Towards a systematic verification of operational wave models

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ABSTRACT

Until recently, there was no formal procedure for exchanging verification statistics for operational wave models. At the end of 1995, a group of wave modellers agreed on a voluntary monthly exchange of wave model data. For comparative purposes, observations are obtained from moored buoys via the GTS. Buoy wind speed and direction, wave height and peak period are compared with model analysis and forecasts from 5 centres running operational wave models. Data files containing time series of model and observed values, as well as summary plots and tables of relevant statistics are gathered and made available to any participating member.

This exchange of basic information has allowed a comparison of the various operational ocean wave forecasting systems (winds and waves) leading to the identification of areas for potential improvements in modelling and prediction of ocean waves.

1. INTRODUCTION

For any operational centre involved in wave prediction, there is a need for monitoring the quality of wave model analysis and forecasts. Most centres have ways to assess the improvement of their models, however prior to the end of 1995, no systematic comparative study of the different wave forecasting system existed.

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Following the 1995 WISE meeting (Wave in Shallow water Environment), a group of wave modellers from different meteorological centres agreed upon exchanging wave model results (analysis and forecasts) at selected locations for which wave and surface wind information can easily be obtained.

The aim of this comparison is to provide each centre with an independent reference which can be used to determine the relative quality of its analysis and forecasts. At this time, five centres are participating in the comparison, the respective implementation of their wave forecasting system is briefly described in section 2. The independent observations are obtained from moored buoys and fixed platforms for which data are made available to the meteorological community via the global telecommunication system (GTS). The necessary data processing of these observations is detailed in section 3. Some of the preliminary results of the comparison are briefly presented in section 4.

2. WAVE MODELS

Table 1: WAVE MODEL DESCRIPTION

	E.C.M.W.F	U.K.M.O	F.N.M.O.C	A.E.S	N.C.E.P
MODEL	WAM 4.0	2nd generation	WAM 4.0	WAM 4.0	WAM 4.0
DOMAIN	global	global	global	Atl. & Pac. North of 25˚N	global
GRID	.5˚x.5 ˚ reduced	0.833˚x1.25˚	1.0˚x1.0˚	1.0˚x1.0˚	2.5˚x2.5˚
Spectral Discretisation	25 frequencies 12 directions	13 frequencies 16 directions	25 frequencies 24 directions	25 frequencies 24 directions	25 frequencies 12 directions
wave physisc	shallow water	deep water	deep water	deep water	deep water
WIND	10 m winds T213	lowest sigma level NWP model	Wind stress T159 NOGAPS	10m winds Atl. regional & Pac. global mod.	lowest sigma level corrected to 10m
WIND INPUT	6 hourly	hourly	3 hourly	3 hourly	3 hourly
Altimeter data	yes	yes	no	no	no
Ice edge	yes	yes	yes	yes	no
Start of forecast	12Z	0 and 12Z	0 and 12Z	0 and 12Z	0 and 12Z
Forecast range	10 days	5 days	6 days	2 days	3 days

In late 1995, the European Centre for Medium range Weather Forecasts (ECMWF), the United Kingdom Meteorological Office (UKMO), the Fleet Numerical Meteorology and Oceanography Center (FNMOC), and the Atmospheric Environment Service (AES) started a project aimed at exchanging model data at given geographical points. They were joined, in May 1996, by the National Centers for

Environmental Prediction (NCEP). Aside from a different atmospheric model used to produce the necessary surface wind forcing, each centre has a different wave model and/or a different implementations of the same model (see table 1). All centres use the WAM model cycle 4 (Komen et al. 1994), except UKMO which has its own second generation wave model (Golding 1983, Holt 1994). AES actually runs two regional models, one for the North Atlantic and one for the North Pacific with a southern boundary at 25° N. The ECMWF wave model is forced by surface winds updated every 6 hours, the other implementation of WAM use winds updated every 3 hours, and the UKMO wave model uses hourly values of surface winds. Both ECMWF (Lionello 1992) and UKMO (Foreman et al. 1994) incorporate ERS altimeter data in their analysis. Finally, only one daily 10 day forecast is issued from ECMWF compared to 2 for the others, albeit with a shorter range (2 to 6 days).

