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Verification of the ECMWF Wave Forecasting System against buoy and altimeter data

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Abstract

We review the present status of ocean wave modelling at the European Centre for Medium-Range Weather Forecasts (ECMWF). Ocean waves are forecasted globally up to ten days by means of the WAM model which is driven by 10 m winds from the ECMWF atmospheric model. Initial conditions are provided by assimilation of ERS-1 data into the first-guess wave field.

The analysed wave height and peak period field are verified against buoy data and show a considerable improvement compared to verification results of a decade ago. This is confirmed by a comparison of first-guess wave height against ERS-1 altimeter data. The main reasons for this improvement are (i) higher quality of ECMWF winds compared to a decade ago, ii) improved physics of the WAM model and (iii) the assimilation of ERS-1 data.

We also study the forecast skill of the ECMWF wave forecasting system by comparing forecasts with buoy data and verifying analysis. Error growth in forecast wave height is less rapid than in forecast wind speed. However, considerable positive mean errors in forecast wave height are found, suggesting a too active atmospheric model in later stages of the forecast. Nevertheless, judging from anomaly correlation scores, the wave forecast seems to be useful up to day five in the forecast in the Northern Hemisphere. Since the wave forecast depends in a sensitive manner on the wind forecast, this confirms the high quality of ECMWF forecasts near the surface.

Finally, we also discuss promising ways of improving the wave forecast and, as an example, mention the positive impact three-dimensional variational (3D-Var) assimilation has on the wave product.

1. Introduction

In the past decade we have seen considerable progress in the field of ocean wave modelling. In the middle of the 1980's a group of mainly European wave modellers, who called themselves the WAM Group, realised that it should be feasible to develop a wave model on first principles, i.e. a model that solves the energy balance equation for surface gravity waves including nonlinear wave-wave interactions. First of all, there was a clear need for improving existing wave models at that time. Although these so-called first and second generation models performed reasonably well in many cases, it turned out that, in rapidly varying circumstances, they could not provide a proper description of the sea state. This was demonstrated in a comparison exercise where about 10 different models were run with the same hurricane wind field, resulting in widely varying maximum wave heights (ranging from 8 to 25 m). The reasons for the shortcomings of the first and second generation models have been discussed extensively in *SWAMP* (1985) and *Komen et al* (1994).

Secondly, the solution of the energy balance equation (including a parametrized version of the nonlinear transfer) requires considerable computing power, which has only become available in recent years. Thirdly, the mathematical and computational developments coincided with the development of remote sensing techniques for measurements of the ocean surface by means of microwave instruments (Altimeter, Scatterometer and Synthetic Aperture Radar (SAR)). In this context it should be noted that there is a rather close relationship between wave model development and satellite remote sensing. Satellite observations can be used to validate the wave model and the model also gives a first check on the accuracy of the observations. Furthermore, a detailed description of the dynamics of the ocean surface is important for a correct interpretation of the radar signals.

At present, the WAM model is widely used as a research tool and it is used operationally in global and regional implementations to make forecasts of the sea state which are useful for many applications such as ship routing and offshore activities, and for the validation and interpretation of satellite observations. The capabilities of the WAM model have been assessed in detail (*WAMDI-group* 1988; *Komen et al* 1994), giving confidence in its performance. Nevertheless, no systematic verification study of WAM model results has been performed so far, except by *Zambresky* (1989), using conventional buoy data, and *Romeiser* (1993), using Geosat Altimeter data. Both authors concluded that, in general, the modelled wave heights (obtained by forcing the WAM model with ECMWF winds) showed good agreement with the data. However, considerable differences were found as well. *Zambresky* (1989) noted that the WAM model rather often has a tendency to under-predict extreme sea states. *Romeiser* (1993) found considerable regional and seasonal differences between modelled wave height and Geosat Altimeter data.

During the Southern Hemisphere winter WAM may underestimate wave height by about 20% in large parts of the Southern Hemisphere and the tropical regions, while for the rest of the time agreement with data is fairly good.

Both those verification studies were using modelled wave heights for 1988 obtained from cycle 2 of the WAM model, while the forcing wind fields were provided by the T106/19L version of the ECMWF atmospheric model. Since 1988 a number of important changes have been introduced in the wind-wave forecasting system at ECMWF. First of all, in September 1991 the resolution of ECMWF's atmospheric model was doubled in the horizontal and nearly doubled in the vertical. Because of the increased horizontal resolution one would expect a better representation of the surface winds which could be beneficial for analysing and predicting ocean waves in the storm tracks, in particular of the Southern Oceans. Secondly, since November 1991 a new version of the WAM model, called cycle 4, was introduced operationally at ECMWF. This new version of the WAM model has been described in detail in *Komen et al* (1994) and, compared to previous cycles of the WAM model, has improved physics regarding wind input and dissipation of wave energy. Thirdly, assimilation of ERS-1 altimeter wave height data started in August 1993, and lastly, in July 1994, the horizontal resolution of the wave model was increased by a factor of two from 3° to 1.5° This increase in horizontal resolution could, as already pointed out by *Zambresky* (1989), have a beneficial impact on the prediction of extreme sea states because more details of the generating wind field are taken into account.

Because of these important changes in the wind-wave forecasting system, it was thought of interest to investigate to what extent we have achieved improvements in wave analysis and wave forecasting at ECMWF. Possible improvements in performance will be judged by comparing analysed wave height with observations from buoys and radar altimeters on board ERS-1 and ERS-2. In addition, since the main goal of ECMWF is in forecasting, special attention is given to the quality of forecast wave height fields. In particular, forecast wave heights are compared with buoy observations and with the verifying analysis. This gives us the opportunity to apply some new verification tools in ocean wave forecasting which have already been in use in weather forecasting quite some time. For example, the anomaly correlations provide information on how much more skill a wave forecast has over wave climatology. It turns out that the anomaly correlation is a sensitive indicator of the quality of the wave forecast, and also of the quality of forecast surface winds.

The programme of this paper is therefore as follows. In Section 2 we briefly describe the cycle 4 physics of the WAM model and we discuss the advantages of this formulation over previous cycles. The verification of analysed wave height against buoy data over the one year period of January 1995 to

December 1995 is given in Section 3, while in Section 4 we compare wave heights with the altimeter wave height from ERS-1. Section 5 is devoted to the verification of forecast wave height against buoy data and against verifying analysis, and the forecast skill is judged against persistence and wave climatology. Finally, Section 6 gives a summary of conclusions and prospects for the future.

2. The WAM model at ECMWF

Since November 1991 cycle 4 of the WAM model has been running (quasi-) operationally at ECMWF. The WAM model is the first model that explicitly solves the energy balance equation for the two-dimensional surface wave spectrum $F(f,\theta)$ where f is the frequency and θ the wave direction. In deep water, the energy balance equation reads

$$\frac{\partial}{\partial t}F + \vec{v}_g \cdot \frac{\partial}{\partial \vec{x}} F = S_{in} + S_{nonl} + S_{diss} \tag{1}$$

where $\vec{v}_g = \partial\omega/\partial\vec{k}$ is the group velocity, and the source functions on the right-hand side represent the physics of the generation of waves by wind, dissipation of energy due to white capping and the energy transfer due to 4-wave interaction (*Hasselmann* 1962). A complete discussion of the physics of wave evolution and wave generation and the actual details of the numerical implementation of the energy balance may be found in *Komen et al* (1994), where a discussion of the performance of the WAM model is also given.

At ECMWF the WAM model has been implemented on the globe (with resolution of 1.5°) and on the Mediterranean and Baltic Sea (with a 0.25° resolution). However, only global results will be discussed in this paper. The wave spectrum has 25 frequencies and 12 directions at each gridpoint. The source term integration time step is 15 minutes, while the advection time step is 30 minutes. The model allows for the possibility of a variable ice edge which is of particular importance in the Southern Ocean. The decision on whether a grid point is ice or water is based on the analysed sea surface temperature. The ice edge is kept fixed during the 10-day forecast.

Before August 1993 the wave analysis was obtained by forcing the wave model with analysed ECMWF wind fields. Since this date ERS-1 altimeter wave height data have been assimilated using an Optimum Interpolation scheme from *Lionello et al* (1992). The inclusion of altimeter data has a beneficial impact on the wave forecast which may last up to 5 days (*Komen et al* 1994).

The WAM model is a fully vectorised code which may be auto-tasked and macro-tasked. In single-tasked mode an average speed of about 500 Mflops is reached on a Cray C-90. At present the macro- tasked version is operational and the 1 day analysis + 10-day forecast cycle is accomplished in less than 7 minutes using 8 processors of a Cray C90. Integrated parameters such as significant wave height, mean period and mean wave direction (for total sea, windsea and swell) are disseminated once a day to the ECMWF member states involved in the wave project. All integrated parameters for analysis and forecast are archived every 6 hrs while the analysed two-dimensional wave spectrum is stored once a day. In addition, monthly means of wave height, mean period, wave direction, surface wind speed and direction have been archived since January 1995. In collaboration with the Portuguese Meteorological Office we have extended the wave climate archive with 3° global results starting from January 1 1987. This enabled us to generate a wave climatology based on 9 years of wave model data, and therefore we are now able to determine the anomaly correlation of significant wave height (cf Section 5).

The cycle 4 version of the WAM model, which is operational at ECMWF, has a certain number of advantages over earlier cycles of the WAM model. First of all, the latest cycle allows the surface stress to be determined, including the dependence on the sea state through the wave-induced stress. This was accomplished by introducing a parametrized version of the quasi-linear theory of wind-wave generation into the WAM model (*Janssen* 1989, *Janssen* 1991) which treats both the generation of waves and the slowing down of air flow because of the air-sea momentum transfer. As a consequence, the sea state dependence on the surface stress may be determined (which shows good agreement with Hexos observations (*Janssen* 1992)). The resulting growth rates of ocean waves by wind turn out to be slightly larger than previous cycles, which were based on the Snyder et al parametrization of the wind input source function S_{in}.

Secondly, the high-frequency part of the wave spectrum shows more realistic levels when compared to observations. Previous cycles tended to overestimate high-frequency levels, as noted by *Janssen et al* (1989b) and *Banner and Young* (1994). By introducing a somewhat stronger wave dissipation at high-frequencies (cf *Janssen* 1991, *Komen et al* 1994) more realistic high-frequency levels were obtained, as shown in Fig 1. In this Figure the modelled high-frequency part of the wave spectrum (i.e. the slice in the wind direction) is compared with *Banner's* (1990) empirical fit for different stages of wave development as measured in terms of the wave age c_p/u_*. Here, c_p is the phase speed of the peak of the wave spectrum while u_* is the friction velocity. Noting that Banner's empirical fit only holds for old wind sea data (with wave age around 25) it is seen that a reasonable agreement exists between the modelled (cy4) and observed high-frequency part of the wave spectrum. This is a considerable improvement as *Banner* *and Young* (1994) reported that earlier cycles of the WAM model gave ratios of modelled to observed high-frequency part of the wave spectrum of the order of 1.7.

Thirdly, cycle 4 of the WAM model shows reduced dissipation of swell. From data assimilation experiments with Geosat Altimeter data, *Lionello et al* (1992) noted a rapid loss of (observed) information when ocean waves were leaving the storm area, suggesting an excessive swell attenuation in previous cycles of the WAM model. *Romeiser* (1993), comparing Geosat Altimeter wave height data with WAM model data for 1988, concluded that the wave model underestimated wave heights in the tropical areas which are dominated by swell. The reason for the reduced swell attenuation in cycle 4 of the WAM model is directly related to the afore-mentioned reduced level of the high-frequency part of the wave spectrum, and the dependence of the dissipation source function on a measure of the mean square slope (*Hasselmann* 1974, *Komen et al* 1984, *Komen et al* 1994). The steeper the waves the larger the wave dissipation so the reduced level of the high-frequency waves may therefore give rise to a reduction of wave attenuation of 50%. It is emphasised that dissipation of swell energy is only important when the ocean waves are just leaving the storm track. Because of the white cap dissipation the ocean waves experience a considerable reduction of their mean square slope (giving a considerable reduction of the attenuation rate) and for the rest of their life time the swells propagate virtually undamped, in agreement with the findings of *Snodgrass et al* (1966).

In order to investigate the impact of the changes introduced in cycle 4 of the WAM model, we hindcasted July 1990, using the analysed ECMWF winds that forced cycle 2 of the WAM model. The monthly means of July 1990 of cycle 2 and cycle 4 of the WAM model are shown in Fig 2 and some substantial differences are seen. The mean wave height in the southern ocean storm track is increased slightly while there is a substantial increase of wave height in the tropical and sub-tropical Indian ocean, the tropical central Pacific and in the southern ocean east of New Zealand. Relative increases in wave height vary between 20-50% in those areas where *Romeiser* (1993) found discrepancies between Geosat Altimeter data and WAM cy2 wave height data, suggesting that cycle 4 of the WAM model has given considerable improvements over earlier cycles of the WAM model.

Before we begin to study the quality of the present wave analysis and forecasting system at ECMWF it should be remarked that the recent increase in resolution from 3 to 1.5 degrees in the horizontal had a beneficial impact on the modelling of extreme wave events. This is shown in Fig 3 where the verification of 1.5 degree results against buoy data is compared with the corresponding results from the 3 degree model. The period was one month long and the area was the North Pacific. Fig 3 illustrates that the high-resolution model data give a closer fit to the observations than the low-resolution data, as is also evident from statistical parameters such as rms error, bias and correlation coefficient which show improvements for the 1.5 degree wave model. The main reason for the improved performance of the high-resolution wave model comes from a better representation of the driving wind field. The spatial variability of the wind field is higher in the high resolution model than in the coarse resolution model. In fact, winds interpolated to a coarse resolution lack variability. Since higher variability will give rise to higher waves (*Cavaleri*, 1994), higher waves are to be expected in the high resolution wave model. This is confirmed by the verification given in Fig 3. As an extra check we forced the high-resolution wave model with low-resolution winds, and a considerable reduction of wave height during extreme events was found. A similar conclusion was reached by *Zambresky* (1989).

3. Verification of wave analysis against buoy data

There have been extensive efforts to evaluate the quality of analysed wave results by comparison with buoy observations, particularly in the 1970's and 1980's when the usefulness of wave prediction first became apparent for applications such as ship routing, coastal defence construction work and off-shore operations (all of which have both an economic and a safety aspect). The typical performance of early global wave models has been summarised by *Cardone* (1987), *Zambresky* (1987) and *Clancy et al* (1986). Using operationally available winds these authors found that the Scatter Index (SI) for the analysed wave height (the ratio of the standard deviation of error to the mean of observed wave height) ranged from 25 to 40%, while the Scatter Index for analysed surface wind speed was of the order of 30% or more. Similar results were obtained for limited area models in shallow water (see, e.g. *Janssen et al* 1984).

On the other hand, when using high quality, manually analysed winds (with much lower rms errors), wave results improved dramatically. An example of this may be found in the Shallow Water Intercomparison Study (SWIM), which compared the performance of three operational wave models for the North Sea (*Bouws et al*, 1985). On average the Scatter Index was around 20% or even lower, suggesting that the quality of wave products is to a considerable extent determined by the accuracy of the driving wind fields.

Let us now discuss how the present ECMWF wave analysis system is performing. Wave analysed fields are operationally evaluated using all available buoy data obtained through the Global Telecommunication System (GTS). On purpose, wave buoy data are not used in the wave analysis, so that the comparison of analysis and buoy data provides an independent test of the quality of the analysed wave height. Apart from actual checks at the instrument level, there is a clear need for data quality assessment. This is evident from Fig 3 where we have plotted modelled wave height against the observed one. The modelled result was obtained by linear interpolation in space (except when the buoy was too close to land; in that event the nearest grid point was taken) and was compared with the observed value valid at one of the synoptic times (0, 6, 12, 18 UT). It should be clear from Fig 3 that in the comparison some invalid buoy observations have been considered; for example, a few buoys reported a constant wave height (e.g. 0 m) during the period of interest.

In addition, it should be emphasized that buoy observations and the model represent different scales. Buoys exhibit high-frequency variability on a timescale of 1 hour which is absent in the model because the model values represent a mean value over a grid box of size 1.5°x1.5°. In other words, since waves propagate across the area where the instrumental sensors are located, one should not consider a single observation at any given time (representing an actual average over a short acquisition time) to be equivalent to the actual statistical wave height computed at each model grid box. Averaging of the observed wave height is therefore preferable where the averaging period should match the scales still represented by the model. With a mean group velocity of about 10 m/s an averaging time of 6 hours thus seems appropriate.

Most buoy data are reported every hour via the GTS, and it is therefore relatively straightforward to use those hourly observations to obtain 6-hourly averaged values centred around the synoptic times. In this procedure spurious observations can be detected and removed from the data record. The resulting filtered data are then compared with the analysed wave heights.

Here we present the verification of analysed wave height and wind speed over the period January 1995 - December 1995 using 30 buoys (their location is given in Fig 4) which produce fairly continuous data records (a prerequisite if filtering is used to produce a consistent data record). The buoys are located in deep water. Unfortunately, some of these instruments are located in regions with high ocean current variability which may influence the generation and propagation of wind waves; wave-current effects are not yet taken into account in the operational version of the WAM model.

Nevertheless, the comparison of analysed wave height to the averaged buoy data already shows a good agreement. This is illustrated by the verification plots for August 1995 and December 1995, given in Figs 5 and 6 respectively. In order to quantify the comparison we have computed the usual statistical parameters which are displayed in Figs 5-6 as well. Although there is a slight underestimation of wave height (of the order to 20 cm), the rms error is small (about 50 cm) while the scatter index is about 16% for the Northern Hemisphere winter and about 20% for the summer period. The monthly variation of bias, rms error and scatter index is displayed in Fig 7. It shows the good performance of the wave forecasting system during the chosen one year period. If one takes the usual measure for quality, namely the scatter index, then Fig 7 illustrates that the quality of the wave analyses is better during the winter than during the summer. It should be pointed out, however, that there are considerable regional variations to be noted. In order to see this, we have plotted in Fig 7 the relevant statistical parameters for the regions Hawaii, North Pacific, US west coast, US east coast and North-East Atlantic as well. A very good wave analysis is then found near Hawaii, the North-East Atlantic and the west coast of the USA where scatter indices are of the order of 15%. In the North Pacific the wave analysis is found to be of a reasonable quality with scatter indices of the order of 20% while the wave analysis is relatively poor on the east coast of the USA where, in particular during the summer, the scatter index is around 25%. Since the quality of the wave model analysis depends critically on the quality of the surface wind, we also present statistics of the 10-metre wind in Figs 5, 6 and 8. Using the same technique to eliminate possible spurious buoy observations, a consistent wind data set was obtained. However, no attempt was made to correct model winds for the actual buoy observation height which is usually of the order of 4 m. This implies that when there is no bias between modelled and observed wind, there is in fact, because of this height difference, a model bias of about 10% of the mean wind speed. In addition, it should be remarked that modelled and observed winds are not independent because information from these observations has been used in the atmospheric analysis. Nevertheless, the comparisons shown in Figs 5 and 6 for August 1995 and December 1995, and the time series for statistical parameters in Fig 8 reveal the quality of the analysed wind speed. The scatter index for wind speed is typically about 20% but shows large regional variations. In the North Atlantic we find on average a scatter index of 17% while the east coast of the USA shows a relatively poor performance with scatter indices in the summer reaching about 25%. The bias in wind speed is generally quite low. Restricting our attention to regions with active wave generation (this excludes Hawaii) and bearing in mind the above-mentioned difference between buoy observation height and model height, it is seen that, except in the North Pacific area, modelled winds are too low by as much as 0.5 m/s (taking a mean wind speed of 8 m/s). Although this is quite a small bias in wind speed, it still may give a considerable bias in significant wave height. This may be seen as follows. Starting from the well-known relation between equilibrium wave height Hs and wind speed U_{10},

$$H_s = \beta U_{10}^2/g \qquad (2)$$

where g is acceleration of gravity and β a constant (we take β=0.22), the wave height bias caused by a wind speed error is found to be

$$\delta H_s = 2\beta\ U_{10}\ \delta U_{10}/g \qquad (3)$$

Then, with a mean wind speed U_{10} of 8 m/s and a negative wind speed bias of -0.5 m/s, we find a wave height bias of about -0.20 m. However, although this may explain the negative bias in wave height found on the east and west coast of the USA, the large bias in wave height found in the North-East Atlantic cannot be understood in terms of wind speed error.

1. Period is December 1987 - November 1988 (from Zambresky 1989). WAM (cy2: 3°x 3°).

	H_s		T_p		U_{10}	
Area (Nobs)	bias	SI	bias	SI	bias	SI
All (13827)	-0.32	0.23	-0.47	0.18	-0.09	0.25
North Pacific (4657)	-0.22	0.21	-0.70	0.17	0.49	0.25
Hawaii (2061)	-0.28	0.17	-0.01	0.21	-0.38	0.17
East coast USA (4284)	-0.38	0.30	-0.71	0.16	0.07	0.30
North-East Atlantic (2825)	-0.40	0.25	-	-	-0.54	0.28

2. Period is January 1995 - December 1995. WAM (cy4: 1.5x1.5)

	H_s		T_p		U_{10}	
Area (Nobs)	bias	SI	bias	SI	bias	SI
All (39288)	-0.27	0.18	-0.47	0.19	0.24	0.21
North Pacific (5473)	-0.25	0.18	-0.44	0.19	0.77	0.23
Hawaii (5324)	-0.19	0.14	-0.05	0.19	-0.19	0.14
East coast USA (7482)	-0.19	0.24	-0.57	0.18	0.30	0.23
North-East Atlantic (8812)	-0.53	0.14	-	-	0.29	0.19
West coast USA (7234)	-0.27	0.15	-0.68	0.17	0.30	0.18

TABLE 1. Statistics obtained by the WAM model driven by ECMWF winds for wave height H_s (m), peak period T_p (s) and wind speed U_{10} (m/s) for different areas. Bias is with respect to observations. SI is scatter index. In brackets are the number of observations (Nobs) used for the statistics.

Panel 2 of Table 1 finally summarises the performance of ECMWF's wind-wave analysis system by giving yearly mean statistics of wave height, peak period and wind speed for the 5 chosen areas. Also, global means are given. It is clear from this table that the North-East Atlantic area may be regarded as an outlier, in particular concerning the bias in wave height (too low by 0.53 m) and peak period (too high by 2-3 seconds). These two statistics seem to be in conflict with each other because with too low waves one would expect a too low peak period. However, inspection of time series of modelled and observed peak period shows that there is always a systematic difference between model and observation. This suggests that the observed peak period in that area is based on a different definition than the modelled one. We therefore have not included peak period statistics in Table 1 for the North-East Atlantic area. Nevertheless, it could be true that swells which are important in the North-East Atlantic are not properly modelled: for example modelled swells may have lower peak frequency than the swells observed by the buoys in that areas. The remarkable thing to point out now is that, in a similar area where swell and wind sea play equally important roles (namely the west coast of the USA), the wave model shows good agreement in both wave height and peak period statistics. Furthermore, since the wind speed statistics in both areas are similar, one might perhaps pose the question whether there is a problem with the type of buoys in the North-East Atlantic. Inspection of a number of time series of buoy 62108, an example of which is shown Fig 9, suggests that there may indeed be problems with the wave height measurements. Periodically, a sudden increase in observed wave height is noticed which exceeds the Pierson-Moskowitz level (cf Eq. (1)) indicating the arrival of swells. But swells are usually more persistent. However, in order to be able to draw definite conclusions, we need additional information which may be provided by the comparison of wave model results against altimeter wave height data (cf section 4).

