remotely sensed wave height data recorded by the ERS-1 satellite. In a number of cases the synoptic weather charts were also consulted for the identification of weather systems. These data sources are discussed briefly in the following sections.

2.1 Forecast Wave Data

UKMO model

The data of the UKMO model from the British Meteorological Office in Bracknell (UKMO) were received via the South African Weather Bureau (SAWB). Two forecasts per day were received, for 00:00 and 12:00 hours.

The forecasts covered an area delineated by latitudes 20° to 65° S and longitudes 0° to 40° E at a 2,5° grid spacing. The data included the significant wave height (H_{mo}), the significant wave height and wave direction for the swell, and the swell and sea wave period. Each forecast covers 120 hours (five days) at the following intervals:

T+0, 12, 24, 36, 48, 72, 96 and 120 hours (T = 00:00 and 12:00)

WAM model

The WAM model data were received directly from the Royal Dutch Meteorological Institute (KNMI) in the Netherlands via e-mail. One forecast per day was received, for 12:00 hours.

The forecasts covered an area delineated by latitudes 21° to 60° S and longitudes 9° to 39° E at a 3,0° grid spacing. The data included the significant wave height (H_{mo}) and wave direction, the significant wave height and wave direction for the swell, and the significant wave height and wave direction for the sea component. The forecast covered a period 72 hours (three days) at six hourly intervals.

2.2 Recorded Wave Data

Wave recording buoys

The wave data used in this study were collected by wave recording buoys at locations offshore of Möwe Bay, Port Nolloth, Slangkop and Durban in water depths of 100m, 100m, 76m and 50m, respectively (Figure 1).

Wave records of approximately 17,5 minute duration were routinely recorded at three-hourly intervals at all these stations. These records were subsequently spectrally analysed and interpreted in terms of the significant wave height and period. However, these records do not contain the wave direction and are therefore omni-directional.

Remotely sensed data

The only remotely sensed data used in this study were obtained from the ERS-1 satellite. These data, consisting of significant wave height, were used to investigate specific forecasts during the period of interest. It was possible to compare observed and predicted wave heights over a large area.

3. COMPARISON METHODOLOGY

The study used a number of methods to compare the predicted data with that observed. It should, however, be noted that only the significant wave height could be analysed as it was the only parameter common to all three data sets. Although the wave direction parameter is included in the forecasts, it is not part of the suite of wave parameters obtained from the recorded data, as non-directional wave recording buoys were used. The methods of comparison are discussed below.

3.1 Data Processing

Both the UKMO and WAM data were received in a grid format. For comparison with measured data at specific locations, the most appropriate grid points had to be identified in the UKMO and WAM data sets. Therefore, the closest grid points to the wave recording buoy locations were selected as shown in Figure 1. Although two UKMO forecasts per day were available, only the 12:00 hour forecasts were used to compare with the 12:00 WAM forecast and the measured data.

For comparison with the offshore wave data from both models, the measured data had to be adjusted for the shallow water effects. Shoaling was therefore taken into account by applying linear shoaling as described in the Shore Protection Manual (CERC, 1984). However, as no wave directions were available, the refraction-effect could not be considered. The bathymetry in the vicinity of all four locations is fairly uniform and the water depth relatively large, thus wave energy-loss due to refraction will not be significant.

3.2 Time-series Comparisons

In order to establish the effectiveness of a wave forecast over a certain period, one can compare the entire forecast with the observed (measured) wave conditions. If the forecast predicted the actual conditions well enough one would have confidence in that forecast. It should, however, be remembered that there can be some variation in the predictions as these are based on meteorological information that is not always 100 per cent correct. One must, therefore, include an estimation of uncertainties for short-term sea state parameters in the wave forecast.

For the purposes of this study a factor "σ" (normalised standard deviation) was applied to both UKMO and WAM data sets. This factor was taken as $\sigma = 0{,}2$ in accordance with standards for wave predictions (PIANC, 1992). Thus, the following formula was implemented:

$$H_{min} = H - (H * \sigma) \quad \text{and} \quad H_{max} = H + (H * \sigma)$$

where H = significant wave height (H_{mo})

These two parameters, H_{min} and H_{max}, thus provide a range in which the observed wave height could occur for a satisfactory prediction.