3. WAVE AND WIND DATA

1	21004	South-East of Japan	20	46003	Aleutian Peninsula
2	22001	East China Sea shelf break	21	46004	Canada West Coast, Middle Nomad
3	41001	US East Coast, E Hatteras	22	46005	US North-West Coast, Washington
4	41002	US South-East Coast, S Hatteras	23	46006	US West Coast, SE Papa
5	41006	US East Florida Coast, Daytona	24	46035	Bering Sea
6	41010	US East Florida , Cape Canaveral East	25	46036	Canada West Coast, South Nomad
7	41018	Caribbean Sea	26	46059	US West Coast, California
8	42001	Mid Gulf of Mexico	27	46184	Canada West Coast, North Nomad
9	42003	Eastern Gulf of Mexico	28	51001	Hawaii North West
10	44004	US North East Coast, Hotel	29	51002	Hawaii South West
11	44008	US North-East Coast, Nantucket	30	51003	Hawaii West
12	44011	US North-East Coast, Georges Bank	31	51004	Hawaii South East
13	44137	Newfoundland, East Scotia slope	32	62029	UK Celtic Sea shelf break (K1)
14	44138	Newfoundland, SW Grand Bank	33	62081	UK East Atlantic (K2)
15	44139	Newfoundland, Banquerau	34	62105	UK East Atlantic (K4)
16	44141	Newfoundland, Laurentian Fan	35	62106	UK North-East Atlantic
17	44142	Nova Scotia, Lahave Bank	36	62108	UK East Atlantic (K3)
18	46001	Gulf of Alaska	37	62163	UK Celtic Sea shelf break (Britanny)
19	46002	US West Coast,Oregon	38	63111	North Sea shelf break (Beryl)
			39	64045	UK North-East Atlantic (K5)

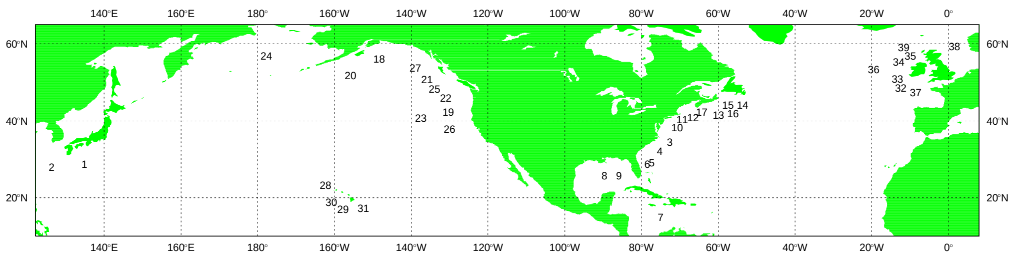


Figure 1: locations of all buoys used in the comparison

Sea state and surface meteorological observations are routinely collected by several national organisations via networks of moored buoys and platforms deployed in their near- and offshore regions (we will use the word buoy for moored buoys or platform as their data are reported under the same WMO header). The geographical coverage of the data is still limited, and at the present wave model resolution, only a small number of all these buoy locations are within the model grid. For this reason, we can only compare the different models at a relatively small number of buoys. These selected buoys are well within the grid of each model, in relatively deep water as most global wave models are deep water models, and have a high rate of data availability.

Figure 1 shows the location of all buoys used for the comparison at one time or the other. The number of buoys has increased over time in an attempt to offer a maximum geographical coverage as well as to replace disabled ones.