Finally, we would like to compare our verification results with the results of *Zambresky* (1989). In that study, results from WAM cy2 driven by winds from the T106/19L version of ECMWF's atmospheric model were compared with buoy observations during the period December 1987 to November 1988. A summary of her verification results for 4 areas is shown in panel 1 of Table 1. In order to avoid problems with sub-grid scale effects, Zambresky averaged the observations over a three hour period, while spurious observations were rejected manually (if needed). Comparing the scatter indices of the present version of the wave analysis system with the earlier one, a considerable improvement is seen in the quality of wind speed and significant wave height in all areas, with the exception of an increased bias in wave height in the North-East Atlantic. The peak period statistics, although having a somewhat reduced bias, have however a similar scatter index. This may be related to the fact that in the present wave analysis system the peak period has similar variability around the mean as observed, while the earlier system showed much reduced variability.

4. Verification of first-guess wave height against ERS-1 altimeter data

The validation of wave model results against satellite data started relatively recently, at least compared to the verification against buoy data. The first validation studies used altimeter wave height data obtained during the SeaSat mission in 1978 (*Janssen et al* 1989a, *Bauer et al* 1992; *Francis and Stratton* 1990). The Scatter Index for wave height was typically between 30-40%, while the bias in wave height was +0.15 m for the WAM model driven with 1000 mb ECMWF winds (*Janssen et al* 1989a) and the wave height bias was quite large (-0.80 m) for the second generation UKMO wave model driven with UKMO lowest level winds (*Francis and Stratton* 1990). The poor performance during the SeaSat period may be attributed, to a large extent, to the poor quality of the driving wind fields. This follows from the study by *Romeiser* (1993) who compared WAM modelled wave height with Geosat data during the year 1988. The WAM model was the same as the one used during the SeaSat periods, but was now driven by 10 m winds obtained from the then operational T106/L19 ECMWF atmospheric model. The seasonal variability of the scatter index parameter as used by Romeiser (defined as the rms wave height error normalised by the square root of the product of mean observed and mean modelled wave height) is depicted in Fig 10 (the lower half of the plot will be discussed later). Although there is considerable seasonal variability, it appears that the mean scatter index for 1988 was found to be around 0.25, a number which is consistent with the findings of *Zambresky* (1989) who verified the modelled WAM wave height against buoy data (cf Table 1).

Let us now compare modelled wave height and wind speed of the present ECMWF wave model system with ERS-1 altimeter data. ERS-1 was launched in July 1991 and reliable altimeter observations were disseminated routinely from the end of 1991. During the commissioning phase between July and the end of 1991, altimeter wave height and wind speed were routinely compared with WAM modelled wave height and ECMWF wind speed to assure the quality of the altimeter products. As a result of this comparison, it was found that the wave height retrieval algorithm gave satisfactory results when compared with modelled wave height (although it should be emphasised that, compared to buoys, ERS-1 altimeter wave heights are too low by about 10% for high sea states). Similarly, regarding the wind speed retrieval, it turned out that the Geosat wind speed retrieval algorithm compared most favourably with the ECMWF wind speed. However, tuning of the radar altimeter backscatter observations is required since the overall gain of the satellite is unknown beforehand and the wind speed determination depends on the absolute determination of the backscatter. Applying a bias correction to the observed backscatter and inserting the corrected backscatter into the Geosat retrieval algorithm gave virtually no bias when the resulting wind speed was compared with the ECMWF winds. Thus, the quality of the altimeter winds depends to a certain extent on the quality of the ECMWF winds from 1991. In particular, when comparing the two products as will be done in a moment, it should be realised that the information obtained from the bias between the two should be regarded with caution, while the standard deviation of error contains valuable information.

Since August 1993 altimeter wave height data has been used to give a better specification of the initial conditions for the wave forecast. It is therefore clear that a validation of the analysed wave height against altimeter wave height data is not very meaningful (except, perhaps, for checking that the assimilation technique of *Lionello et al* 1992 works) thus, it was decided to compare first-guess wave height fields with altimeter wave height data. In this case, modelled and observed wave height may be regarded as independent because the altimeter data have not been used in previous wave analyses. In addition, the locations where the first-guess wave field (which is a 6 hour forecast) is compared with the altimeter data are different from the locations where altimeter data were used in the last analysis. Nevertheless, it may be argued that the quality of the first-guess wave field should have benefited from the use of altimeter wave height data in previous analysis cycles. In particular, swell systems which may have quite a long memory should benefit from the observed information. To a certain extent, this was indeed found in the study reported in Komen et al (1994), where results of 30 forecasts starting from wave analysis with and without altimeter wave data were compared. The two sets of forecasts were verified against altimeter data, and the forecasts based on analyses with altimeter data showed a considerable reduction in the bias which could last up to 5 days in the forecast. Differences between root mean square errors of the two sets of forecasts were less dramatic, and were small from day 1 in the forecast. This suggests that the rms error of the first-guess wave field (when compared to altimeter data) shows hardly any dependence on whether altimeter data have been used in the previous analyses or not.

The ERS-1 altimeter data are received real time from the European Space Agency (ESA) through the GTS. The along track resolution is 7 km, corresponding to approximately one measurement per second. In order to obtain observations that represent similar spatial and temporal scales to the wave model, the altimeter time series are smoothed by averaging over 30 observations, giving a resolution of 200 km.

Unrealistic, rapid changes in the signal were filtered out by applying quality control in a similar manner to that of *Janssen et al* (1989a) and *Bauer et al* (1992). ERS-1 data and model data are routinely compared in this fashion, and examples of this comparison are shown in Figs 11 and 12 for August 1995 and December 1995, while Fig 13 shows the seasonal variation of statistical parameters such as modelled mean, bias and standard deviation of error for three areas (Northern Hemisphere, Tropics and Southern Hemisphere) and the globe. The comparisons for both significant wave height and wind speed are shown.

Several interesting features of this comparison should be noted. First of all, the mean difference between modelled and observed wave height is typically about 20 cm. This positive bias, which has been present since the introduction of the high-resolution (1.5x1.5) version of the WAM model at ECMWF, cannot be regarded as a negative aspect in view of the known under-estimation of wave height by the altimeter for high sea states (*Carter et al* 1992). The standard deviation of first-guess error is fairly low (being typically 50 cm or less in the extratropics while 30 cm or less in the Tropics), considering that the expected observed wave height error is the maximum of 10% in the wave height or 50 cm. Similarly, modelled analysed wind speed may be regarded of high quality because of the low bias and a standard deviation of error which is 2 m/s or less. Scatter indices obtained from the wave height comparison range from 15 to 20% and are consistent with the results we have found in our verification study with buoy data (cf Table 1). A similar conclusion is reached regarding the wind speed comparison.

An exception has to be made for the North-East Atlantic area. We selected a box west of the United Kingdom and Ireland and determined the wave-height statistics. The comparison with the altimeter data showed a positive bias of 30 cm, and a scatter index of only 13% (compare with Fig 7). The favourable agreement between modelled wave height and altimeter data is confirmed by the scatter diagram for February 1995 as shown in Fig 14. This suggests that there are problems with the selected buoys in the North-East Atlantic.

In order to conclude our discussion on the validation of first-guess wave height by means of altimeter data, we compare results for the year 1995 with those obtained by *Romeiser* (1992) who, as already mentioned, studied the quality of WAM model results over the year 1988. We determined the symmetrical scatter index as defined by Romeiser for the Northern Hemisphere, Tropics and Southern Hemisphere and plotted the resulting scores in Fig 10. The considerable improvement of the ECMWF wave analysis system over the past 7 years is evident from this Figure. Before we discuss possible reasons for this progress we first discuss some pertinent details of the seasonal variations of the symmetrical scatter index for wave height. First of all, there is a pronounced increase in scatter index for 1988 during the Northern Hemisphere summer, which is absent during the 94-95 season. Realising that Romeiser's scatter index is based on the root mean square error and not on the standard deviation of error, it may be noted that this increase during the summer is probably related to an increase in bias of modelled wave height. In the Northern Hemisphere and the Tropics the bias is caused by the afore-mentioned under representation of swell in earlier cycles of the WAM model, while in the Southern Hemisphere winter the underestimation of modelled wave height was probably caused by too weak winds. It is emphasised that in the present wave analysis system these problems no longer occur, as is evident from Fig 13.

We conclude this section by means of a brief discussion of the possible reasons for the improved performance of the ECMWF wave analysis system over the past decade. First of all, it is thought that the quality of the driving wind fields has improved considerably. This is evident from the comparison with buoy data summarised in Table 1 which shows a considerable reduction in the scatter index for wind when comparing results from 1988 with those of 1994-95. Unfortunately, Romeiser did not compare ECMWF winds with altimeter winds for the year 1988, but the present day results for modelled winds as compared to altimeter winds are impressive (for example, in the Northern Hemisphere the scatter index for altimeter wind speed ranges between 20 and 25% which is somewhat higher than seen from the buoy comparison).

Secondly, a number of changes have been introduced in the WAM model giving, for example, an improved representation of the swell-component of the wave field. In addition, the increase of resolution from 3°x3° to 1.5°x1.5° has resulted in better performance during extreme events.

Finally, it is thought that the assimilation of altimeter data in the WAM model has also contributed to some extent to an accurate first-guess wave field. Although data assimilation impact studies only showed improvements in the bias of the wave forecast (and not in the standard deviation of error), it seems likely that the swell component of the wave field (which may have a longer memory of the assimilated data) has benefited from the assimilation of altimeter data in the wave analysis. This claim is supported by results of an experiment where the wave forecasting system was run for the month of December 1995 without data assimilation. Verifying the analysed waves against ERS-1 altimeter data showed that, compared to the operational results with data assimilation, the standard deviation of error hardly changed but the bias changed by about 20-25 cm which is considerable, in particular in the tropical areas.

5. Quality of wave forecast

In the previous sections we have seen that nowadays the ECMWF wave analysis system is producing reasonably accurate analysed wave height fields. Although the wave model community has only paid little attention to verifying wave forecasts (an exception is perhaps Cavaleri et al 1994), it should be clear that at ECMWF, with its main emphasis on forecasting, there is a keen interest in the quality of the wave forecast.

The quality of the forecast is usually judged by a comparison with the verifying analysis. Using the experience gained from the atmospheric community, this enabled us to introduce some new verification tools in ocean wave forecasting in a relatively easy manner. We mention skill scores based on persistence and the anomaly correlation. It will be seen that, in particular, the anomaly correlation is a sensitive indicator for the quality of the wave forecast.

We have recently introduced an additional quality control of the wave forecast based on verification against buoy data. Results of the forecast verification against buoy data will be analysed first, after which we present results from the comparison of wave forecast with the verifying analysis.

a. Verification of wave forecast against buoy data

At ECMWF a 10 day global wave forecast is issued once a day and uses the 12Z wave analysis as initial condition. Because the wave forecast is only done once a day there are fewer possibilities to collocate modelled wave height with buoy data than in the case of wave analysis which is produced 4 times a day. For this reason the wave forecast is compared with buoy observations over a 4 month period. Fig 15 shows the comparison of analysed and forecast wave height with buoy data for the period of June to September 1995, while Fig 16 shows a similar comparison for wind speed. Only forecasts up to day 5 are presented. The comparison of wave height illustrates the slow deterioration of the modelled wave height with time, although forecasts up to 2 days still agree relatively well with the buoy observations. Also, the wind speed comparison shows the deterioration of the quality of the wind forecast, although at a somewhat more rapid pace. The slower degradation of the wave height forecast may be attributed to the fact that a considerable part of the wave height field consists of swell generated by winds earlier in the forecast which are therefore of higher quality. All this is also evident from Fig 17 where the scatter index of wave height and wind speed for all buoys is plotted as a function of forecast day up to day 10. Over the 5 day period the wind speed scatter index increases by a factor of 2.2 while the wave height scatter index only increases by a factor of 1.7. In the same Figure we have also shown the error growth for different regions. Clearly, results differ considerably from region to region. Regions which have mainly swell, such as Hawaii, show only a very small error growth while the wind sea dominated area of the North Pacific gives the most rapid error growth. The east coast of the USA appears to be the worst case mainly because it has by far the largest analysis error.

It is of considerable interest to try to understand the causes of error growth in wave height. To this end, in Fig 18 we have plotted the rms error for wave height and wind speed as a function of forecast day. It is a common belief in atmospheric modelling that the error growth of atmospheric quantities, such as wind speed, is linear with time (A Hollingsworth, personal communication; only a perfect model would show exponential error growth). This indeed follows from the wind speed plot in Fig 18. However, the error growth curve for wave height differs as, initially, the error growth is much flatter and only later in the forecast is there a linear growth with time. It is important to understand the different behaviour of error growth in wave height. In order to do that it seems obvious from the previous discussions to distinguish between wind sea and swell components of the wave field. Regarding error growth in swell, it seems reasonable to assume that this is virtually independent of forecast time. This assumption is supported by the error growth curves of Fig 17 which show this to be case for the Hawaii error. Denoting the error in swell wave height by σ_{sw} we then pose that, based on the verifications of model wave height against buoy data and altimeter data, σ_{sw} is 12% of the average wave height. Thus, with an average wave height of 1.6 m, we have

$$\sigma_{sw} = 0.20 \text{ (m)} \qquad \textbf{(4)}$$

Next, it is assumed that the error in the wind sea component of the wave field is mainly determined by the error in the wind field. Since for the period of interest the mean wind speed is about 6-7 m/s, it seems fair to assume that, on average, we are dealing with equilibrium wind waves so that Eq. (3) applies. Denoting the error in wind sea wave height by σ_{ws}, we therefore have

$$\sigma_{ws} = \frac{2\beta U_{10}}{g} <\delta U_{10}^2>^{1/2} \tag{5}$$

where $<\delta U_{10}^2>$ is the rms error in wind speed which is known from the wind speed forecast statistics. Assuming that for the case of all buoys the wind sea and swell components of the wave field have equal weight, the following error σ_H in wave field is found,

$$\sigma_H = \sqrt{\sigma_{ws}^2 + \sigma_{sw}^2} \tag{6}$$

Using the modelled mean wind speed and the wind speed error, in the wave height error plot of Fig 18 we have plotted the results of Eq. (6) as well, which look reasonable. Eq. (6) therefore provides an explanation for the initial flat error growth in wave height, because the error in the swell part of the wave field also plays a role. On the other hand, since the swell error is only 0.2 m, it is evident that the error in wind speed, resulting in the wind sea error (5), is dominant. This just supports the common belief in the wave model community that a considerable part of errors in wave height is caused by errors in the wind field. Thus, Fig 18 may be regarded as a nice illustration of this belief.

We should finally point out that a somewhat different interpretation of the results in Fig 18 is also possible. What is needed to explain the initial slow growth of wave height error is, in addition to the wind sea error, an additional constant (in time) error. In the above, this error was assumed to be related to errors in swell(-propagation) but other errors may contribute as well. For example, buoy data are not perfect as they have a relative error of 5-10%. There are, no doubt, also wave model errors but the magnitude of these errors is not known. An upper estimate of the model error may now be given by assuming that the constant background error is only caused by the model, thus we obtain a model wave height error of the order of 12% of mean wave height. This model error is, however, small compared to errors caused by the wind field. In fact, with a mean wind speed of 7 m/s, an extremely small rms error in analysed wind speed of 70 cm/s is needed to obtain errors in the modelled wind sea wave height which are of comparable magnitude to the above estimate of the model error. Thus, with present day rms errors in wind speed of about 1.5 m/s (cf Fig 18), which are considerably smaller than errors found a decade ago, it is concluded that wind speed errors still dominate the wave forecast error.

b. Verification of wave forecast against analysis

Having obtained sufficient confidence in the quality of the wave height analysis, it seems a good idea to judge the reliability of the wave forecast by means of a comparison with the verifying analysis.

A number of verification scores have a certain historical background, and it seems appropriate to explain their meaning in this context. Scores are intended to express, to a certain extent, the usefulness of a forecast and, as a benchmark ('yardstick'), one uses information which is already available. For example, one may ask to what extent the wave forecast has more skill than a persistence analysis (in which during the whole forecast the state is given by the initial condition). In practice, a 10 day wave forecast always beats the persistence analysis, as follows from a comparison of the rms error of wave forecast with persistence analysis. A more useful (but also more 'impressive') yardstick to judge the quality of the wave forecast is the wave climatology. (Incidentally, the ECMWF wave climatology was produced from a 9 year hindcast using analysed ECMWF winds and an example of wave height climatology is shown in Fig 19.) Thus, the anomaly correlation for wave height, defined as the normalised correlation of forecast anomaly and verifying analysis anomaly (both anomalies with respect to climatology), measures how much more skill the wave forecast has over climatology. However, in case of positive correlation, when the forecast beats the climatology one does not necessarily have a forecast which is regarded as useful by the forecaster. The relation between usefulness of the forecast and anomaly correlation is not straightforward and can only be established by means of the subjective step that forecasters assess by inspection of weather maps whether, for a given anomaly correlation, a forecast is useful or not. In this way weather forecasts were found to be useful when the anomaly correlation exceeded 60%. However, such a relationship has not been established yet for ocean-wave forecasting. Despite this shortcoming, it will be seen that the anomaly correlation is a sensitive tool for measuring the skill of a wave forecast.

Several verification scores for wave height are nowadays determined routinely. An example for April 1995 for several regions is shown in Fig 20. The panels show the anomaly correlation of wave forecast, the anomaly correlation of persistence, the mean error of the forecast, the standard deviation of error of the forecast, the mean of the verifying analysis and the standard deviation of error of persistence as a function of the forecast day. It is seen from the wave forecast anomaly correlation plot that in the Northern Hemisphere the forecast is useful up to day 5, in the Southern Hemisphere the forecast is useful up to day 4, while in the Tropics, which has much lower variability, the forecast is useful up to day 7. On the other hand, the persistence analysis in the extra-tropics already loses its value after day 1 in the forecast. The mean error of forecast wave height is quite small in the Northern Hemisphere, being only 5% of the mean wave height, while in the Tropics and Southern Hemisphere the mean error is somewhat larger. Finally, in the Northern Hemisphere the standard deviation of forecast error is up to day 3 in the forecast below the one from the comparison between first-guess and altimeter data, and reaches about 1 m at day 10 of the wave forecast. In contrast to this the quality of the forecast in the Southern Hemisphere seems to deteriorate somewhat faster.

Thus, the scores over April 1995 confirm the experience of atmospheric forecasting that the quality of the forecast is better in the Northern than Southern Hemisphere. The mean error and standard deviation of forecast error are at an acceptable level. It should be pointed out, however, that there may be considerable seasonal variations in the wave forecast scores. This is shown in Figs 21-23 where, over the year 1995, we present the evolution of mean forecast error, standard deviation of error and forecast skill for the Northern and Southern Hemisphere. Here, the forecast skill is defined as the forecast period in which the anomaly correlation is larger than 60%.

Regarding the time series for the Northern Hemisphere scores, we note a small mean forecast error since April 1995, while before that date mean forecast errors are quite considerable, in particular during the last three days of the forecast. The time series for the standard deviation of forecast error follows a seasonal cycle where, as expected during the stormy seasons, the standard deviation is the largest. The time series for the forecast skill shows variations of the order of ½ day around a mean value which appears to be slightly larger than 5 days. [It is noteworthy that, even for the relatively small limited area of the North Atlantic, the mean forecast skill is 5 days.] The Southern Hemisphere scores during the Southern Hemisphere winter show considerable biases in the latter part of the wave forecast and there is a less clear seasonal cycle in the standard deviation of forecast error. The forecast skill in this part of the world appears to be about 4.4 days.

The growth of the mean forecast error with forecast error is, unfortunately, a rather serious problem. In order to see this we have compared the mean of the day 7 forecast for May 1995 with the verifying analysis in Fig 24. Although the average forecast error is only 0.4 m (see Fig 20), there are regional differences of about 1 to 1.5 m (e.g. south-west of Australia) while a considerably larger amount of swell is also radiated towards the tropics. However, problems seem to be less severe over the year 1995 than 1994. This is illustrated in Fig 25. Now comparing the results of 1994 and 1995 (see Fig 20) it is seen that from April 1995 the Northern Hemisphere mean error has reduced by a factor of two. There is also a reduction of Southern Hemisphere mean error but to a lesser extent.

The reason for the reduction of mean forecast error is probably related to a reduction of overactivity of the atmospheric model during the later stages of the forecast. In April 1995 a new version of the ECMWF atmospheric model was introduced. Previous versions of the ECMWF model showed too high levels of kinetic energy during the forecast. This new version of the model has a fully-interpolating semi-Lagrangian scheme and a new gravity wave drag scheme with mean orography. The above changes led to a favourable error reduction. These changes also gave rise to a considerable reduction of mean forecast error in wave height as followed from the comparison of wave results from the operational forecast with results from a parallel run over the period June 1-19, 1994. The parallel run also showed a considerable improvement in Northern Hemisphere anomaly correlations, as shown in Fig 26. By comparing monthly mean anomaly correlations for April 1994 with April 1995, significant improvements with the new version of the ECMWF model are to be noted, suggesting that the new version of the ECMWF model is robust. The forecast skill has improved by about 1.5 days. Finally, we note that the atmospheric forecast skill has also improved (about ½ to ¾ day) but to a lesser extent. This, once more, illustrates that wave results are sensitive to the quality of the atmospheric winds.

6. Conclusions

We have reviewed the present status of wave modelling at ECMWF. Ocean waves, driven by ECMWF 10 metre winds, are forecasted by the WAM model (cy4) which solves the energy balance equation for the wave spectrum. Initial conditions are provided by assimilation of ERS-1 altimeter data into the first-guess wave field.

Comparison of analysed wave data with independent buoy observations reveals the high quality of the wave analysis. Furthermore, the first-guess wave field also seems to be of good quality as follows from the verifications against altimeter wave height data. It appears that considerable progress has been made in comparison with wave model results a decade ago. Plausible reasons for this progress are a) the continued improvement of the atmospheric analyses, b) improvements in wave modelling with respect to wind input and dissipation and c) the inclusion of altimeter data in the wave analysis.

Regarding wave forecasting it is not so easy to compare with results in the past. This is partly caused by the fact that in the past there was more interest in wave analysis than wave forecasting. On the other hand, we have introduced tools, such as anomaly correlation, which have not been used before in wave modelling.

Nevertheless, the comparison of forecast wave height with buoy observation has shown the slow deterioration of the quality of the wave forecast with time. It is suggested that the error growth is determined on the one hand by a constant error (which we termed the error in swell) and on the other hand an error caused by uncertainties in wind speed. Verification of wave forecast against verifying analyses suggests that in the Northern Hemisphere we have a reasonable forecast up to day 5 while the forecast skill in the Southern Hemisphere is somewhat less.