3.3 Specific Timeslots

Another way of comparing the wave forecasts with measured data is to consider specific forecast timeslots. Both the model data sets have predictions for 12, 24, 48 and 72 hours ahead. It was therefore possible to compare the predicted and measured data at the specific timeslots, graphically and statistically.

Scatter plots of the predicted and measured total wave height were prepared at all four locations for the above mentioned timeslots. Statistical parameters such as the correlation coefficient and the root mean square error (RMSe) were also determined for these comparison sets (Khandekar, 1989). The RMSe is given by the following expression:

$$RMSe = \sqrt{\frac{1}{N}\sum (Model - Observed)^2}$$

where:
Model = predicted value; Observed = observed value; N = number of values

3.4 Wave Contours

As mentioned previously both the UKMO and WAM data come in a grid format. It is thus possible to present these data sets in a contour plot. Predicted wave conditions for a large section of the Southern Atlantic Ocean can therefore be presented. These were plotted with the ERS-1 satellite tracks. The predicted wave heights along the satellite tracks could then be compared to wave heights recorded by the ERS-1 satellite.

Due to the vast number of individual predictions (every timeslot), it is not practical to prepare a contour plot for each of them. Therefore, only a selected number were chosen which could be examined.

4. RESULTS

4.1 Time-series Comparisons

Using the procedure described in Section 3.2, both UKMO and WAM forecasts were plotted with the observed data recorded off Möwe Bay, Port Nolloth, Slangkop and Durban for the period 14 November to 31 December 1994. Examples of the comparisons are presented in Figure 2 for Möwe Bay, Port Nolloth, Slangkop and for Durban.

For the purposes of this study the assumption was made that up to a two-day-ahead (48 hours) and three-day-ahead (72 hours) wave forecasts are practical. The observed values had to fall within approximately 80 per cent of the predicted ranges in each wave forecast in order for the forecast to be deemed satisfactory. This meant that only one prediction value of the UKMO forecasts for both the 48 and 72 hours could be out of range. As the WAM data produced more values, two predictions in 48 hours and three predictions in 72 hours could be out of range and the forecast would still be acceptable. However, if the erroneous prediction values were consecutively out of range, the forecast was rejected.

Based on these criteria, the percentage of satisfactory wave forecasts are presented in Table 1. For each location and for the two models these percentages are given for the 48 hour and 72 hour forecast period. It is evident that the WAM model produced more satisfactory forecasts than the UKMO model for the Möwe Bay, Port Nolloth and Slangkop area. For example, at Möwe Bay 92 per cent of the WAM wave forecasts were satisfactory while 67 per cent of the UKMO forecasts were satisfactory. Both models produced better results over the 48 hour forecast period than over the 72 hour period. The low percentage of acceptable forecasts for the Slangkop location is again addressed in Section 4.2.

TABLE 1: Percentage satisfactory wave forecasts

Location	UKMO model (%)		WAM model (%)	
	48 hour	72 hour	48 hour	72 hour
Möwe Bay	67	64	92	89
Port Nolloth	60	44	81	73
Slangkop	39	11	56	44
Durban	64	51	45	33

4.2 Specific Timeslots

Using the procedure described in Section 3.3, scatter plots were done for both the UKMO and WAM forecasts with the observed data recorded off Möwe Bay, Port Nolloth, Slangkop and Durban for the period 14 November to 31 December 1994.

UKMO data

Two examples of the scatter plots are presented in Figure 3, showing the 24 and 48 hour timeslot results for Slangkop. The solid line also shown in the figures represents the 1-to-1 (1:1) ratio of the predicted versus the observed wave heights. The correlation coefficient and RMSe values for the 24 hour timeslot are given in Table 2.