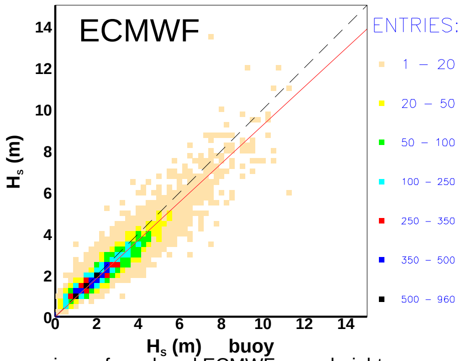
The buoy data are transferred continuously via the GTS to most national meteorological centres and are usally archived locally. It is therefore a simple matter to build collocations between these observations and the corresponding model values interpolated to the buoy locations. A direct comparison between model values and buoy observations is undesirable as measurements may still contain erroneous data points. Furthermore, model and observed quantities represent different time and spatial scales. From the buoy records, monthly time series are reconstructed and used to perform a basic quality check on the data. This quality check procedure will only keep values that are within acceptable physical range (e.g., $0 < Hs < 25m$), will try to detect faulty instruments by removing all constant records of one day long or more, and will remove outliers by looking at the deviation from the mean of each monthly data record and from the deviation from one hourly value to the next. Spatial and temporal time scale are made comparable by averaging the quality checked hourly observations in 4 hour time windows centred around the synoptic times (0, 6, 12, 18Z). No height correction is yet applied to the reported 10m wind measurements, even though buoy anemometers are usually not at 10 meter height. This quality check procedure is run at ECMWF. For completeness, the ECMWF collocation files also include the raw synoptic unaveraged observations. Other centres build similar buoy-model collocations or have agreed to provide corresponding model values at as many buoy locations as possible.

Every month, each participating centre creates files which contain model monthly time series of 10m wind speed and direction, wave height and wave period at the selected buoy locations. It was decided to look at the analysis and forecasts up to day 5 (when available, see table 1). These files are transferred via FTP to the UKMO server, where they are combined with the observations processed by ECMWF.

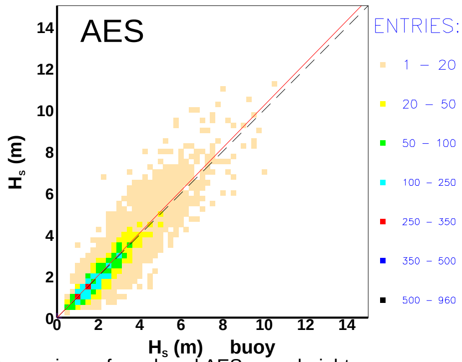
4. DATA PRODUCT

It is up to each individual centre and any interested individual to retrieve the combined files from the UKMO server. The statistical analysis of the data is left to each centre which may decide to look at it from their own perspective. However, ECMWF has a semi-automatic procedure to analyse the monthly results from which tables and summary graphs are produced. These tables and graphs are also available every month from the UKMO server. The same software can be used to look at longer periods.

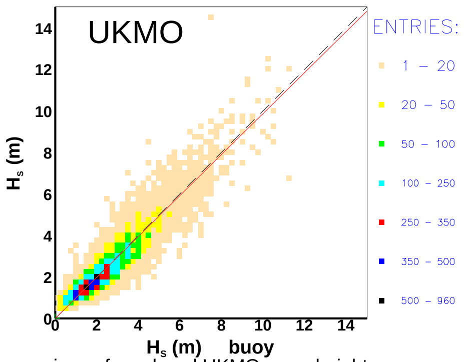
For example, figure 2a shows scatter diagrams of the collocation between all buoy and model wave heights for the 12Z analysis for the period December 1995 to November 1997. The corresponding statistics are summarised in table 2. The day 2 forecasts for the same period are displayed in figure 2b and table 3. Note that for these plots, we only considered collocation points which were common to the 3 centres which issue forecast for at least 5 days from 12Z (i.e. ECMWF, UKMO, FNMOC).



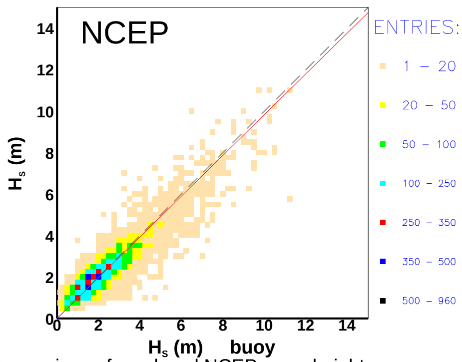
Comparison of analysed ECMWF wave height with averaged buoy data.