In spite of the overall good quality of wave forecast and analysis, it should be emphasised that there are also areas where wave modelling is less accurate. An example is the east coast of the USA. The relatively poor quality of the wave analysis in the North East Atlantic is probably caused by the unreliable behaviour of the wave buoys in that area, because verifications against altimeter data show good agreement. In the summer of 1995 we asked the UK Met Office (which is in charge of the North East Atlantic buoys) whether there were perhaps problems with these buoys. A program to replace the communications systems on these buoys was already in hand, and by December 1995 the systems on all the buoys had been upgraded, resulting in a more accurate report of wave conditions (M Holt, personal communication). In fact, we have seen during the autumn of 1995 a gradually improved agreement between model and observations (cf Fig 7). It is therefore concluded that wave model results are now sufficiently reliable to be used for quality control of wave height observations. Examples of the quality control of observations by the ECMWF atmospheric model are given in *Hollingsworth* (1986).

At ECMWF there is a continuous effort to improve analysis and forecast. The relatively poor results on the east coast of the USA could perhaps be alleviated by the introduction of the effects of the Gulf stream. Prediction of extreme events could be improved by including effects of gustiness (*Cavaleri et al* 1994). Finally, wave modelling could also benefit from improvements in weather forecasting. We have already discussed the recent improvements in the ECMWF atmospheric model which resulted in benefits for wave modelling. However, an improved atmospheric analysis achieved by new data assimilation techniques and new types of data may also give rise to improved wave analysis and forecasting. Recently, ECMWF has completed the considerable task of upgrading its data assimilation to a three-dimensional variational approach (3D-Var). The new scheme is able to handle the wealth of data from the scatterometer which provides information on the surface wind field. Results from a 42 day parallel run suggest an improved wind speed analysis over the Southern Hemisphere as follows a comparison with altimeter wind speed. Also, a reduction of 10% in standard deviation of wave height error is found, as is shown in Fig 27. Finally, the forecast skill has improved by half a day. Since variational assimilation is only beginning, further progress in weather and wave forecasting is expected to occur in the near future.

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REFERENCES

Banner, M L, 1990: Equilibrium spectra of wind waves. *J Phys Oceanogr*, **20**, 966-984.

Banner, M L and I R Young, 1994: Modelling spectral dissipation in the evolution of wind waves. Part I: Assessment of existing model performance. *J Phys Oceanogr*, **24**, 1550-1570.

Bauer, E, S Hasselmann, K Hasselmann and H C Graber, 1992: Validation and assimilation of seasat altimeter wave heights using the WAM wave model. *J Geophys Res*, **C97**, 12671-12682.

Cardone, V J, 1987: The present status of operational wave forecasting in Proceedings of the symposium 'Measuring Ocean Waves from Space', John Hopkins APL Technical Digest, **8**, 24-32.

Carter, D J T, P G Challenor and M A Srokosz, 1992: An assessment of Geosat wave height and wind speed measurements. J Geophys Res, C7, 11383-11392.

Cavaleri, L, 1994: 'Wind variability' in Komen et al, 1991, 320-331.

Cavaleri, L, G Burgers, H Günther, V Makin and L Zambresky, 1994: 'Forecast', in Komen et al, 1994, 307-314.

Clancy, R M, J E Kaitala and L F Zambresky, 1986: The Fleet Numerical Oceanography Center Global Spectral Ocean Wave Model, *Bull American Met Soc*, **67**, 498-512.

Francis, P E and R A Stratton, 1990: Some experiments to investigate the assimilation of SEASAT altimeter wave height data into a global wave model. *Quart J Roy Meteor Soc*, **116**, 1225-1251.

Hasselmann, K, 1962: On the non-linear energy transfer in a gravity-wave spectrum, part 1: General theory. *J Fluid Mech*, **12**, 481.

Hasselmann, K, 1974: On the spectral dissipation of ocean waves due to white capping. *Boundary Layer Meteorol*, **6**, 107-127.

Hollingsworth, A, D B Shaw, P Lönnberg, L Illari, K Arpe, A J Simmons, 1986: Monitoring of observation and analysis quality by a data assimilation system. Mon Wea Rev, **114**, 861-879.

HEXOS: Smith, S D, R J Anderson, W A Oost, C Kraan, N Maat, J De Cosmo, K B Katsaros, K L Davidson, K Bumke, L Hasse and H M Chadwick, 1992: Sea surface wind stress and drag coefficients: the Hexos results. *Boundary Layer Meteorol*, **60**, 109-142.

Janssen, P A E M, 1989: Wave-induced stress and the drag of air flow over sea waves. *J Phys Oceanogr*, **19**, 745-754.

Janssen, P A E M, 1991: Quasi-linear theory of wind wave generation applied to wave forecasting. *J Phys Oceanogr*, **21**, 1631-1642.

Janssen, P A E M, 1992: Experimental evidence of the effect of surface waves on the airflow. *J Phys Oceanogr,* **22**, 1600-1604.

Janssen, P A E M, G J Komen and W J P de Voogt, 1984: An operational coupled hybrid wave prediction model. *J Geophys Res*, **C89**, 3635-3654.

Janssen, P A E M, P Lionello, M Reistad and A Hollingsworth, 1989a: Hindcasts and data assimilation studies with the WAM model during the Seasat period. *J Geophys Res*, **C94**, 973-993.

Janssen, P A E M, P Lionello and L Zambresky, 1989b: On the interaction of wind and waves. *Philos Trans Roy Soc*, London, **A329**, 289-301.

Komen, G J, K Hasselmann and S Hasselmann, 1984: On the existence of a fully developed wind sea spectrum. *J Phys Oceanogr*, **14**, 1271-1285.

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

Lionello, P, H Günther and P A E M Janssen, 1992: Assimilation of altimeter data in a global third generation wave model. J Geophys Research, **C97**, 14453-14474.

Romeiser, R, 1993: Global validation of the wave model WAM over a one year period using Geosat wave height data. *J Geophys Res*, **C98**, 4713-4726.

Snodgrass, F E, G W Groves, K Hasselmann, G R Miller, W H Munk and W H Powers, 1966: Propagation of ocean swell across the Pacific. *Philos Trans Roy Soc*, London, **A249**, 431.

Snyder, R L, F W Dobson, J A Elliot and R B Long, 1981: Array measurements of atmospheric pressure fluctuations above surface gravity waves. *J Fluid Mech*, **102**, 1-59.

SWAMP group: J H Allender, T P Barnett, L Bertotti, J Bruinsma, V J Cardone, L Cavaleri, J Ephraums, B Golding, A Greenwood, J Guddal, H Günther, K Hasselmann, S Hasselmann, P Joseph, S Kawai, G J Komen, L Lawson, H Linné, R B Long, M Lybanon, E Maeland, W Rosenthal, Y Toba, T Uji and W J P de Voogt, 1985: Sea wave modelling project (SWAMP). An Intercomparison study of wind wave prediction models, part 1: Principal results and conclusions, in: Ocean wave modelling; Plenum, New York, 256 p.

SWIM group: E Bouws, J A Ewing, J Ephraums, P Francis, H Günther, P A E M Janssen, G J Komen, W Rosenthal and W J P de Voogt, 1985: Shallow water Intercomparison of wave prediction models (SWIM). *Quart J Roy Meteor Soc*, **111**, 1087-1113.

WAMDI group: S Hasselmann, K Hasselmann, E Bauer, P A E M Janssen, G J Komen, L Bertotti, P Lionello, A Guillaume, V C Cardone, J A Greenwood, M Reistad, L Zambresky and J A Ewing, 1988: The WAM model - a third generation ocean wave prediction model. *J Phys Oceanogr*, **18**, 1775-1810.

Zambresky, L, 1987: The operational performance of the Fleet Numerical Oceanography Center Global Spectral Ocean-Wave Model, in Proceedings of the symposium 'Measuring Ocean Waves from Space', John Hopkins APL Technical Digest, 8, 33-36.

Zambresky, L, 1989: A verification study of the global WAM model. December 1987-November 1988. ECMWF Tech Report 63, ECMWF, Reading.

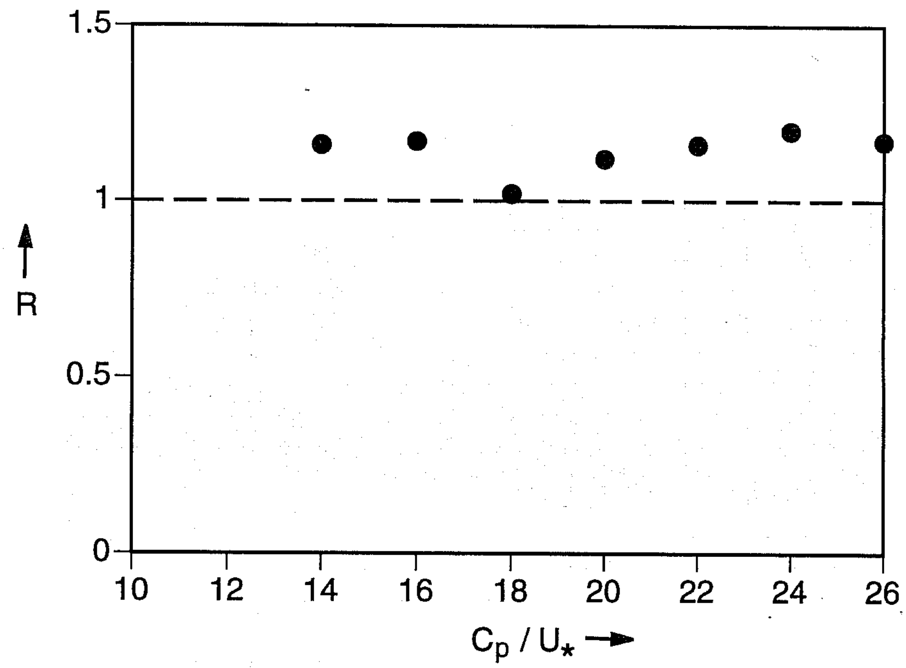


Fig 1 Ratio of modelled to observed high-frequency part of the spectrum (sliced in the wind direction) as a function of wave age c_p/u_*.

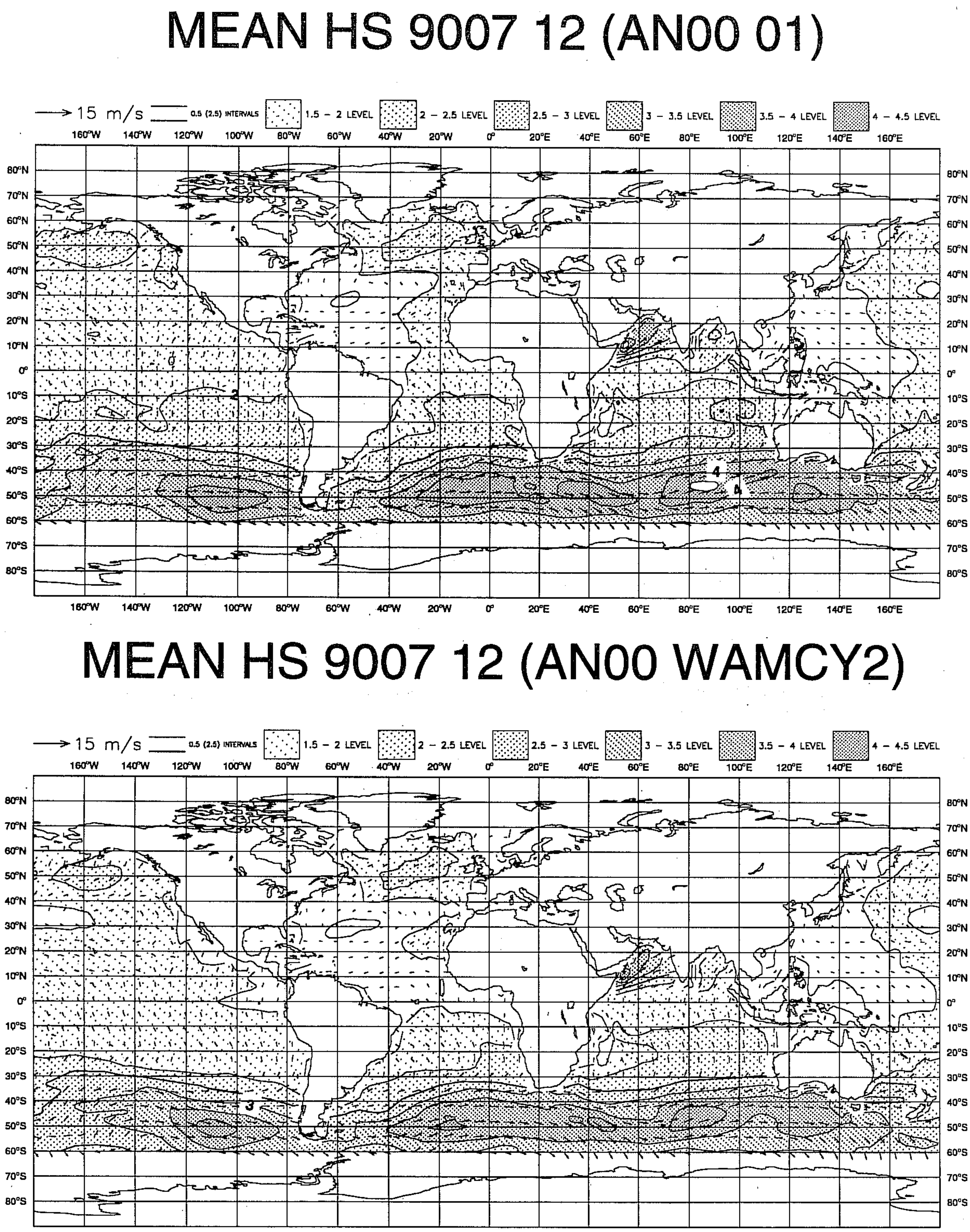
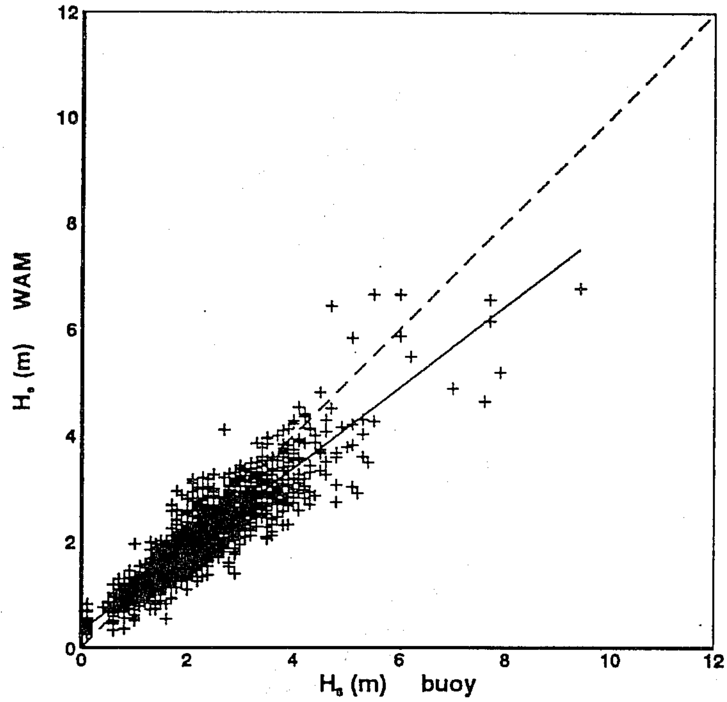
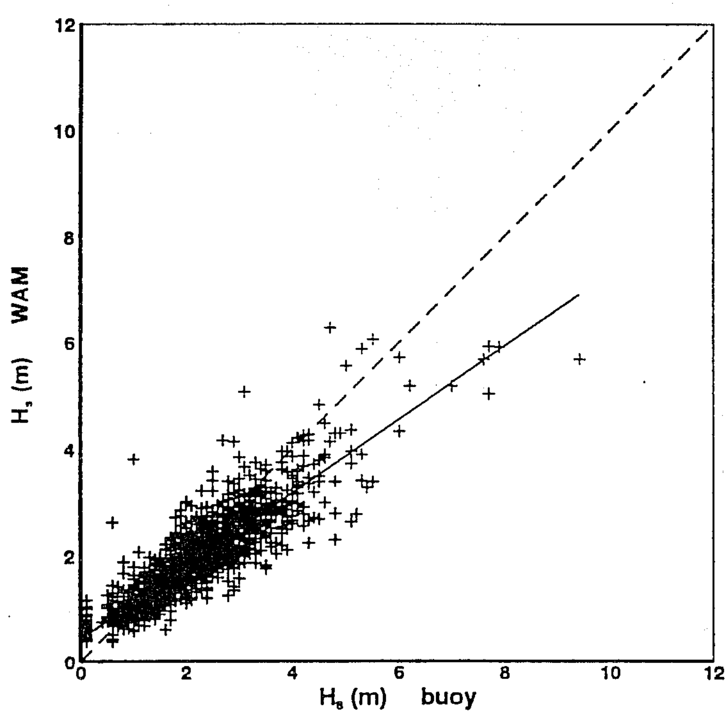


Fig 2 Comparison of monthly mean wave height for July 1988. Upper panel cycle 4 of WAM, lower panel cycle 2 of WAM.



ENTRIES = 2008
MODEL MEAN = 1.937 STDEV = 0.820
BUOY MEAN = 2.123 STDEV = 0.976
LSQ FIT: SLOPE = 0.766 INTR = 0.311
RMSE = 0.447 BIAS = -0.186
CORR COEF = 0.912 SI = 0.191



ENTRIES = 2008
MODEL MEAN = 1.875 STDEV = 0.766
BUOY MEAN = 2.123 STDEV = 0.976
LSQ FIT: SLOPE = 0.691 INTR = 0.409
RMSE = 0.533 BIAS = -0.248
CORR COEF = 0.881 SI = 0.222

Fig 3 Verification of analysed wave height against buoy observation: upper panel 1.5° WAM, lower panel 3° WAM. Area is North Pacific and period is 19 April to 19 May 1994.

BUOY LOCATIONS

1	21004	Japan South-East Coast	16	46036	US North-West Coast
2	22001	East China Sea shelf break	17	46059	US West Coast
3	41001	US East Coast	18	46184	Canada West Coast
4	41002	US South-East Coast	19	51001	Hawaii North-West
5	41006	US East Florida Coast	20	51002	Hawaii South
6	41018	Caribbean Sea	21	51003	Hawaii West
7	42001	Gulf of Mexico	22	51004	Hawaii South-East
8	44008	US North-East Coast	23	62029	UK Celtic Sea shelf break
9	44011	US North-East Coast	24	62081	UK East Atlantic
10	46001	Gulf of Alaska	25	62105	UK East Atlantic
11	46002	US West Coast	26	62106	UK North-East Atlantic
12	46003	Aleutian Peninsula	27	62108	UK East Atlantic
13	46005	US North-West Coast	28	62163	UK Celtic Sea shelf break
14	46006	US West Coast	29	63111	North Sea shelf break
15	46035	Bering Sea	30	64045	UK North-East Atlantic

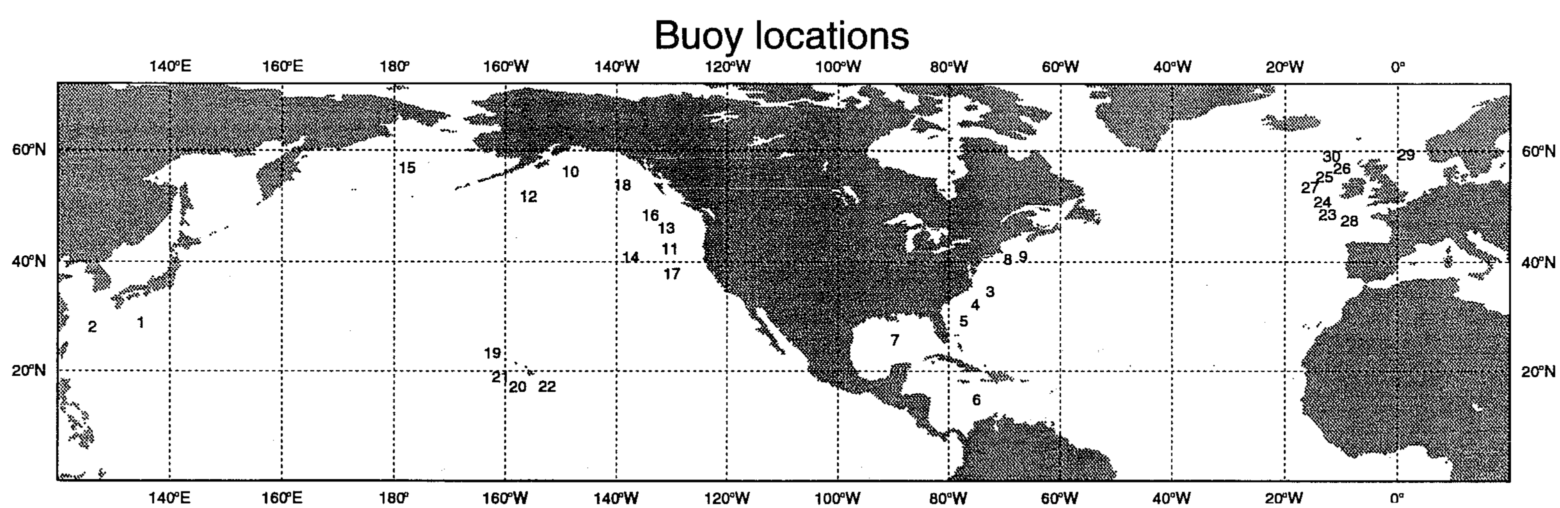
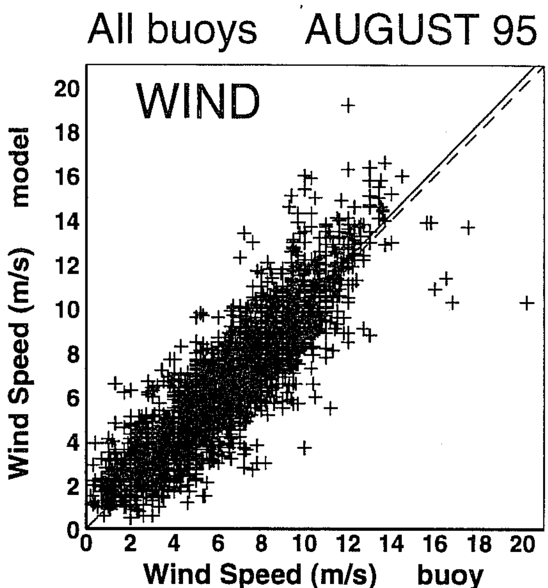
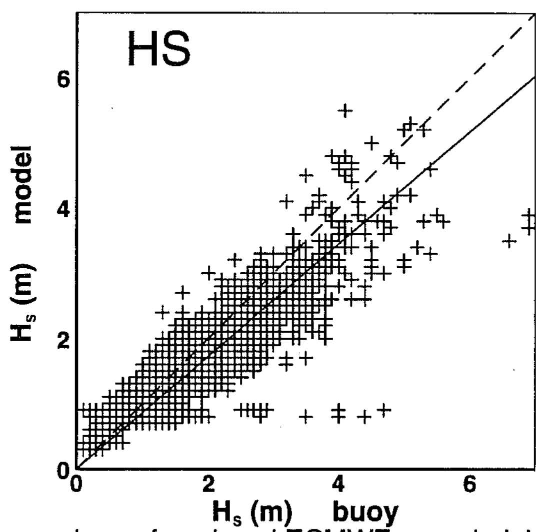


Fig 4 Location of buoys used in the verification study of analysed wave height, wave period and wind speed.