TABLE 2: UKMO statistics: 24 hour timeslot

Location	Average wave height (m)		Correlation coefficient	RMSe (m)
	Measured	Predicted		
Möwe Bay	1,86	1,84	0,644	0,34
Port Nolloth	2,01	1,82	0,652	0,53
Slangkop	2,22	1,86	0,631	0,69
Durban	1,81	2,00	0,503	0,53

From the results it appears that the values for Möwe Bay, Port Nolloth and Durban locations are distributed fairly symmetrically around the 1:1 line. However, at the Slangkop location there is a definite bias towards under-prediction. This was evident in the scatter plots of all four timeslots. In order to eliminate this bias, linear regression was performed on the 12-hour data set. The regression line should coincide with the 1:1 line if perfect agreement between observed and predicted data exists. In order to eliminate the under estimation of the predicted results, data points were adjusted proportionately to get better correlation between observed and predicted values. The data sets of the other three timeslots (24, 48 and 72 hours) were also adjusted in a similar manner using the 12 hour regression function. These re-analysed results are presented in Table 3. Using this regression function it was possible to improve the comparison of the predicted with the observed wave heights for all four timeslots at Slangkop.

In general the correlation between the observed and predicted values was found to be low. As can be expected, the correlations decreased over time with the 12 hour timeslot having the highest correlations. The average correlation coefficients for the 12, 24, 48 and 72 hour timeslot (for all four locations combined) were found to be approximately 0,6, 0,6, 0,5 and 0,4 respectively. In general, the predictions, therefore, do not compare all that well with the observed conditions. However, by applying the regression function to the Slangkop data, an average coefficient of about

0,8 was found. As was expected, the correlation for 72 hour forecasts was the lowest on average.

TABLE 3: UKMO: Re-calculated Slangkop statistics

Timeslot (hours)	Average wave height (m)		Correlation coefficient	RMSe (m)
	Measured	Predicted		
12	2,35	2,35	0,88	0,45
24	2,22	2,11	0,86	0,40
48	2,20	2,20	0,80	0,45
72	2,21	2,24	0,62	0,65

The RMSes on the other hand, range from approximately 0,3 m to 0,85 m; the lowest RMSe values being in the 12 hour timeslot. It is also noteworthy that Möwe Bay has the lowest values for all timeslots, on average 0,36 m. This implies the predictions for Möwe Bay were the most accurate of the locations considered. By applying σ (0,2) to the average predicted wave height (Tables 2 and 3), an uncertainty value of 0,38 is determined. Therefore, because this value compares well with the RMSe, one can conclude that the prediction for Möwe Bay should be satisfactory and typically within $\pm$ 20 per cent of the actual wave height.

The average RMSe for the Slangkop location was found to be 0,71 m while an average uncertainty value of 0,39 m was calculated. This difference of 0,32 m and the low correlation indicates that the predictions for this location are unsatisfactory. However, following the re-analysis the high correlation coefficient of 0,8 and the average RMSe of 0,49 m suggest reasonable predictions. Based on the average predicted wave height an uncertainty value of 0,45 m was determined. This value therefore compares well with the average RMSe. Thus, the predictions close to the Slangkop location appear to have been reasonable. Satisfactory forecasts can therefore be obtained with some level of calibration.

Durban has the highest RMSe value, 0,84 m (72 hour) with an average value of approximately 0,65 m. Application of σ to the average predicted wave height yields an uncertainty value of 0,41 m which is about 0,2 m less than the average RMSe. Apart from inadequate input data for the wave forecast model, these discrepancies could also be attributed to the effect of the Agulhas Current on wave conditions along the south and south-east coast of South Africa.

The average RMSe at the Port Nolloth location was found to be 0,61 m while the average uncertainty value of 0,4 m was calculated. Therefore, these forecasts for this location could not be rated as satisfactory as a correlation coefficient of 0,6 was obtained.

WAM data

Figure 3 also presents two examples of the scatter plots showing the 24 and 48 hour timeslots for Slangkop. The solid line also shown in the figures represents the 1-to-1 (1:1) ratio of the prediction versus the observed wave heights. The correlation coefficient and RMSe values for the 24 hour timeslot are given in Table 4.