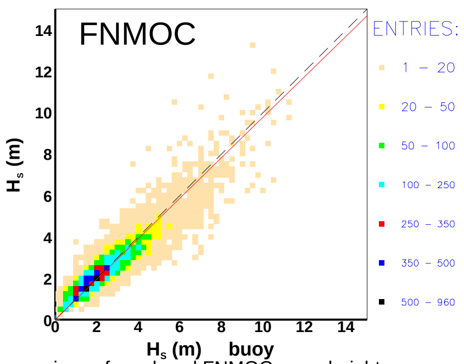
Comparison of analysed AES wave height with averaged buoy data.



Comparison of analysed UKMO wave height with averaged buoy data.



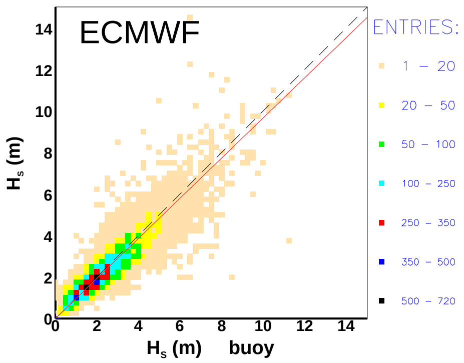
Comparison of analysed NCEP wave height with averaged buoy data.



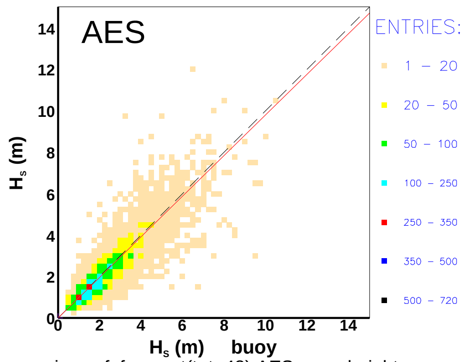
Comparison of analysed FNMOC wave height with averaged buoy data.

Figure 2a: Scatter diagram for 12Z analysed wave heights with respect to averaged buoy data (see text) from December 1995 to November 1997. Only buoys for which ECMWF, UKMO and FNMOC model data were available were used to produce the statistics. Buoys used are (see figure 1), 1, 2, 3, 4, 5, 8, 9, 10, 11, 18, 19, 20, 21 22, 23, 24, 25, 27, 28, 29, 30, 31, 32, 33, 34, 36, 38. Note that AES results are limited to buoys along the American coasts and NCEP statistics started in May 1996.

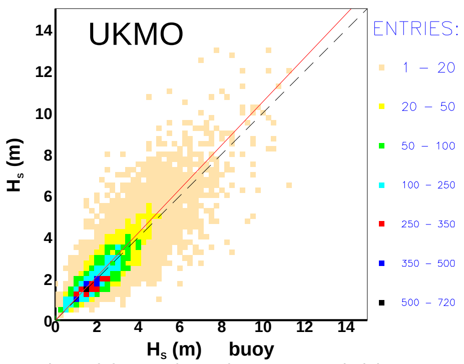
One clearly sees the degradation of the quality of the forecasts with respect to the analysis. Similar scatter diagrams are also generated for the 10m wind speed, and show an even faster degradation of the forecast quality. The slower degradation of the wave forecasts can be attributed to the presence of swell which is generated earlier in the forecast with winds of better quality (Janssen et al. 1997). The typical evolution of the forecast error in function of the forecast range is presented in figure 3 for a summer and a winter month. Only buoy data common to ECMWF, UKMO, FNMOC were considered in the collocation statistics. AES statistics are produced only with buoys along the continental US and Canada (statistics per region are discussed below). NCEP has slightly less data points and its forecasts only extend to day 3. Note also that NCEP statistics for August 1997 (figure 3b) reflect an operational failure in their wave analysis. This problem was apparently present for several months as discussed in figure 8.