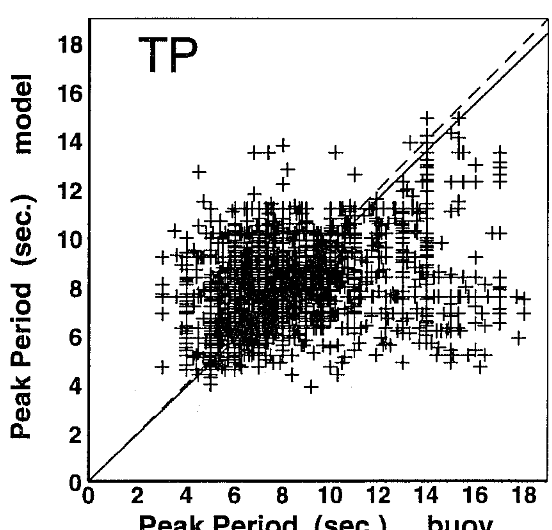
Comparison of analysed ECMWF wind speeds with averaged buoy data.

ENTRIES = 3358
MODEL MEAN = 6.484 STDEV = 2.743
BUOY MEAN = 6.384 STDEV = 2.624
LSQ FIT: SLOPE = 0.924 INTR = 0.588
RMSE = 1.304 BIAS = 0.100
CORR COEF = 0.883 SI = 0.204
SYMMETRIC SLOPE = 1.020



Comparison of analysed ECMWF wave heights with averaged buoy data.

ENTRIES = 3525
MODEL MEAN = 1.604 STDEV = 0.650
BUOY MEAN = 1.828 STDEV = 0.831
LSQ FIT: SLOPE = 0.695 INTR = 0.334
RMSE = 0.452 BIAS = -0.224
CORR COEF = 0.888 SI = 0.214
SYMMETRIC SLOPE = 0.862

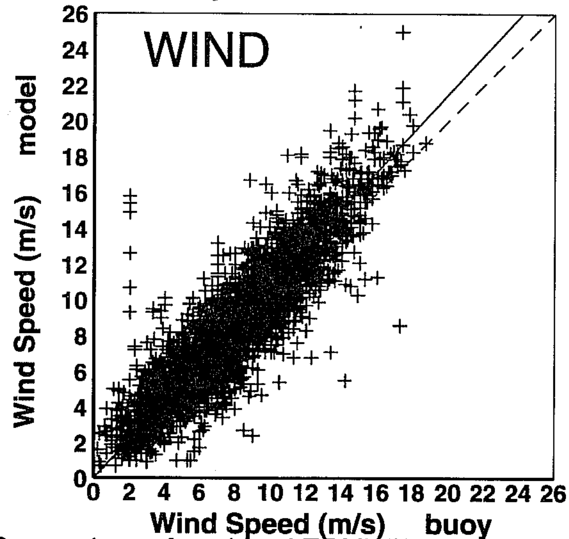


Comparison of analysed ECMWF peak periods with averaged buoy data.

ENTRIES = 3446
MODEL MEAN = 8.098 STDEV = 1.523
BUOY MEAN = 8.141 STDEV = 2.441
LSQ FIT: SLOPE = 0.205 INTR = 6.426
RMSE = 2.415 BIAS = -0.043
CORR COEF = 0.329 SI = 0.297
SYMMETRIC SLOPE = 0.970

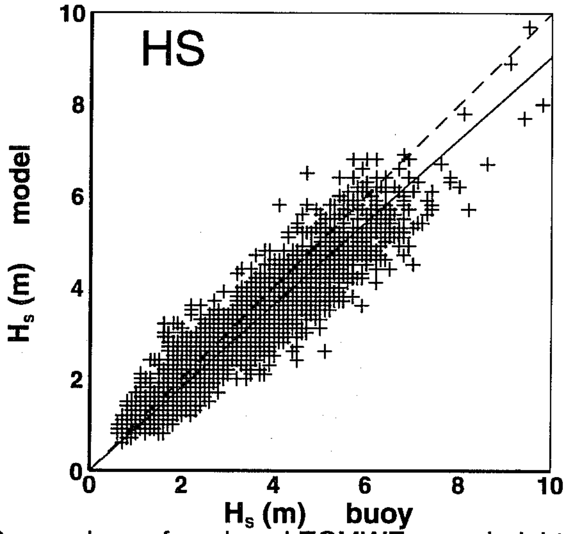
Fig 5 Comparison of analysed wind speed, wave height and wave period with buoy measurements for August 1995.

All buoys DECEMBER 95



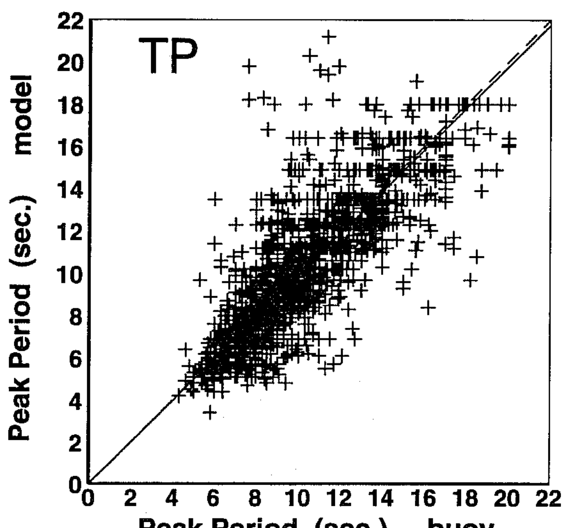
Comparison of analysed ECMWF wind speeds with averaged buoy data.

ENTRIES = 3161
MODEL MEAN = 8.615 STDEV = 3.639
BUOY MEAN = 8.069 STDEV = 3.249
LSQ FIT: SLOPE = 0.999 INTR = 0.554
RMSE = 1.733 BIAS = 0.546
CORR COEF = 0.892 SI = 0.204
SYMMETRIC SLOPE = 1.075



Comparison of analysed ECMWF wave heights with averaged buoy data.

ENTRIES = 3311
MODEL MEAN = 2.890 STDEV = 1.215
BUOY MEAN = 3.166 STDEV = 1.400
LSQ FIT: SLOPE = 0.815 INTR = 0.309
RMSE = 0.564 BIAS = -0.276
CORR COEF = 0.939 SI = 0.155
SYMMETRIC SLOPE = 0.906



Comparison of analysed ECMWF peak periods with averaged buoy data.

ENTRIES = 2293
MODEL MEAN = 10.317 STDEV = 3.108
BUOY MEAN = 10.485 STDEV = 2.979
LSQ FIT: SLOPE = 0.875 INTR = 1.143
RMSE = 1.742 BIAS = -0.167
CORR COEF = 0.839 SI = 0.165
SYMMETRIC SLOPE = 0.989

Fig 6 Same as Fig 5 but now for December 1995.

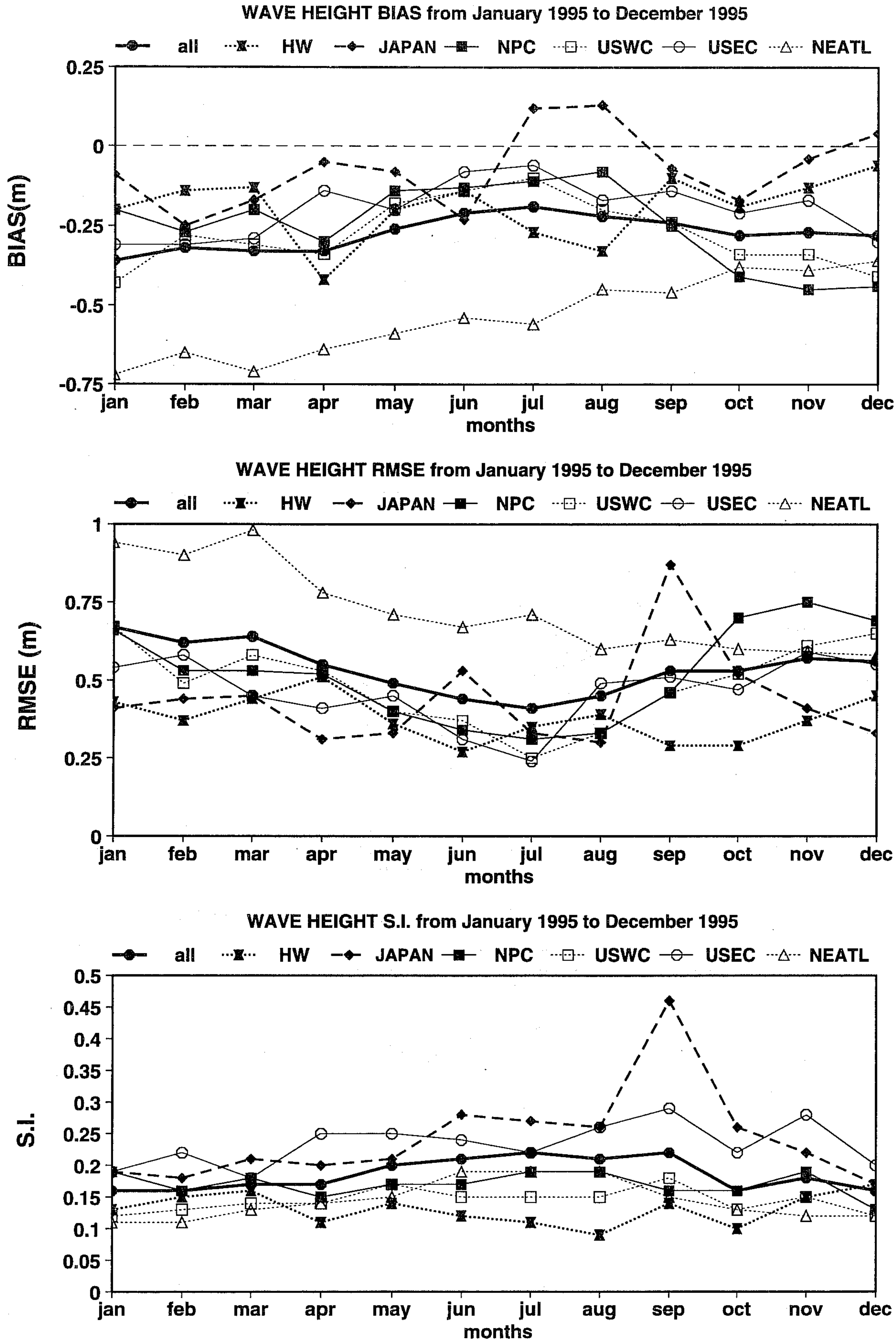
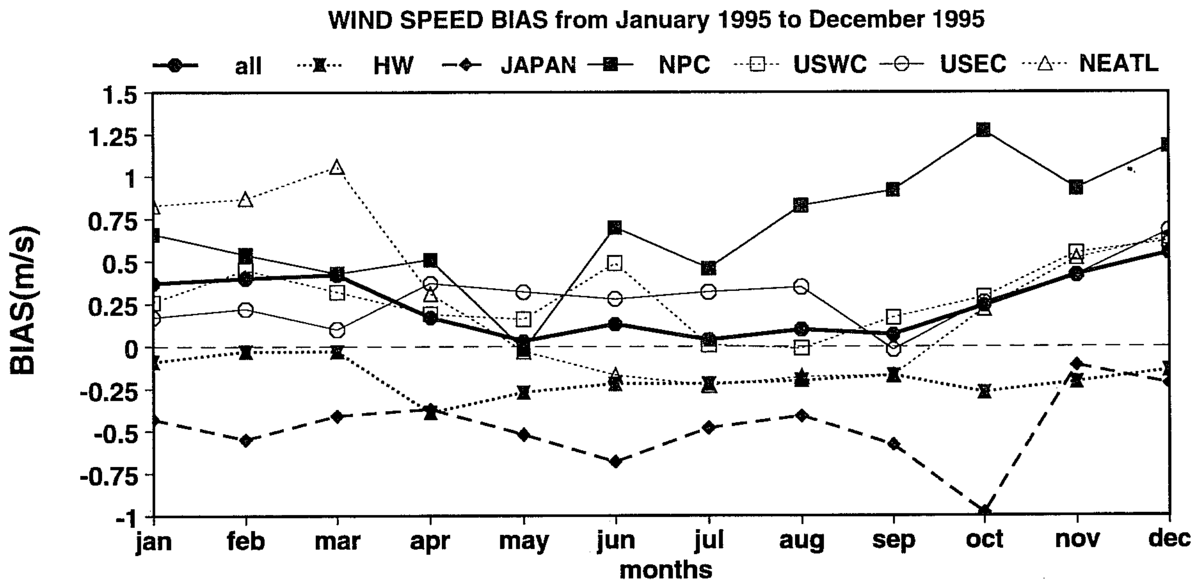
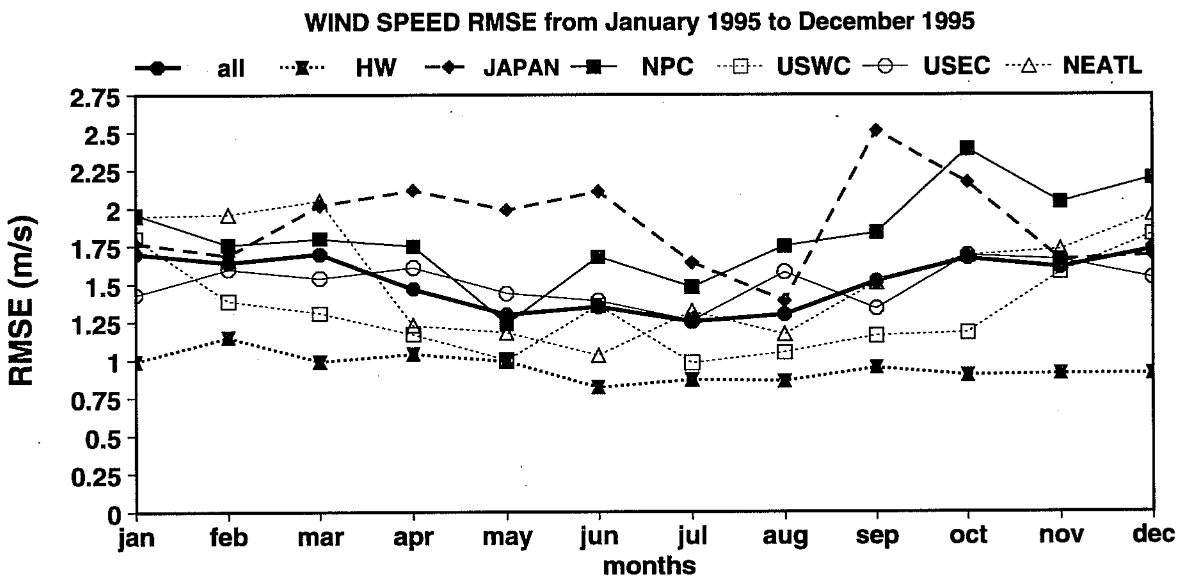


Fig 7 Monthly variation of bias, rms error and scatter index for analysed wave height for the year 1995. Symbols refer to different areas.





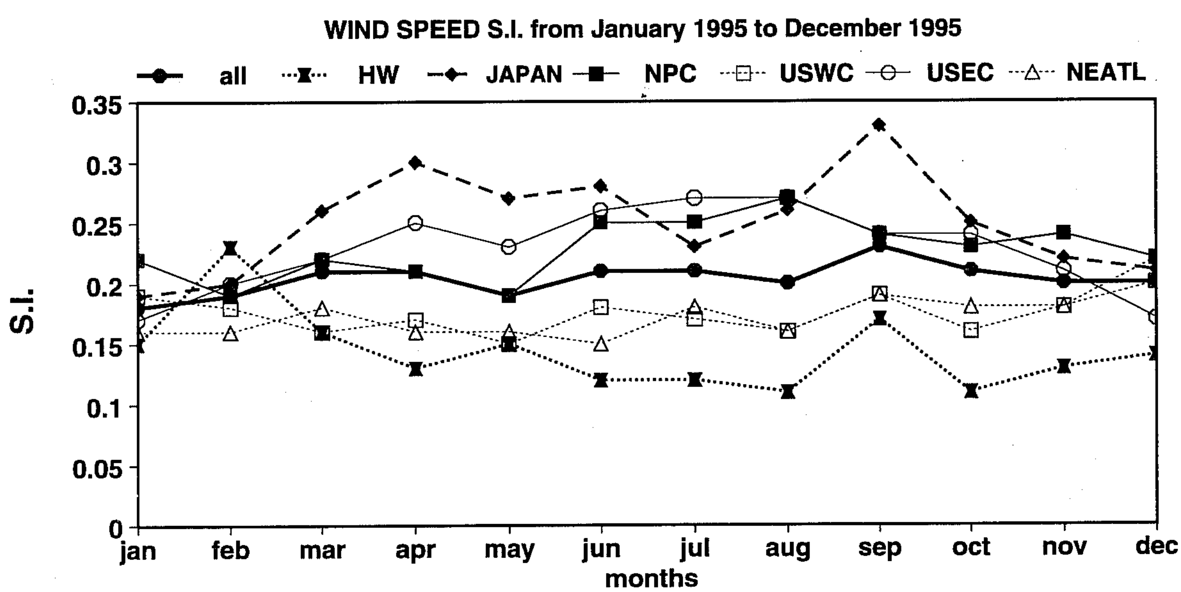
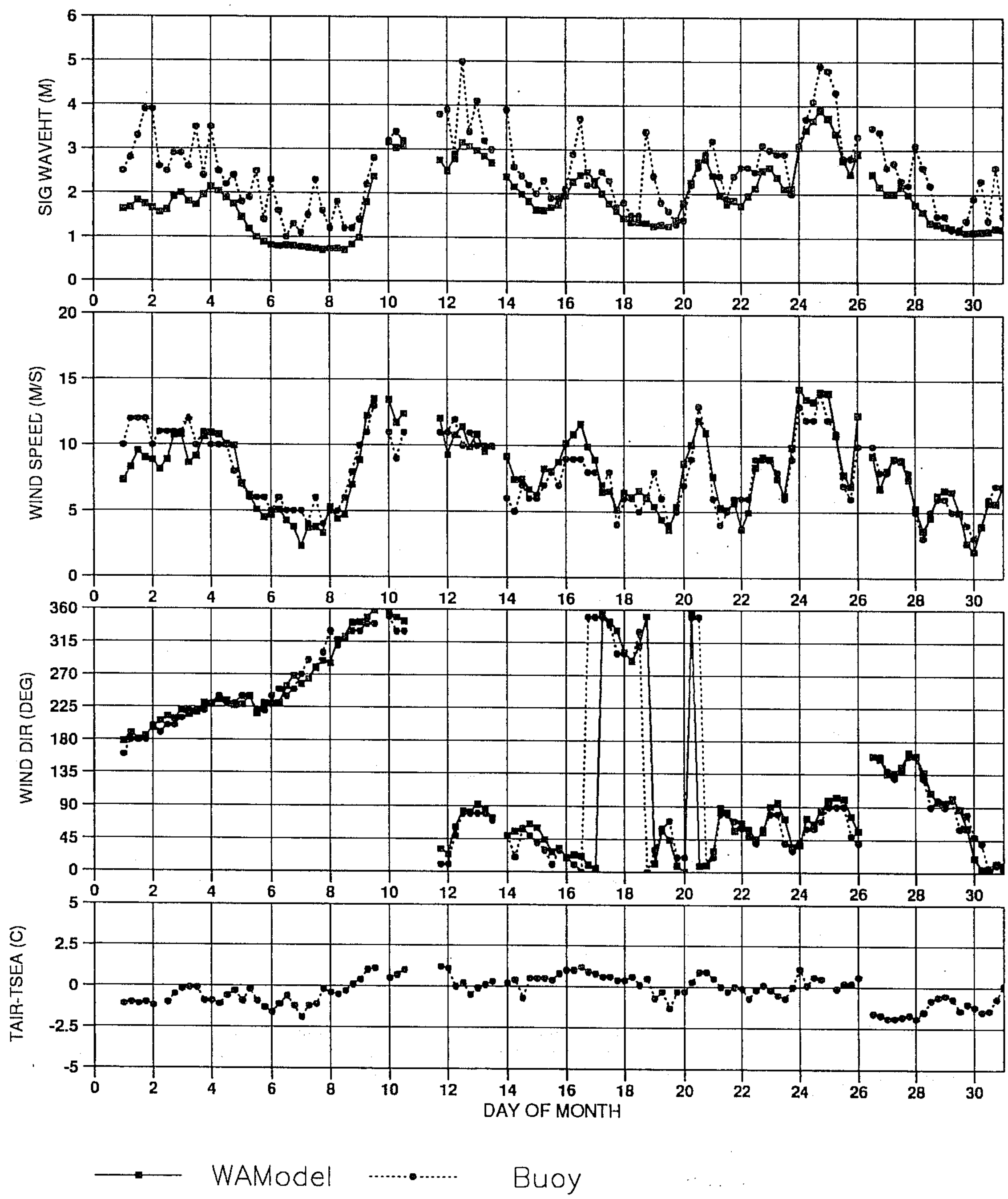


Fig 8 Same as Fig 7 but now for wind speed.

BUOY 62108 (53.6N, 15.5W)
AUGUST 1995



WAVES

MODEL MEAN = 1.9 STDEV = 0.7
BUOY MEAN = 2.5 STDEV = 0.9
LSQ FIT: SLOPE = 0.68 INTR = 0.18
RMSE = 0.81 BIAS = -0.62
CORR COEF = 0.80 SI = 0.21

WINDS

MODEL MEAN = 7.9 STDEV = 2.9
BUOY MEAN = 7.9 STDEV = 2.6
LSQ FIT: SLOPE = 0.97 INTR = 0.22
RMSE = 1.37 BIAS = -0.02
CORR COEF = 0.88 SI = 0.17

Fig 9 Time series of wave height wind speed, wind direction and air-sea temperature difference in August 1995 for buoy 62108.