TABLE 4: WAM statistics: 24 hour timeslot

Location	Average wave height (m)		Correlation coefficient	RMSe (m)
	Measured	Predicted		
Möwe Bay	1,84	1,89	0,86	0,23
Port Nolloth	2,00	2,05	0,87	0,33
Slangkop	2,19	2,41	0,77	0,53
Durban	1,77	2,18	0,45	0,76

From the figures it appears that the values for Möwe Bay and Port Nolloth locations are distributed fairly symmetrically around the 1:1 line. However, at the Slangkop location there was also a slight bias towards over-predicting wave heights below 2,5 m and under-predicting wave heights above 2,5 m. In order to eliminate this bias, linear regression was performed on the 12-hour data set, as in the case of the UKMO data (Section 4.2). The data sets of the other three timeslots were also adjusted in a similar manner using the 12 hour regression function. These re-analysed results are presented in Table 5.

TABLE 5: WAM: Re-calculated Slangkop statistics

Timeslot (hours)	Average wave height (m)		Correlation coefficient	RMSe (m)
	Measured	Predicted		
12	2,32	2,32	0,90	0,41
24	2,19	2,18	0,90	0,33
48	2,17	2,17	0,89	0,34
72	2,18	2,15	0,82	0,42

The correlation between the observed and predicted values was found to be quite satisfactory, except for the Durban location. As expected, the correlations decreased over time with the 12 hour timeslot having the highest correlations.

The average correlation coefficients for the 12, 24, 48 and 72 hour timeslots were found to be approximately 0,7, 0,7, 0,7 and 0,6 respectively. The average correlation coefficients for the Möwe Bay, Port Nolloth, Slangkop and Durban location were found to be about 0,8, 0,8, 0,7 and 0,4 respectively. In general, the predictions, therefore, compare well with the observed conditions except at the Durban location. However, by applying the "regression" function to the Slangkop data, an average coefficient of almost 0,9 was found at this location. As was expected, the correlation of 72 hour forecast was, on average the lowest on average.

The RMSe's on the other hand range from approximately 0,2 m to 0,8 m. The lowest RMSe values being in the 12 hour timeslot. It is also noteworthy that Möwe Bay has the lowest values for all timeslots, on average 0,26 m. By applying σ (0,2) to the average predicted wave height, an average uncertainty value of 0,39 m is determined. Therefore, because this value compares well with the RMSe, and the correlation is good for Möwe Bay, one can conclude that the forecasts are satisfactory.

The average RMSe for the Slangkop location was found to be 0,56 m while an average uncertainty value of 0,47 m was calculated (Section 3.2). Although the difference is quite small and the correlation fair, the re-analysis resulted in a high correlation coefficient of 0,9 and an average RMSe of 0,38 m suggesting satisfactory predictions. Based on the average predicted wave height an average uncertainty of 0,44 was determined. This value therefore compares well with the average RMSe. Thus, reliable wave forecasts close to the Slangkop location can be obtained with some level of calibration.

As in the case of the UKMO forecasts, the Durban location has the highest RMSe value, 0,76 m (for the 24 hour timeslot) with an average value of approximately 0,69 m. Application of σ to the average predicted wave height yields an average uncertainty value of 0,42 m which is about 0,3 m less than the average RMSe. This implies a greater than 20 per cent uncertainty in the predicted wave height. Apart from inadequate input data for the wave forecast model, these discrepancies could also be attributed to the effect of the Agulhas Current on wave conditions along the south and south-east coast of South Africa.

The average RMSe at the Port Nolloth location was found to be 0,36 m while the average uncertainty value of 0,42 m was calculated. Thus, the forecasts for this location also appear to be reasonable as a correlation coefficient of 0,8 was obtained.

4.3 Wave Contours

Five case studies were selected to present specific predictions spatially together with the ERS-1 data. All the forecasts used were produced at 12:00 (T =12:00).

An example of the predicted wave height contours of the UKMO and WAM forecasts as well as the ERS-1 tracks are presented in Figure 4. The wave height versus latitude plots are also given in these figures. The ERS-1 tracks were selected so that they would correspond with the time of the predicted wave heights.

It would be difficult to determine which model produced the best wave forecasts as only five cases were examined. However, these results give an indication of how well specific predictions compared spatially using the ERS-1 data.

5. DISCUSSION

The time-series comparisons determined for the UKMO and WAM wave forecasts, revealed that the WAM model produced a larger percentage of satisfactory forecasts than the UKMO model. However, the UKMO forecasts appear to have been more successful at the Durban location. As expected all cases the forecasts for the 48 hour forecast period were more reliable than for the 72 hour period.