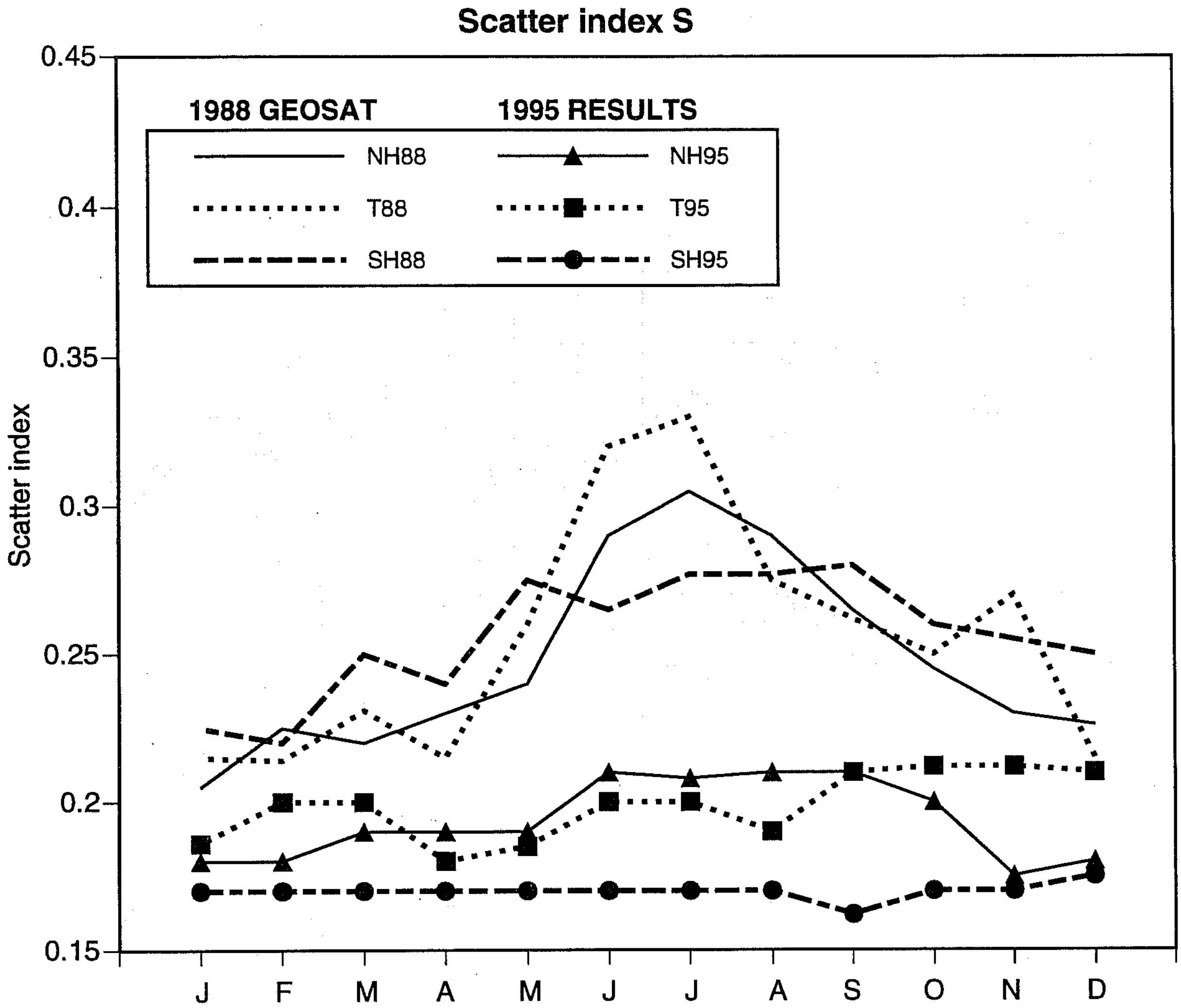
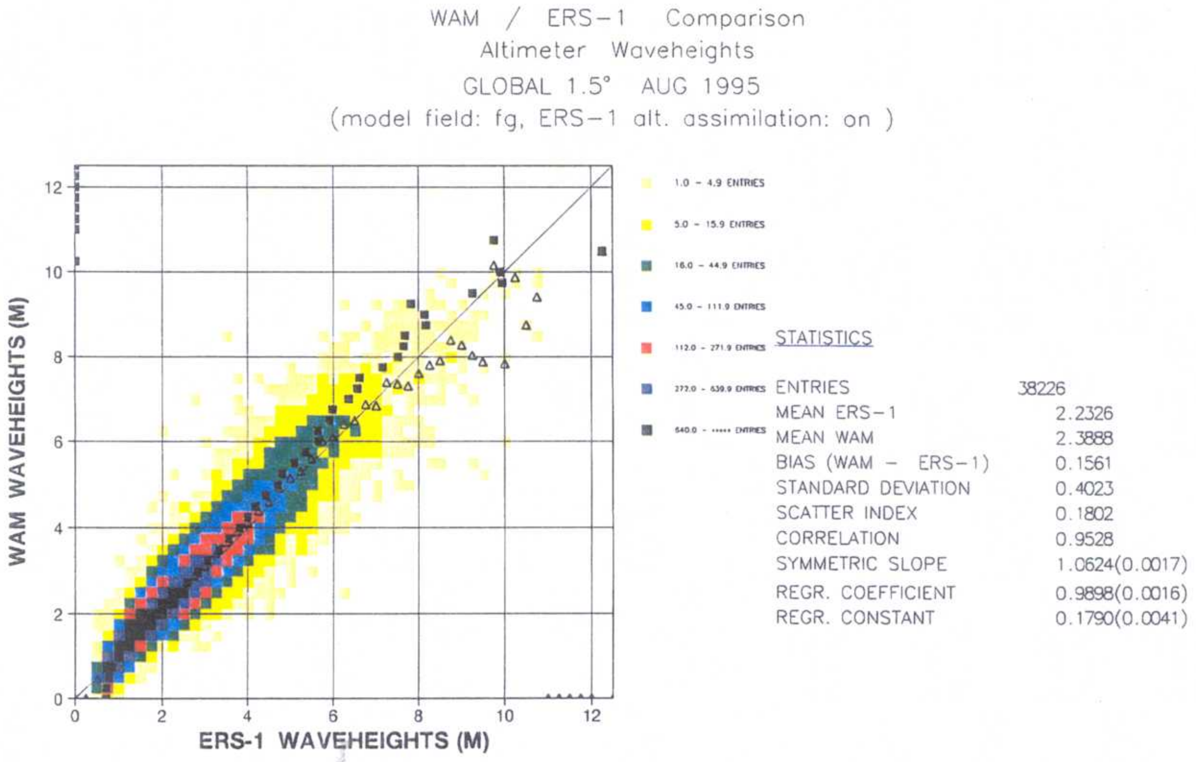


Fig 10 Monthly variation of Romeisers scatter index obtained from comparison of analysed wave height with Geosat Altimeter (year 1988) data for Northern Hemisphere, Tropics and Southern Hemisphere. For comparison, scatter indices for 1995 are also shown which are obtained from the comparison of first-guess wave height and ERS-1 Altimeter.



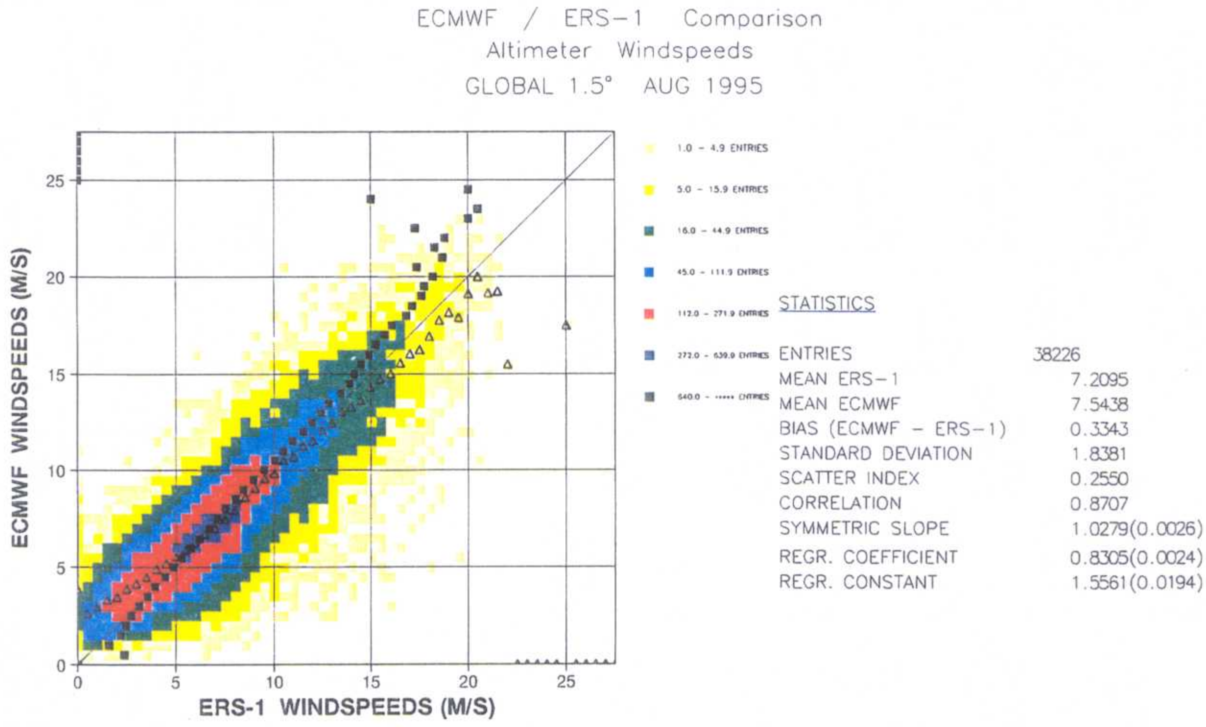
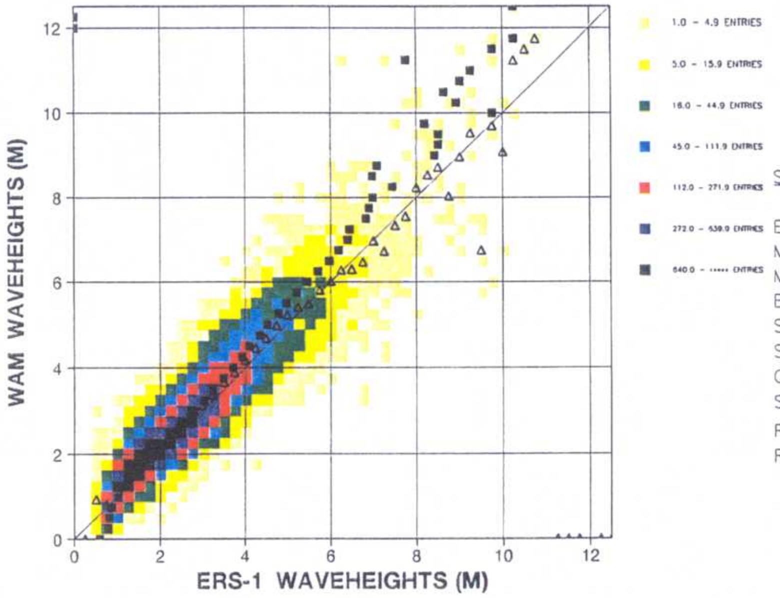


Fig 11 Comparison of first-guess wave height and analysed wind speed with altimeter data for the whole globe for August 1995. Triangles denote mean altimeter as a function of modelled parameter, while squares denote mean modelled parameter as a function of altimeter.

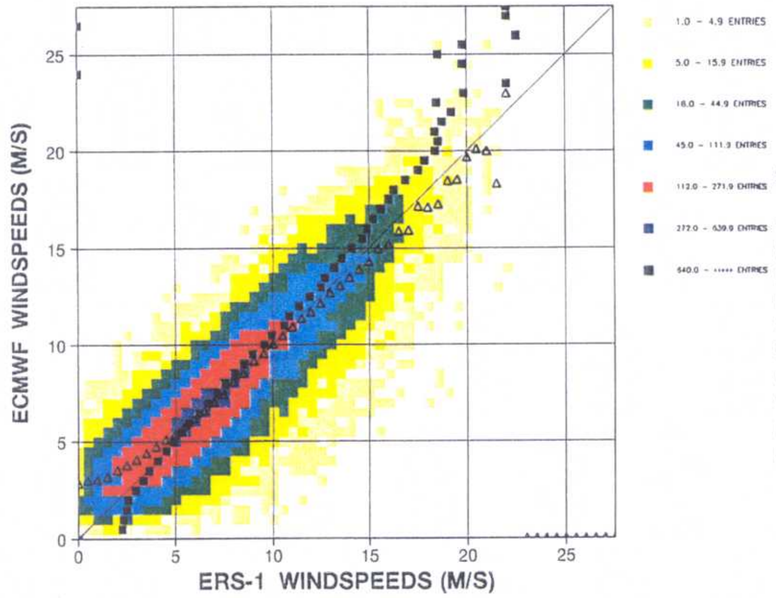
WAM / ERS-1 Comparison
Altimeter Waveheights
GLOBAL 1.5° DEC 1995
(model field: fg, ERS-1 alt. assimilation: on)



STATISTICS

ENTRIES	39892
MEAN ERS-1	2.2920
MEAN WAM	2.4983
BIAS (WAM - ERS-1)	0.2063
STANDARD DEVIATION	0.3998
SCATTER INDEX	0.1744
CORRELATION	0.9395
SYMMETRIC SLOPE	1.0777(0.0019)
REGR. COEFFICIENT	0.9636(0.0018)
REGR. CONSTANT	0.2896(0.0045)

ECMWF / ERS-1 Comparison
Altimeter Windspeeds
GLOBAL 1.5° DEC 1995



STATISTICS

ENTRIES	39892
MEAN ERS-1	7.3721
MEAN ECMWF	7.6810
BIAS (ECMWF - ERS-1)	0.3089
STANDARD DEVIATION	1.8009
SCATTER INDEX	0.2443
CORRELATION	0.8771
SYMMETRIC SLOPE	1.0296(0.0025)
REGR. COEFFICIENT	0.8583(0.0024)
REGR. CONSTANT	1.3536(0.0194)

Fig 12 Same as Fig 11, but now for December 1995.

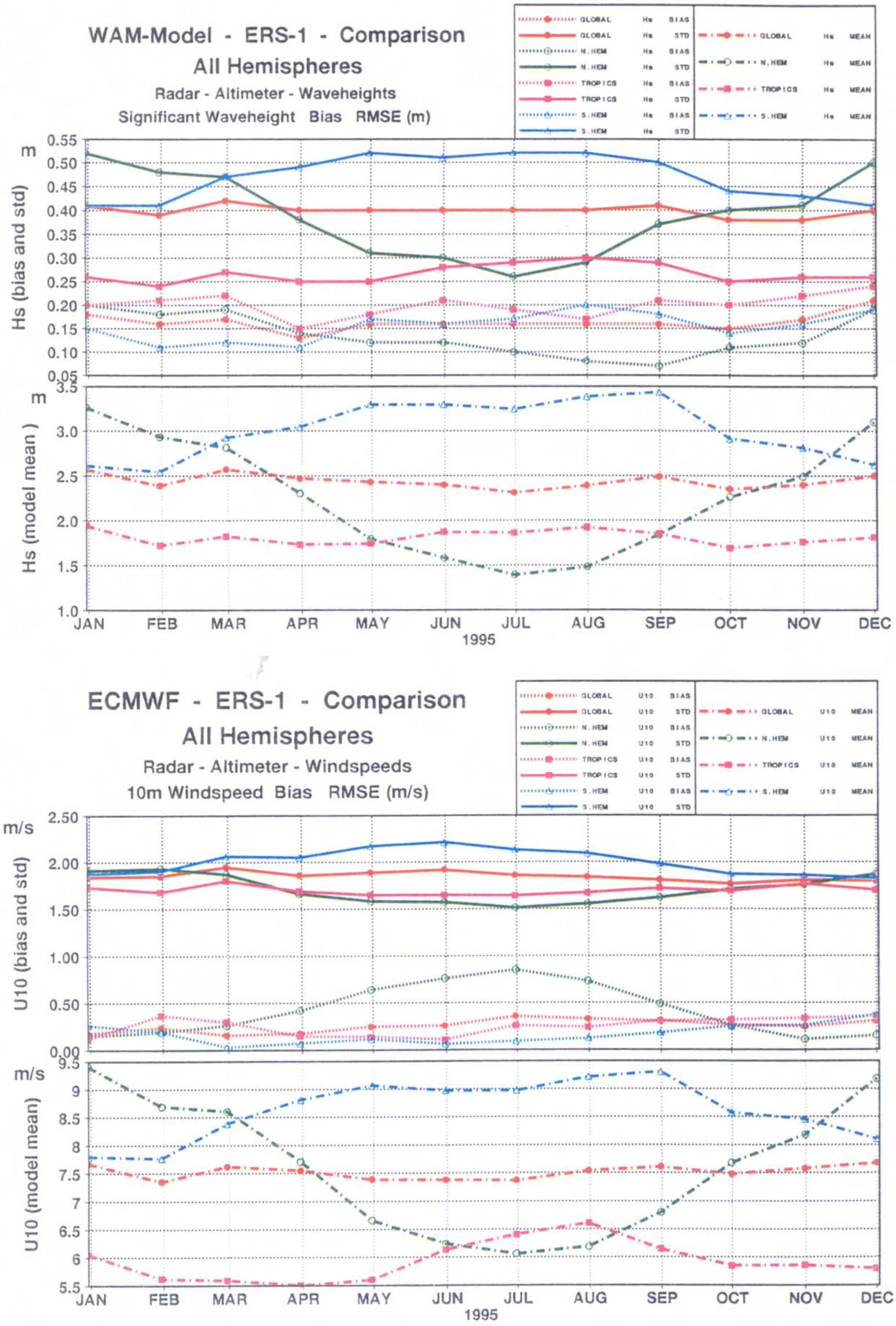


Fig 13 Seasonal variation of mean modelled parameter, bias and standard deviation of error for the globe, Northern Hemisphere and Southern Hemisphere . The upper panel shows results from the comparison of first-guess wave height with altimeter wave height, while the lower panel shows corresponding results for analysed wind speed.

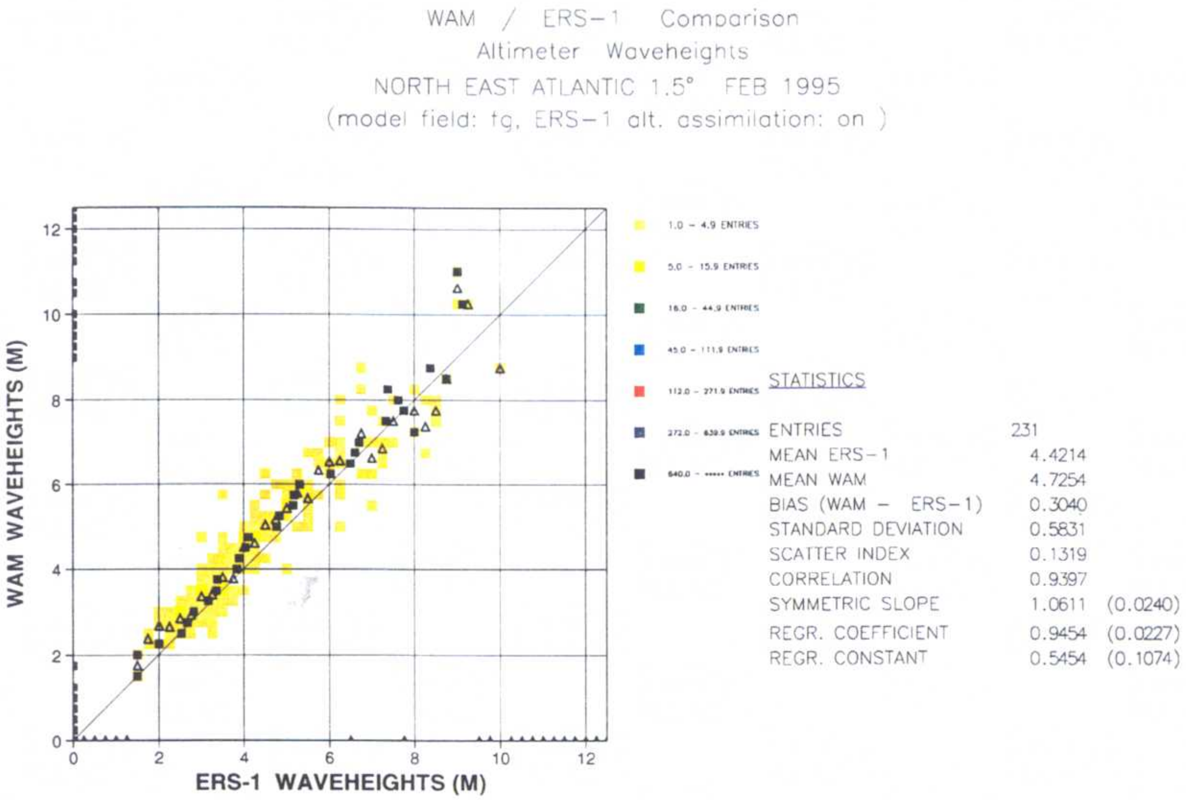
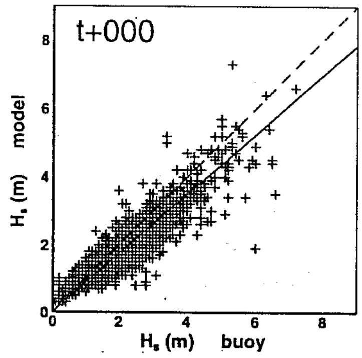


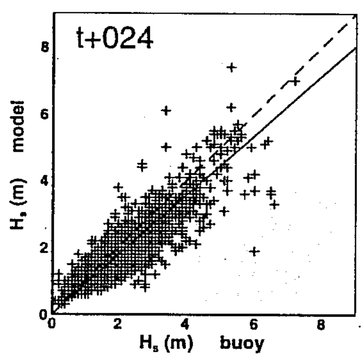
Fig 14 Verification of modelled first-guess wave height against altimeter wave height data for a limited area (0-20° W; 50-60° N) in the North-East Atlantic.

All buoys JUNE to SEPTEMBER 95



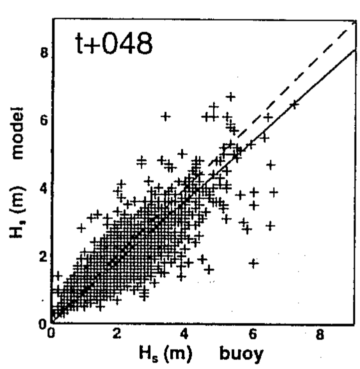
Comparison of analysed ECMWF wave heights with averaged buoy data.

ENTRIES = 3435
MODEL MEAN = 1.644 STDEV = 0.742
BUOY MEAN = 1.856 STDEV = 0.905
LSQ FIT: SLOPE = 0.746 INTR = 0.259
RMSE = 0.440 BIAS = -0.212
CORR COEF = 0.909 SI = 0.207
SYMMETRIC SLOPE = 0.873



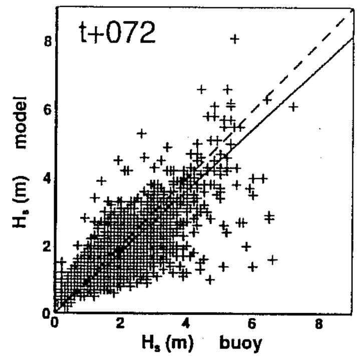
Comparison of forecast(t+24) ECMWF wave heights with averaged buoy data.

ENTRIES = 3435
MODEL MEAN = 1.680 STDEV = 0.759
BUOY MEAN = 1.856 STDEV = 0.905
LSQ FIT: SLOPE = 0.738 INTR = 0.310
RMSE = 0.467 BIAS = -0.176
CORR COEF = 0.879 SI = 0.233
SYMMETRIC SLOPE = 0.893



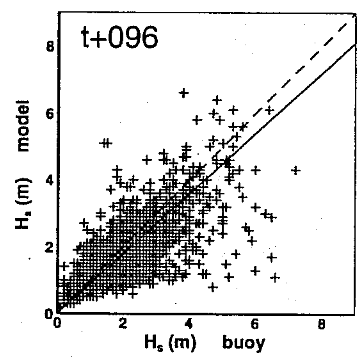
Comparison of forecast(t+48) ECMWF wave heights with averaged buoy data.

ENTRIES = 3435
MODEL MEAN = 1.705 STDEV = 0.771
BUOY MEAN = 1.856 STDEV = 0.905
LSQ FIT: SLOPE = 0.723 INTR = 0.362
RMSE = 0.502 BIAS = -0.151
CORR COEF = 0.849 SI = 0.258
SYMMETRIC SLOPE = 0.906



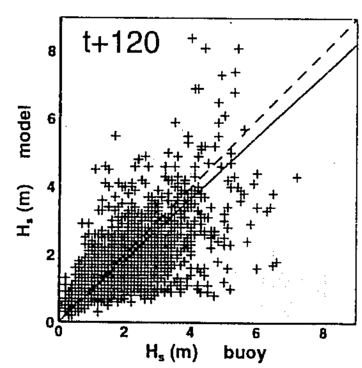
Comparison of forecast(t+72) ECMWF wave heights with averaged buoy data.

ENTRIES = 3435
MODEL MEAN = 1.709 STDEV = 0.767
BUOY MEAN = 1.856 STDEV = 0.905
LSQ FIT: SLOPE = 0.663 INTR = 0.478
RMSE = 0.585 BIAS = -0.147
CORR COEF = 0.783 SI = 0.305
SYMMETRIC SLOPE = 0.907



Comparison of forecast(t+96) ECMWF wave heights with averaged buoy data.

ENTRIES = 3435
MODEL MEAN = 1.699 STDEV = 0.751
BUOY MEAN = 1.856 STDEV = 0.905
LSQ FIT: SLOPE = 0.602 INTR = 0.582
RMSE = 0.648 BIAS = -0.157
CORR COEF = 0.726 SI = 0.339
SYMMETRIC SLOPE = 0.900

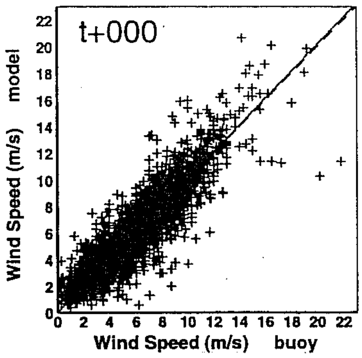


Comparison of forecast(t+120) ECMWF wave heights with averaged buoy data

ENTRIES = 3435
MODEL MEAN = 1.714 STDEV = 0.801
BUOY MEAN = 1.856 STDEV = 0.905
LSQ FIT: SLOPE = 0.578 INTR = 0.641
RMSE = 0.731 BIAS = -0.142
CORR COEF = 0.653 SI = 0.386
SYMMETRIC SLOPE = 0.916

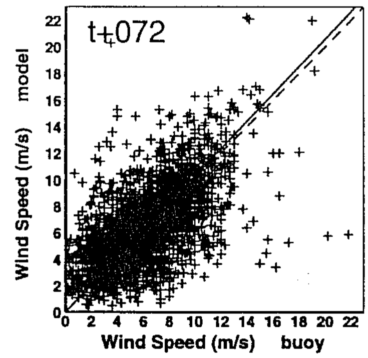
Fig 15 Verification of analysed and forecast wave height against buoy data for the period of June to September 1995.

All buoys JUNE to SEPTEMBER 95



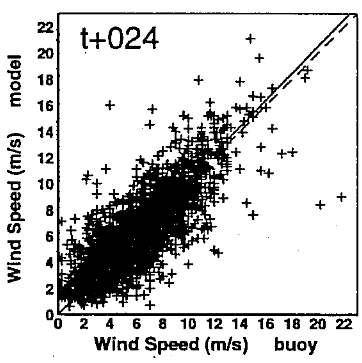
Comparison of analysed ECMWF wind speeds with averaged buoy data.

ENTRIES = 3228
MODEL MEAN = 6.347 STDEV = 2.846
BUOY MEAN = 6.325 STDEV = 2.725
LSQ FIT: SLOPE = 0.925 INTR = 0.498
RMSE = 1.338 BIAS = 0.022
CORR COEF = 0.886 SI = 0.211
SYMMETRIC SLOPE = 1.010



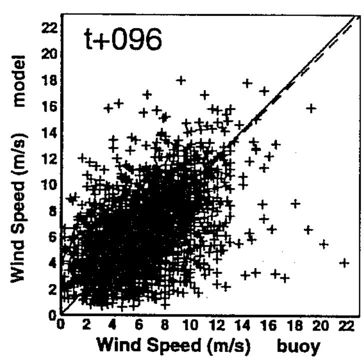
Comparison of forecast(t+72) ECMWF wind speeds with averaged buoy data.

ENTRIES = 3228
MODEL MEAN = 6.491 STDEV = 2.826
BUOY MEAN = 6.325 STDEV = 2.725
LSQ FIT: SLOPE = 0.645 INTR = 2.408
RMSE = 2.419 BIAS = 0.166
CORR COEF = 0.622 SI = 0.382
SYMMETRIC SLOPE = 1.028



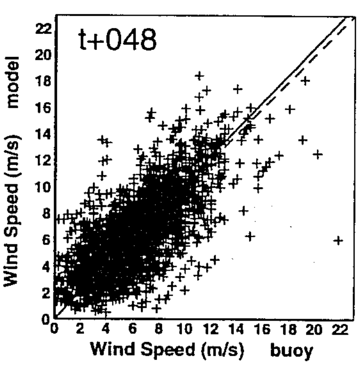
Comparison of forecast(t+24) ECMWF wind speeds with averaged buoy data.

ENTRIES = 3228
MODEL MEAN = 6.474 STDEV = 2.822
BUOY MEAN = 6.325 STDEV = 2.725
LSQ FIT: SLOPE = 0.839 INTR = 1.169
RMSE = 1.719 BIAS = 0.149
CORR COEF = 0.810 SI = 0.271
SYMMETRIC SLOPE = 1.025



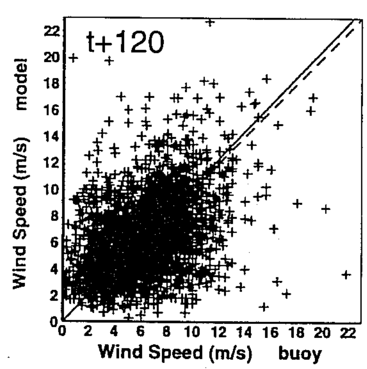
Comparison of forecast(t+96) ECMWF wind speeds with averaged buoy data.

ENTRIES = 3228
MODEL MEAN = 6.443 STDEV = 2.718
BUOY MEAN = 6.325 STDEV = 2.725
LSQ FIT: SLOPE = 0.515 INTR = 3.183
RMSE = 2.678 BIAS = 0.118
CORR COEF = 0.517 SI = 0.423
SYMMETRIC SLOPE = 1.015



Comparison of forecast(t+48) ECMWF wind speeds with averaged buoy data.

ENTRIES = 3228
MODEL MEAN = 6.525 STDEV = 2.767
BUOY MEAN = 6.325 STDEV = 2.725
LSQ FIT: SLOPE = 0.742 INTR = 1.830
RMSE = 2.024 BIAS = 0.199
CORR COEF = 0.731 SI = 0.318
SYMMETRIC SLOPE = 1.029

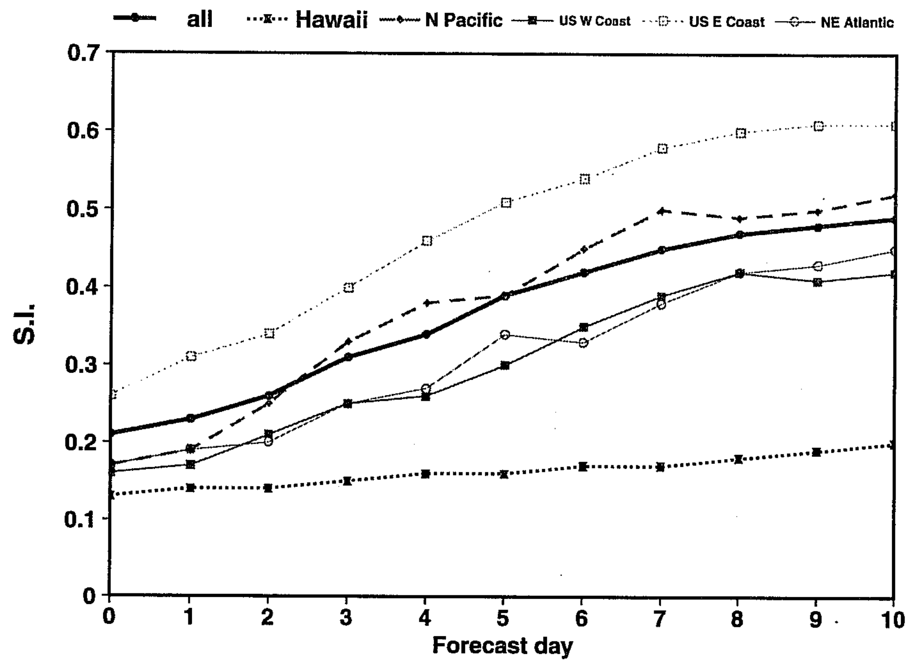


Comparison of forecast(t+120) ECMWF wind speeds with averaged buoy data.

ENTRIES = 3228
MODEL MEAN = 6.498 STDEV = 2.808
BUOY MEAN = 6.325 STDEV = 2.725
LSQ FIT: SLOPE = 0.417 INTR = 3.859
RMSE = 3.023 BIAS = 0.172
CORR COEF = 0.405 SI = 0.477
SYMMETRIC SLOPE = 1.028

Fig 16 Same as Fig 15 but now for wind speed.

WAVE HEIGHT SCATTER INDEX (JUNE 95 to SEPTEMBER 95)



WIND SPEED SCATTER INDEX (JUNE 95 to SEPTEMBER 95)

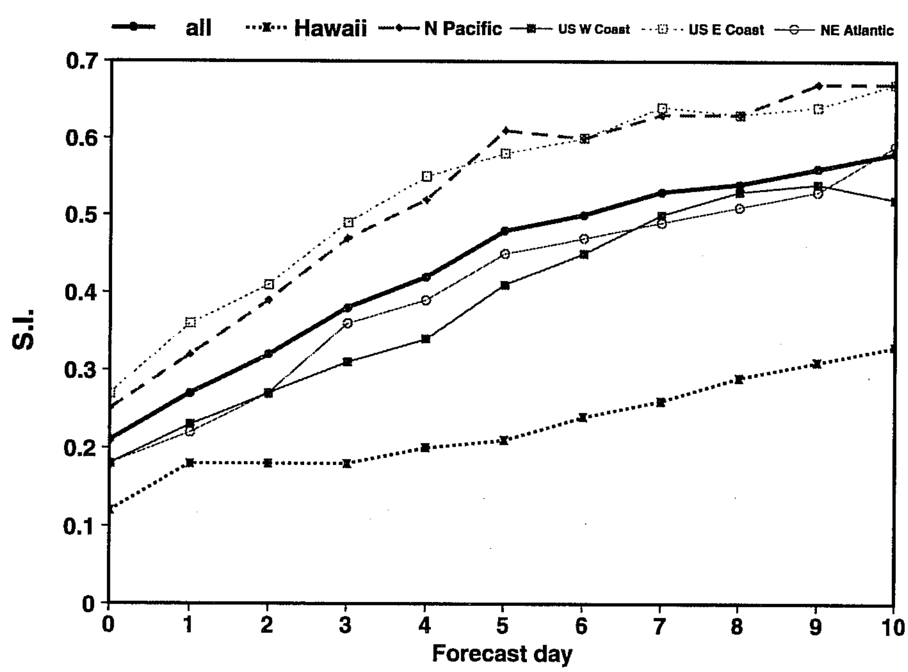


Fig 17 Evolution of scatter index for wave height and wind speed as a function of forecast day. Symbols refer to different areas as displayed in legend.

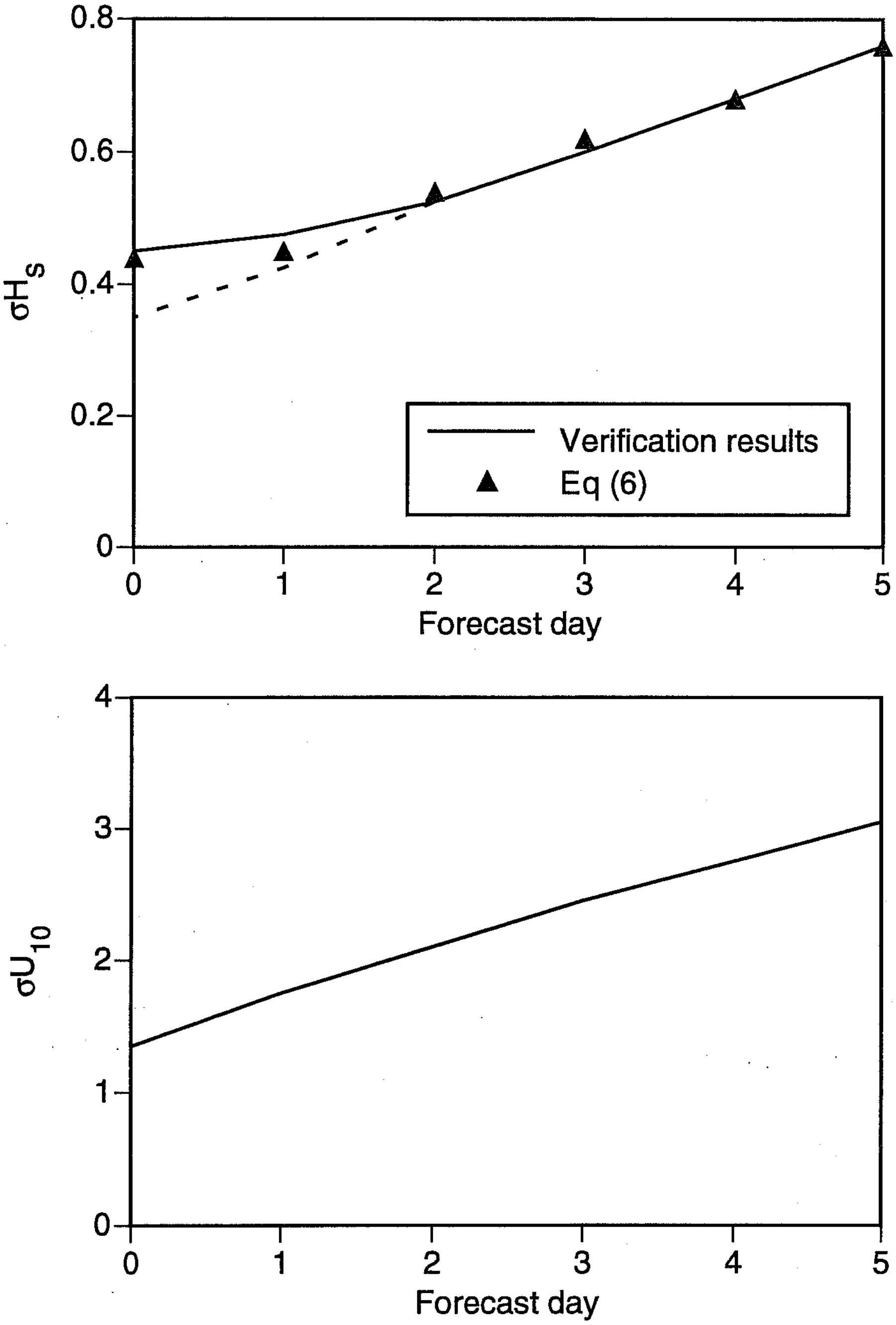


Fig 18 Rms error growth in wave and wind forecast for all buoys during the period June - September 1995.

MEAN HS 87-9401 12 (AN00 01)

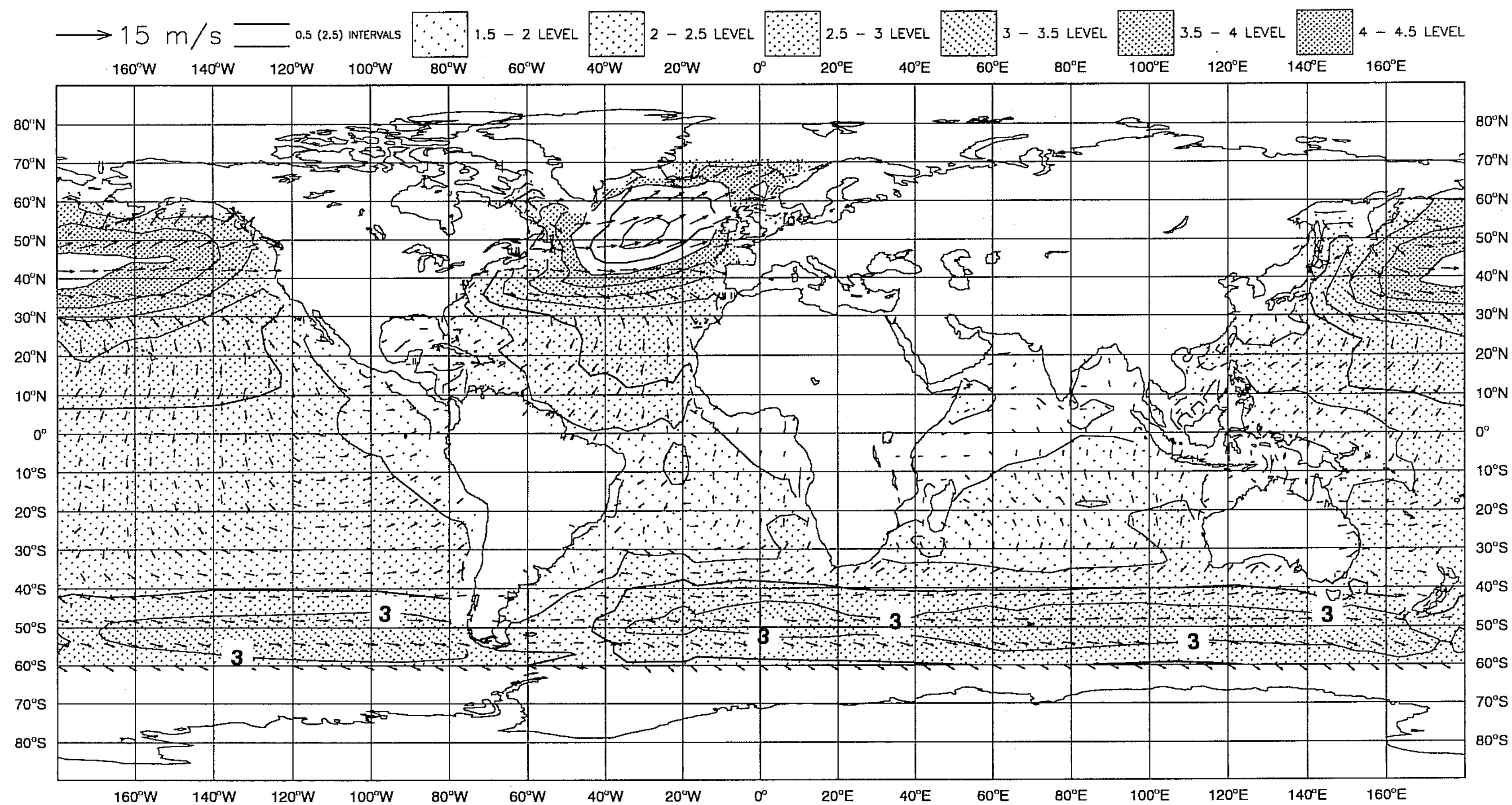


Fig 19 Wave height climatology for January.

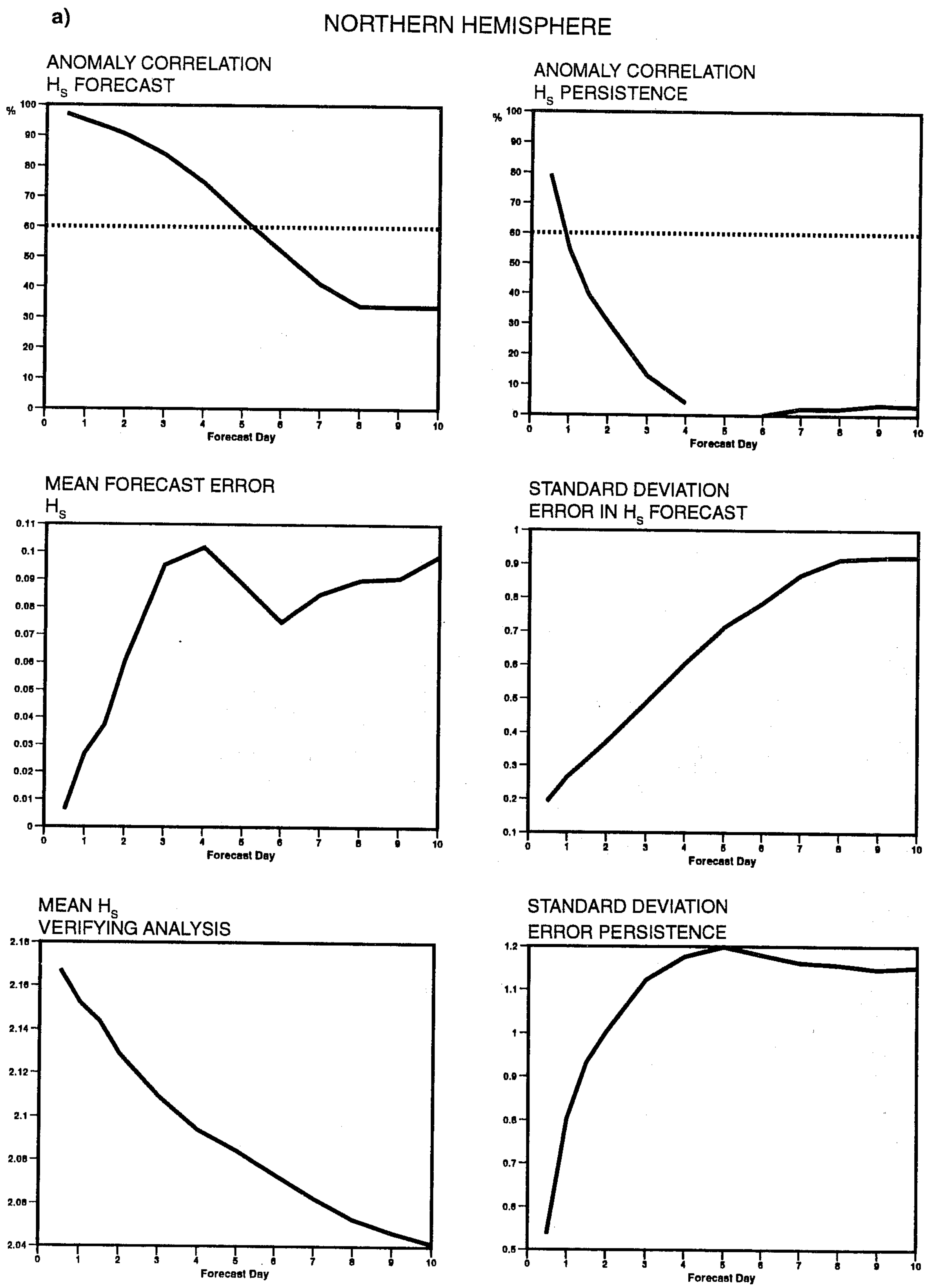


Fig 20 (a) Forecast verification scores for April 1995. Northern Hemisphere.