It appears that during calm and also gradually varying conditions both models predict wave heights quite well. Wave height conditions that increased over a period of a day or more were predicted satisfactorily on a number of occasions. However, when the wave height increases rapidly (less than a day), the predictions tended to be poor. Under these storm conditions, WAM forecasts compared better with the observed wave heights than the UKMO forecasts. The UKMO forecasts also frequently under-predicted the wave heights during these events.

By examining the results of the timeslot-comparison, it was found that the RMSe's of the WAM forecasts are, on average, more than 20 per cent lower than the RMSe's of the UKMO forecasts. The correlation coefficients, on the other hand, are 33 per cent higher at the Möwe Bay and Port Nolloth locations and, 12 per cent higher at Slangkop. At the Durban location these coefficients were found to be approximately the same.

The five cases selected for plotting the wave height contours are not enough to unequivocally determine which model produced the best results. In order to determine this, more specific predictions (i.e., 24, 36, 48, 72 hours) of every forecast would have to be used.

Although it has been established that the forecasts of the WAM model compare most favourably with the observed data, the wave forecasts can still be improved. It should also be recognised that this study was performed in the summer season when mild to moderate wave conditions prevail for most of the time. During the winter season (June to August) extreme wave conditions prevail more frequently and are also more variable. These large fluctuations in wave height are coupled to the passage of intense low pressure systems which are more frequent during the winter months.

For both forecast values, the mathematical formulation used to determine the generation and propagation of wave conditions are state-of-the-art and are continuously being improved. However, the input data (the atmospheric forces) used to drive these models determines the reliability of a wave forecast to a large extent. In the southern hemisphere the input data are unfortunately sparse which results in poor spatial data representation. Currently the input data consist mainly of data from coastal weather stations and some remotely sensed data sources. To improve the wave forecasts in the Southern Atlantic Ocean, it would be essential to improve the number and quality of input data sources. This could be done through the deployment of more offshore weather buoys. In addition the use of wave recording buoys off the coast of South Africa for verification purposes, would contribute to greater reliability of wave forecasts.

6. CONCLUSIONS

Considering the three comparative methods that were used to compare the UKMO and WAM forecasts with the observed data, obtained from wave recording buoys offshore of Möwe Bay, Port Nolloth, Slangkop and Durban as well as wave height data remotely sensed by the ERS-1 satellite, the following conclusions can be drawn:

The time-series comparison results showed that the WAM model produced a larger percentage of satisfactory wave forecasts than the UKMO model at the locations of Möwe Bay, Port Nolloth and Slangkop. On average, the WAM model produced over 35 per cent more satisfactory forecasts than the UKMO model.

By analysing the wave forecasts in terms of correlations coefficients and Root Mean Square errors (RMSes) it was found that the forecasts produced by the WAM model provided the best results.

The RMSes of the WAM forecasts are, on average, more than 20 per cent lower than the RMSes of the UKMO forecasts. The correlation coefficients are 33 per cent higher at the Möwe Bay and Port Nolloth locations and 12 per cent higher at Slangkop. At the Durban location these coefficients were found to be approximately the same.

Although it was not possible to determine which model produced the best results by comparing the predicted wave heights with remotely sensed wave heights along satellite tracks, it was found that this method may be useful in establishing the spatial reliability of the forecasts in terms of specific predictions (timeslots).

This comparative study was done during the months of November and December with mild to moderate wave conditions prevailing for most of the time. These results should therefore be considered to be more relevant for the summer season than for the winter season.

The differences between the results of the two models could amongst other things be attributed to the following factors:

- The UKMO is a second generation model whereby the non-linear tranfer of wave energy is parameterised. The WAM model, which is a third generation model, solves the non-linear wave energy tranfer function.

- In addition, different atmospheric input data sets are used to drive the two models, which would influence the output of these models.

It is concluded that the WAM model produces the most favourable results. However, these forecasts can still be improved by increasing the number of the input data sources (offshore weather stations) and also by evaluating the numerical modelling procedures of the wave forecast model.