b) TROPICS

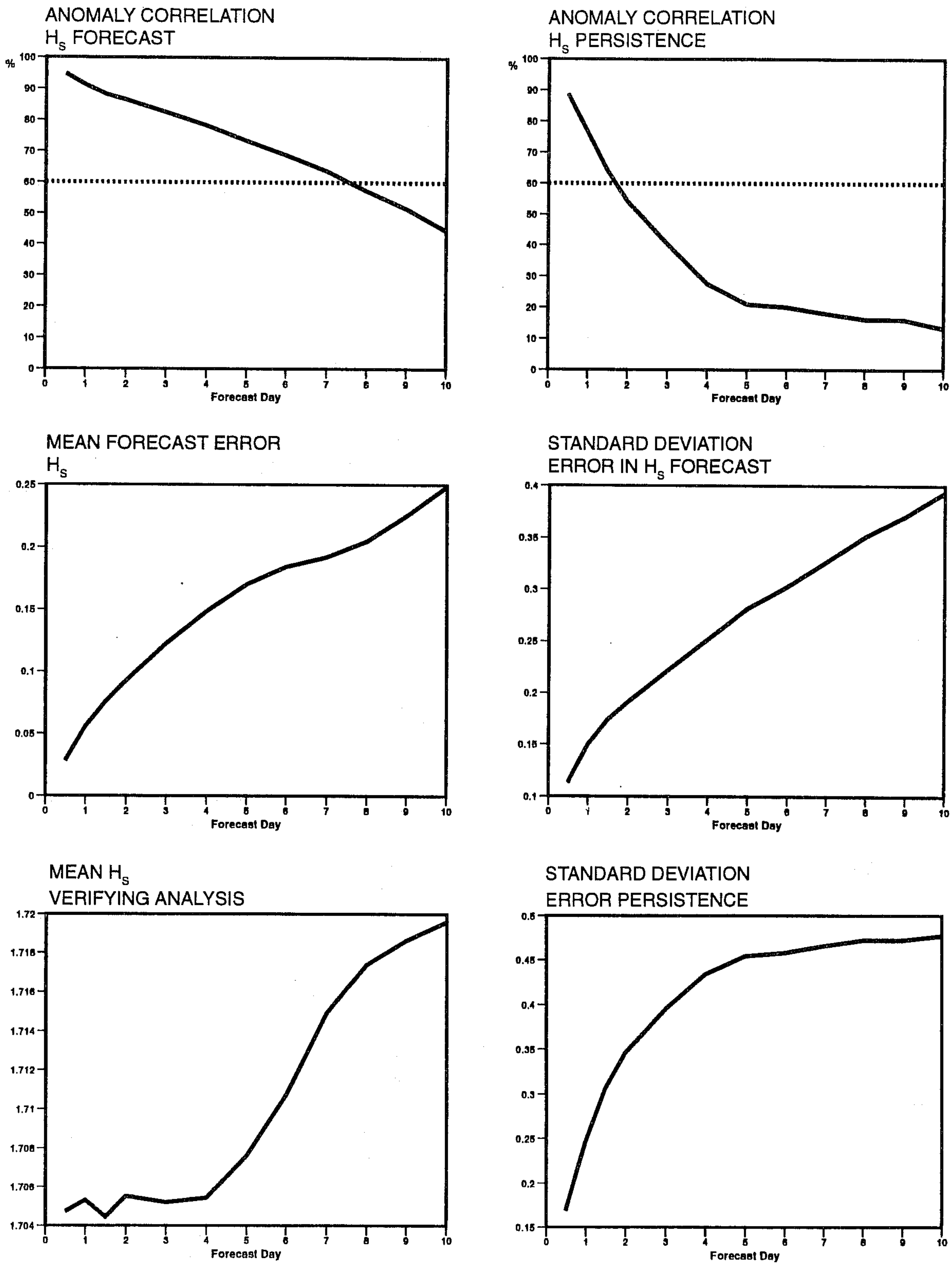


Fig 20 (b) Forecast verification scores for April 1995. Tropics.

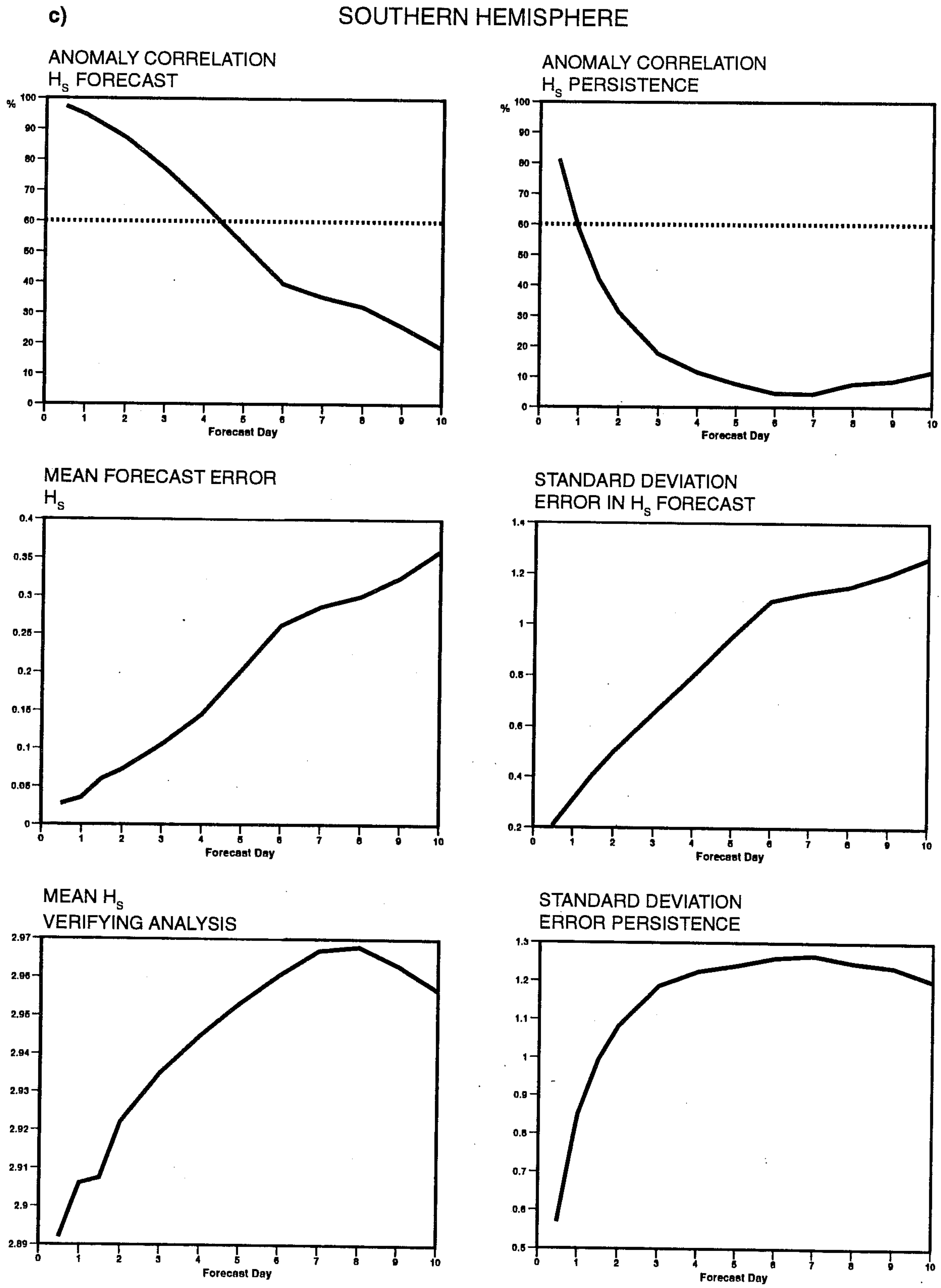
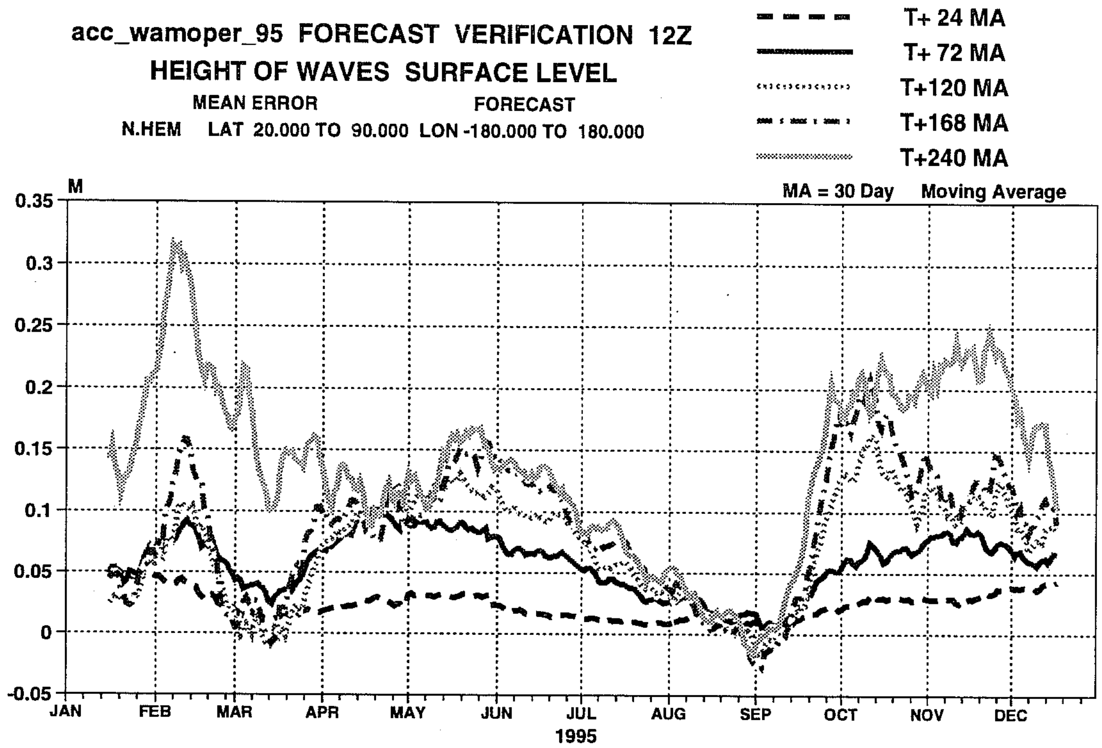


Fig 20 (c) Forecast verification scores for April 1995. Southern Hemisphere.



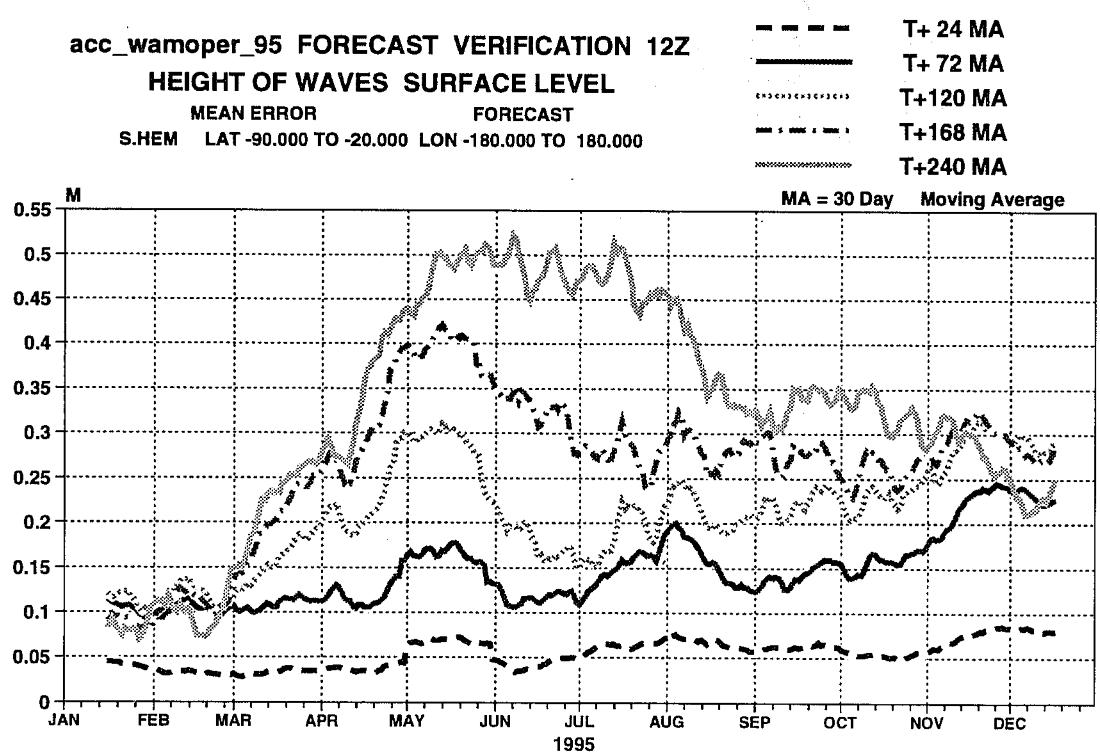
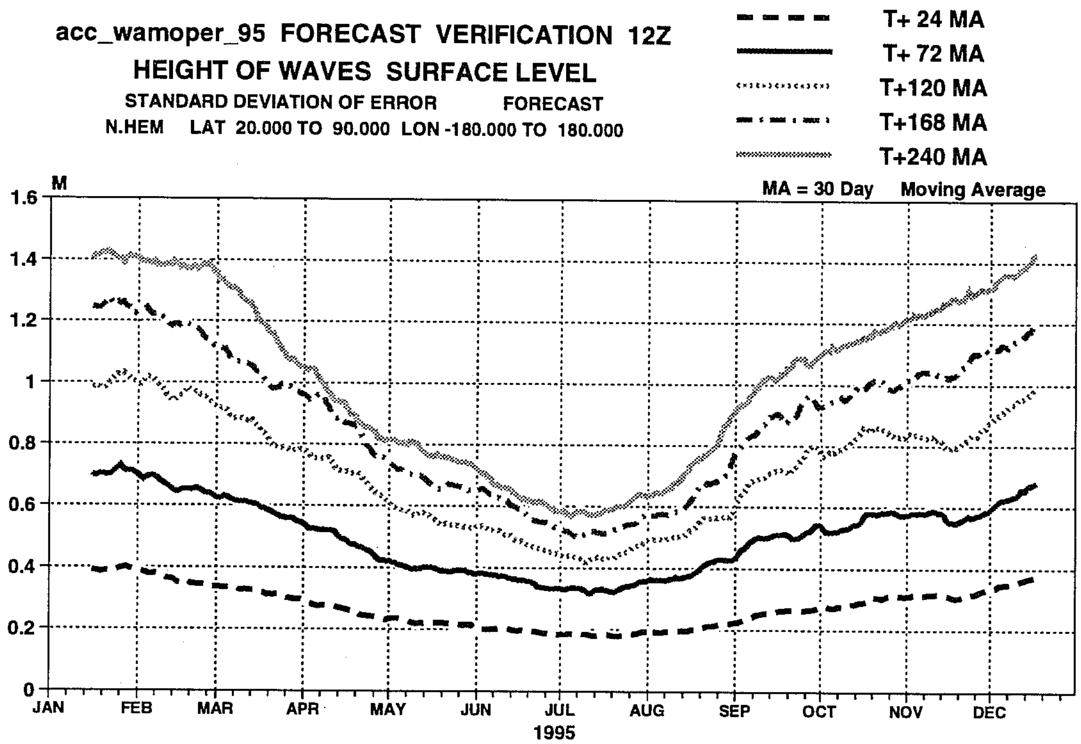


Fig 21 Mean forecast error in wave height for Northern and Southern Hemisphere for the year 1995.



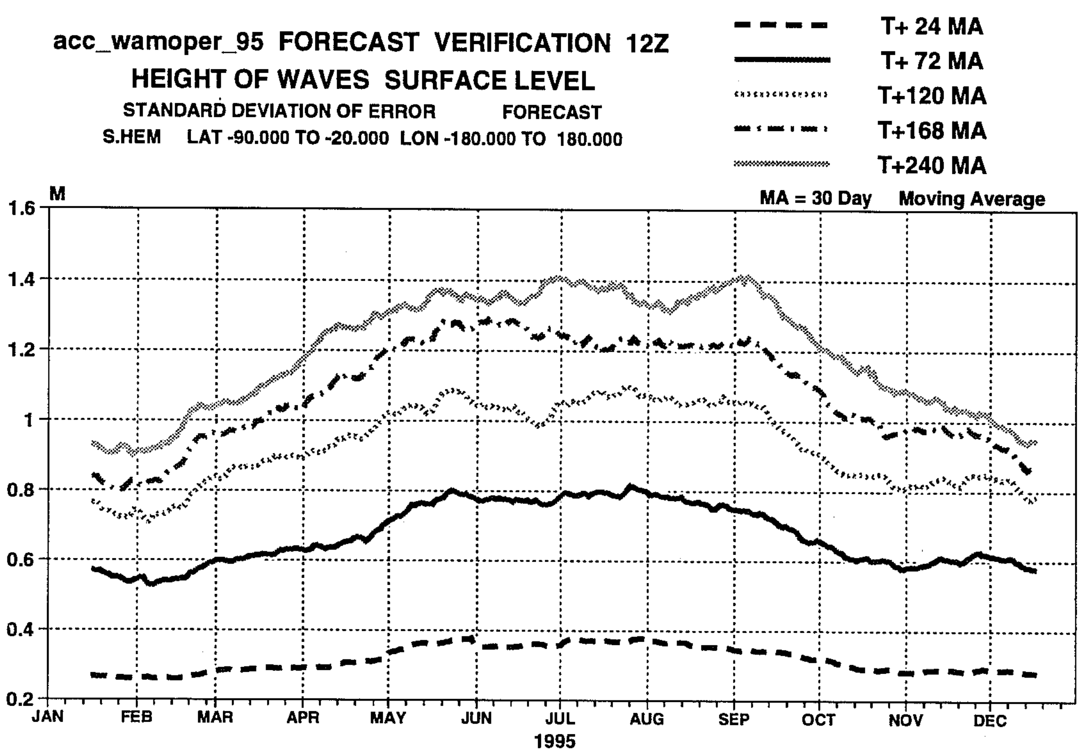
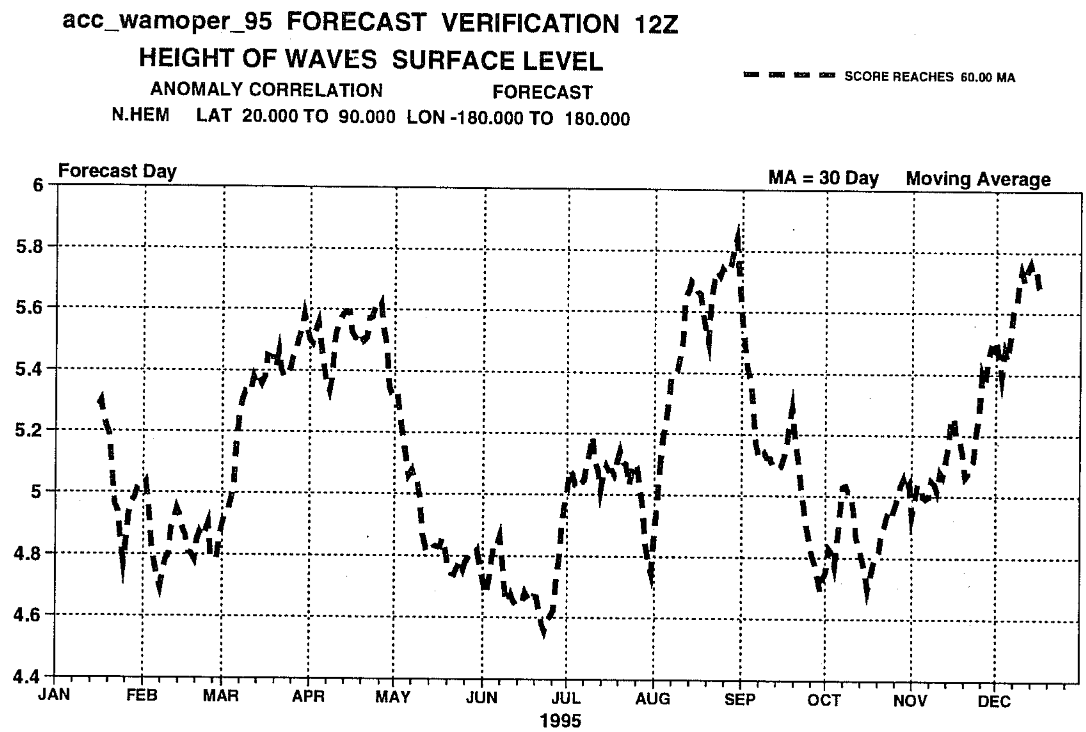


Fig 22 Standard deviation of wave height error for Northern and Southern Hemisphere over the year 1995.



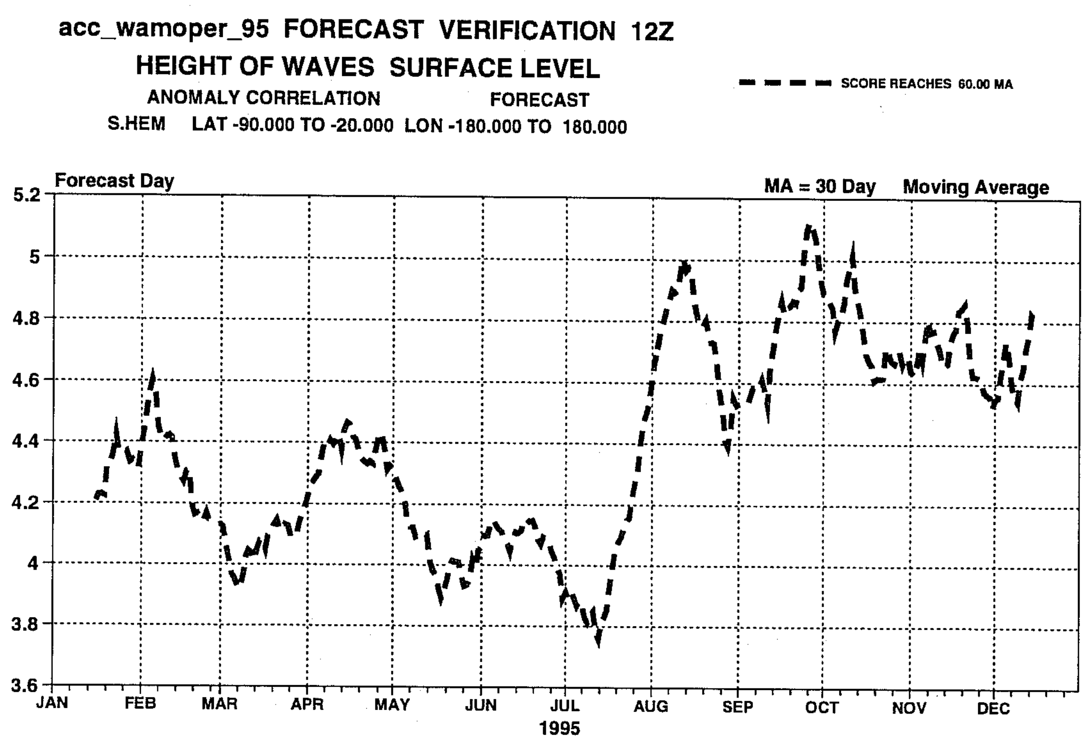
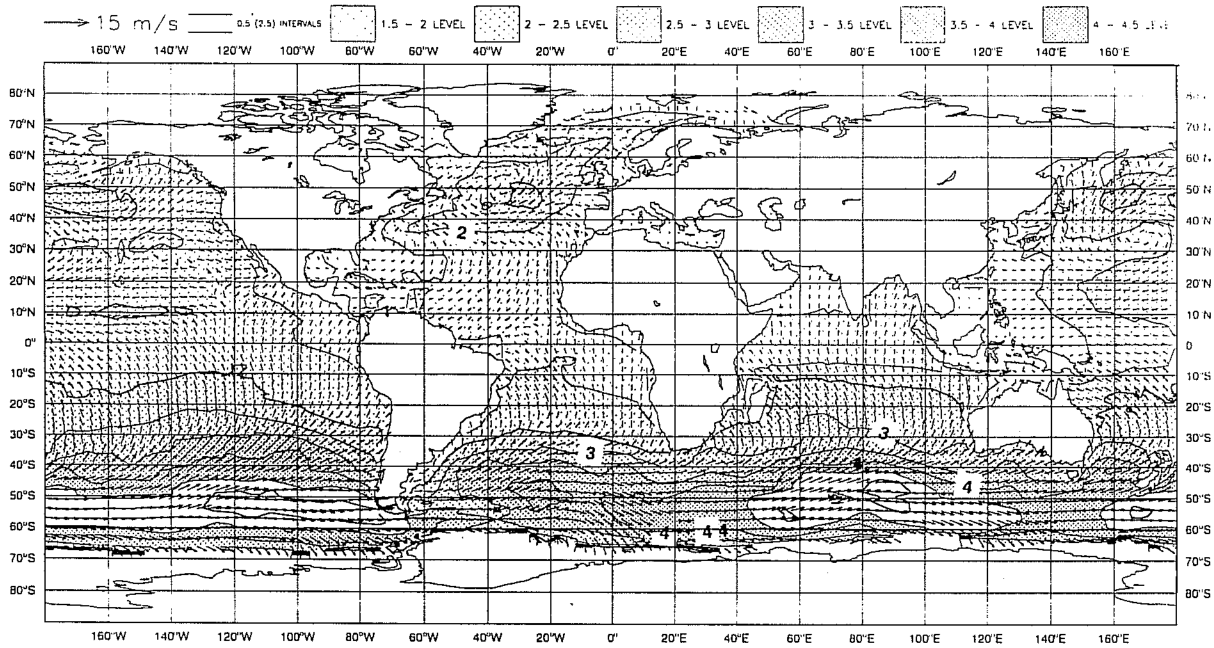


Fig 23 Forecast skill in wave height for Northern and Southern Hemisphere over the year 1995.