7. RECOMMENDATIONS

Based on the conclusions the following recommendations can be made:

The WAM model should be implemented locally for providing the necessary wave forecasts for the South African region. (Note: the model has been installed at the head office of the SAWB; the model is presently running on a trial basis).

In order to establish the effectiveness of the WAM and UKMO forecasts during storm conditions, a similar comparison study should be conducted for the autumn and winter seasons (March to August).

The Agulhas Current is also a prominent feature along the south and south-east coast and influences the wave conditions in this region. This current-wave interaction should therefore also be investigated for incorporation in the wave forecast models in order to have reliable forecasts along both the south and south-east coast.

An essential component of the numerical modelling of the atmospheric forces and wave conditions are the data sources. As these are sparse in the southern hemisphere, especially in the Southern Atlantic Ocean, data coverage should be increased by, for example, the deployment of offshore weather buoys. The present network of wave recording buoys along the coast of South Africa (called WAVENET) and maintained by the CSIR, could be used for verification purposes in the wave forecasting procedures. These strategies should improve the reliability of the wave forecasts and also the general weather forecasts.

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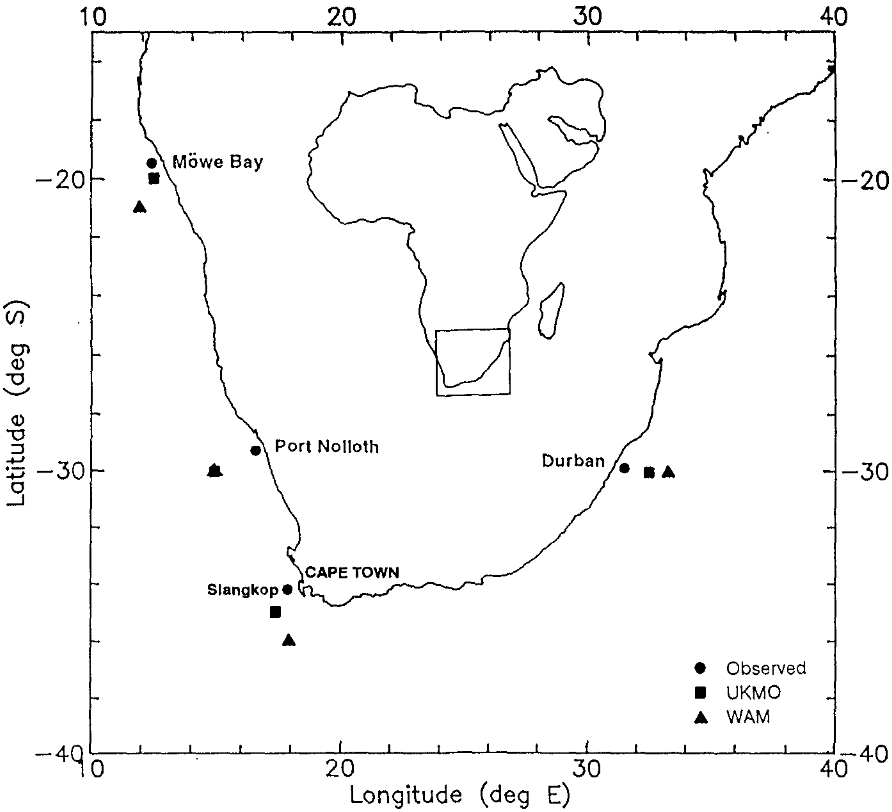