MEAN HS 9505 12 (FC168 01)



MEAN HS 9505 12 (AN00 01)

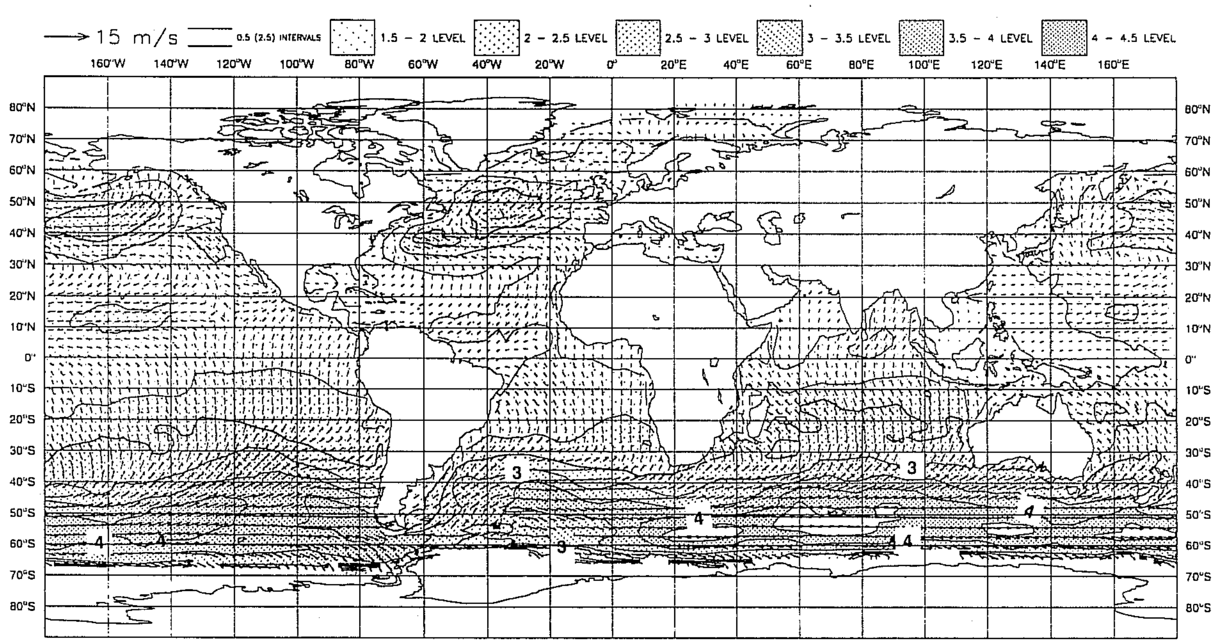
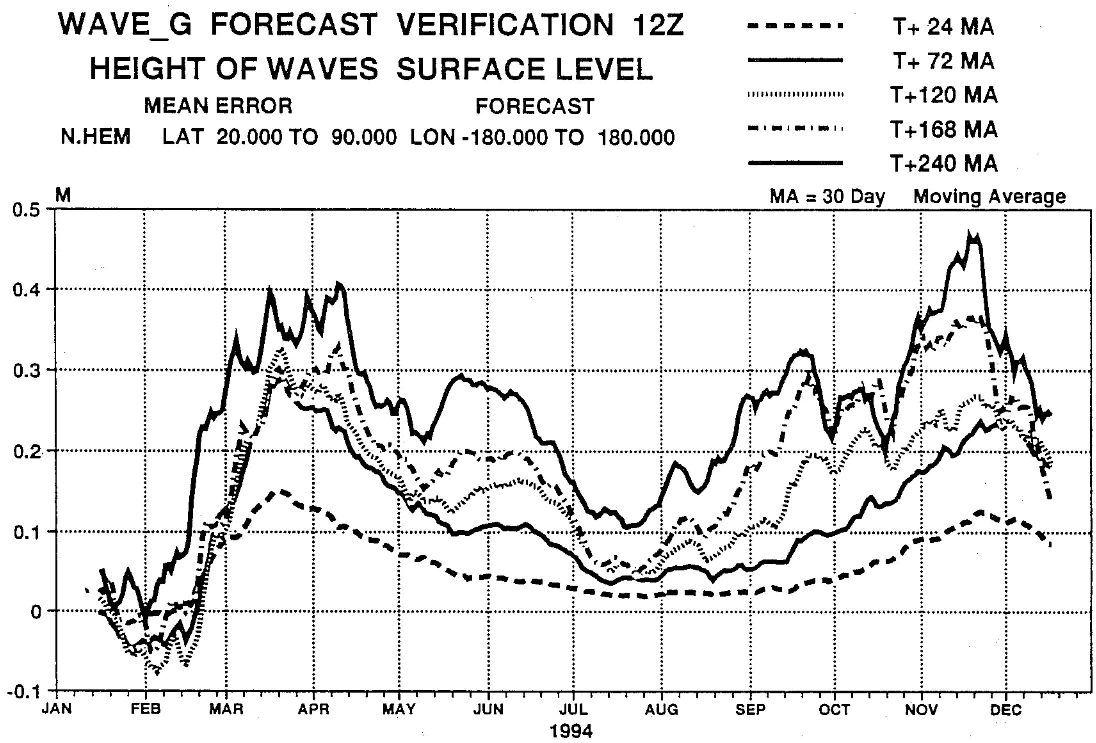


Fig 24 Comparison of monthly mean forecast wave height (day 7) with analysed wave height for May 1995.



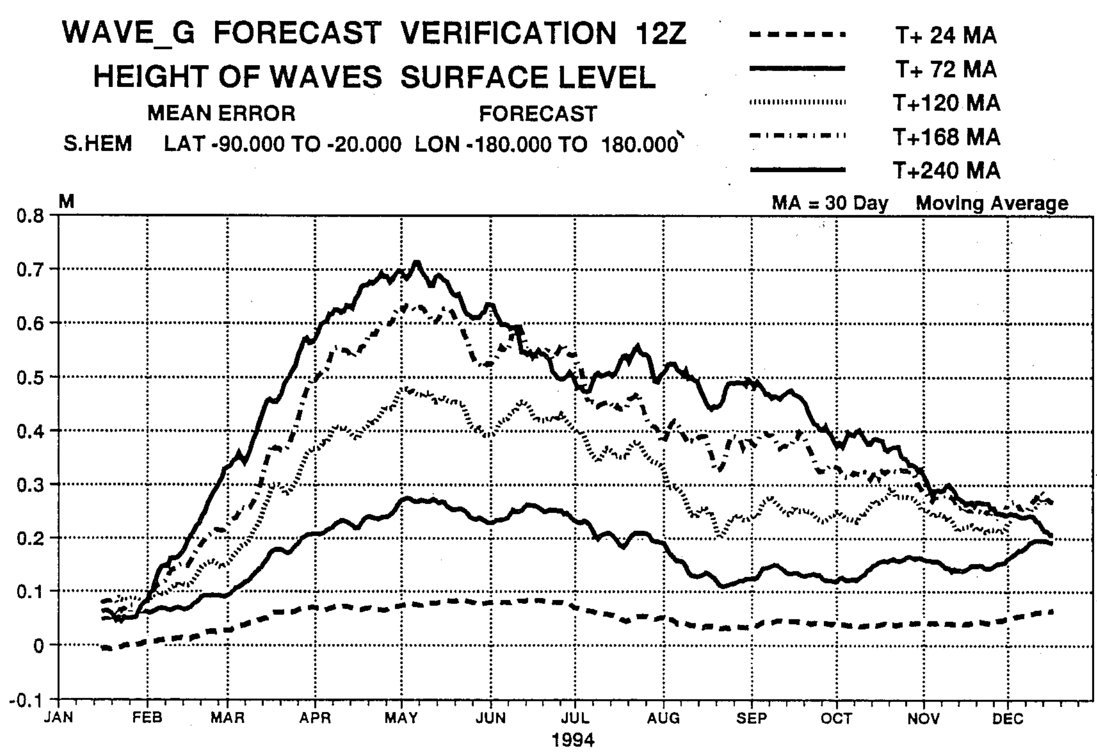
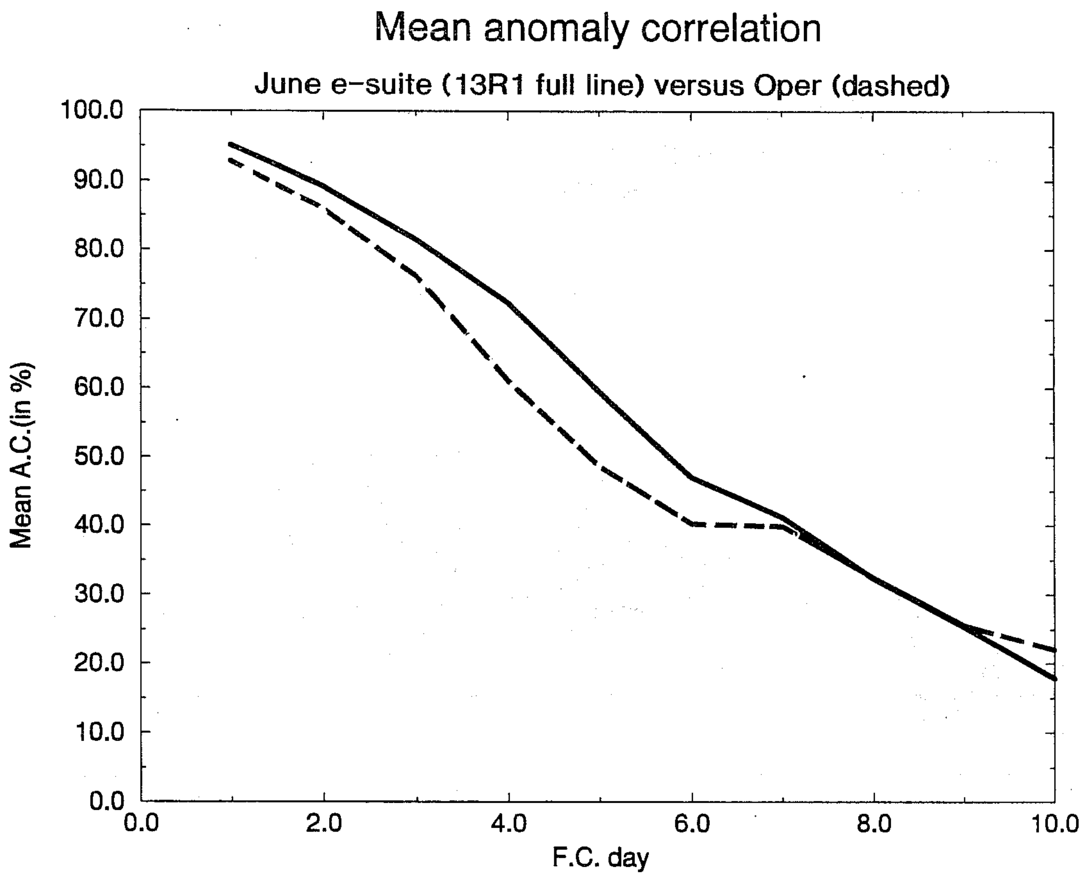


Fig 25 Mean forecast error in wave height for Northern and Southern Hemisphere over the year 1994.



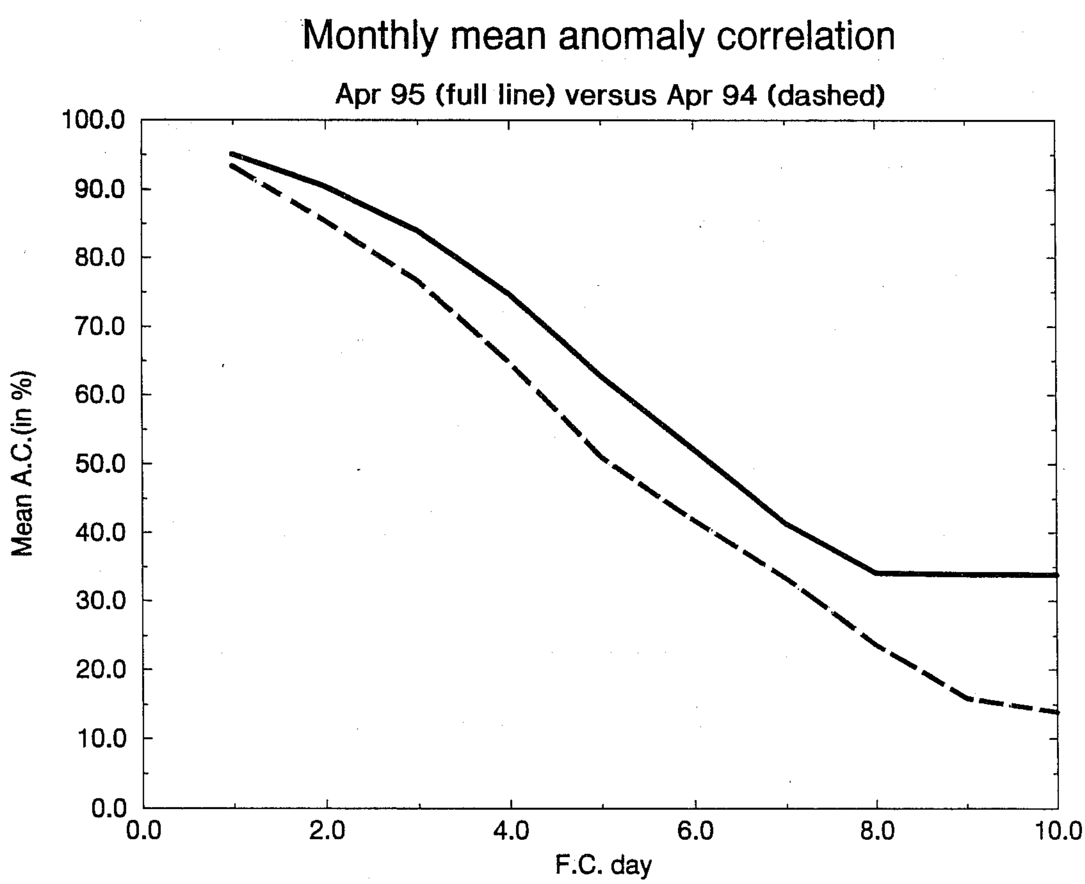
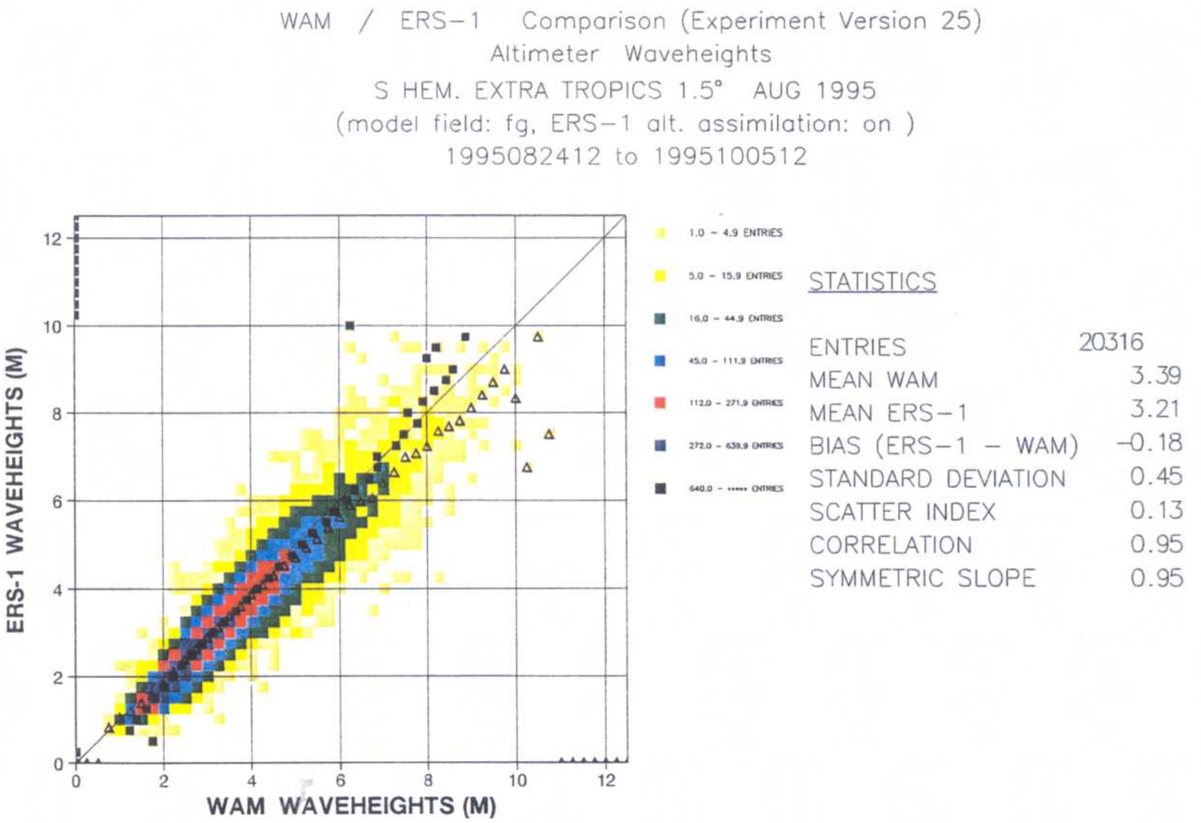


Fig 26 Monthly mean anomaly correlation for June e-suite and operations (upper panel). The lower panel compares anomaly correlation for April 1994 and April 1995. Area is Northern Hemisphere.



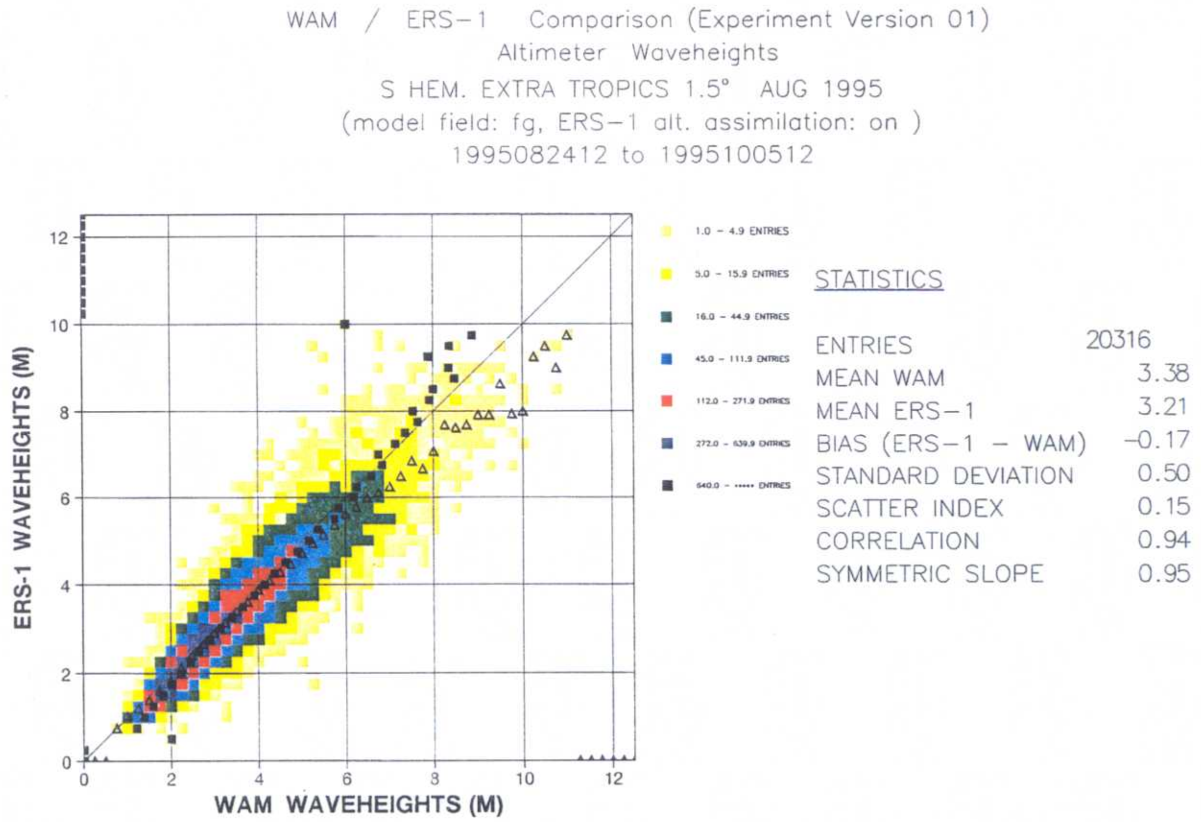


Fig 27 First-guess wave height comparison with altimeter wave height data for 3D-Var e-suite. Upper panel: WAM model as driven by 3D-Var winds. Lower panel: WAM model driven by operational winds. Length of e-suite is 43 days and area is Southern Hemisphere.