Figure 1: Location map

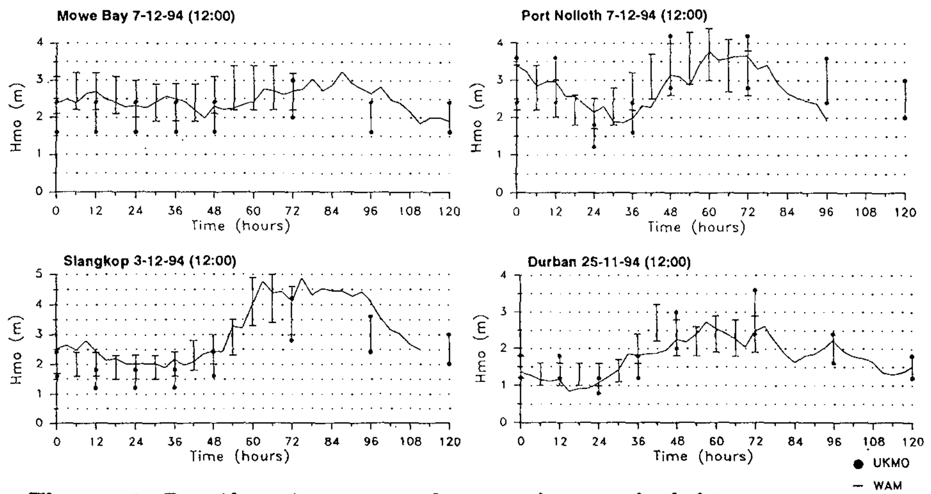

Figure 2: Predicted versus observed wave height

LOCATION: SLANGKOP

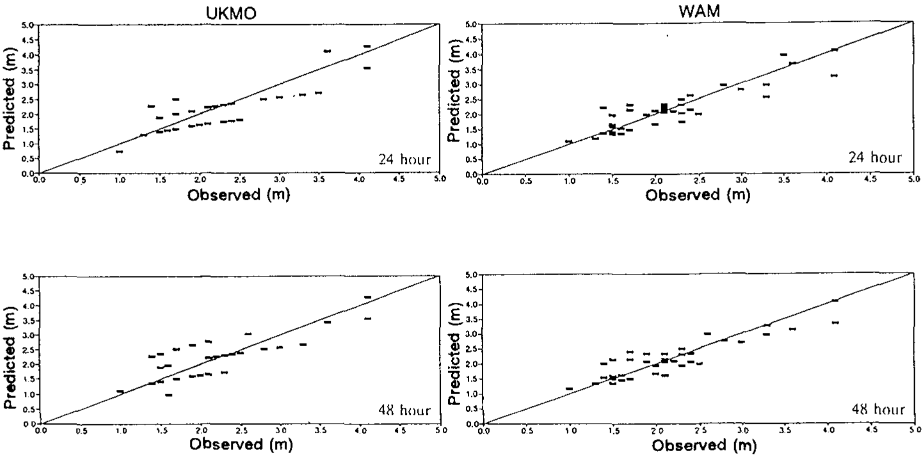

Figure 3: Scatter plots for Slangkop location

FOR 12 HOUR FORECAST

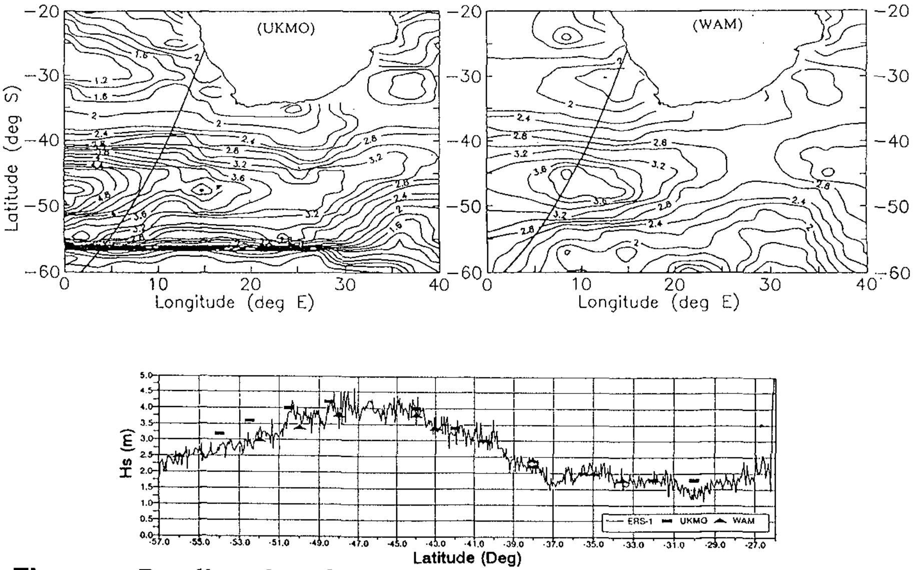

Figure 4 Predicted and recorded wave heights along ERS-1 track