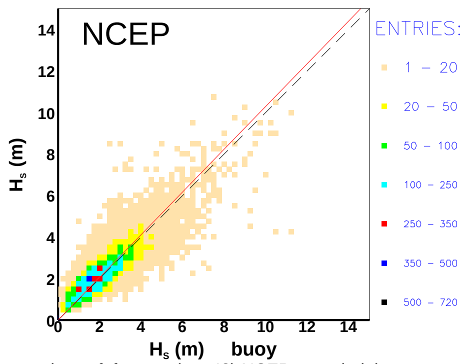
Comparison of forecast(t=t+48) ECMWF wave height with averaged buoy data.



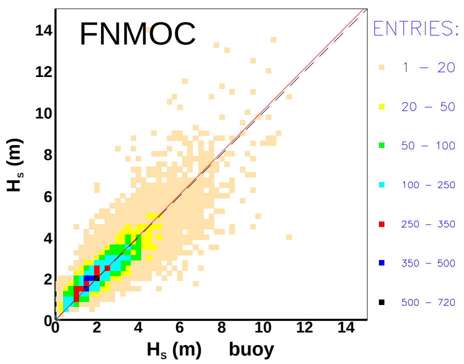
Comparison of forecast(t=t+48) AES wave height with averaged buoy data.



Comparison of forecast(t=t+48) UKMO wave height with averaged buoy data.



Comparison of forecast(t=t+48) NCEP wave height with averaged buoy data.



Comparison of forecast(t=t+48) FNMOC wave height with averaged buoy data.

Figure 2b: Same as figure 2a but for the day 2 forecasts started from 12Z analysis.

Table 2: Analysed wave height statistics

t+000	Buoys	ECMWF	UKMO	FNMOC	AES	NCEP
number of entries	15569	15569	15569	15569	7489	11900
Mean (m)	2.41	2.27	2.39	2.43	2.44	2.29
Standard deviation (m)	1.34	1.16	1.31	1.17	1.49	1.15
Bias (m)	----	-0.14	-0.02	0.02	-0.02	0.03
R.M.S.E. (m)	----	0.47	0.52	0.51	0.57	0.53
Scatter index	----	0.18	0.21	0.21	0.23	0.24
symmetric slope	----	0.93	0.99	0.98	1.02	0.98

Table 3: Day 2 forecast wave height statistics for forecasts started at 12Z.

t+048	Buoys	ECMWF	UKMO	FNMOC	AES	NCEP
number of entries	15547	15547	15547	15547	7029	11070
Mean (m)	2.41	2.35	2.52	2.50	2.31	2.37
Standard deviation (m)	1.34	1.34	1.46	1.25	1.39	1.17
Bias (m)	----	-0.06	0.11	0.08	-0.10	0.13
R.M.S.E. (m)	----	0.59	0.75	0.68	0.68	0.64
Scatter index	----	0.24	0.31	0.28	0.28	0.28
symmetric slope	----	0.97	1.05	1.01	0.98	1.03

Table 2 & 3 :Analysed and day 2 forecast wave height statistics from December 1995 to November 1997. Negative bias denotes lower model values with respect to buoy observations. The scatter index is defined as the standard deviation of the error normalised by the observation mean. The symmetric slope refers to the ratio of the sum of the squares of the model results with the sum of the squares of the observations.

The time series of the monthly wave height RMSE for the analysis as well as day 2 and 4 forecasts are presented in figure 4 for ECMWF, UKMO, FNMOC. They clearly show the seasonal variation of the error, as well as the seasonal rate of degradation of the forecasts. Larger errors occur in winter when waves are higher. The 3 centres have a comparable RMSE for the winter analysis, whereas, in the summer, ECMWF has clearly smaller errors. On average the ECMWF forecast error has a slower growth than the other centres.

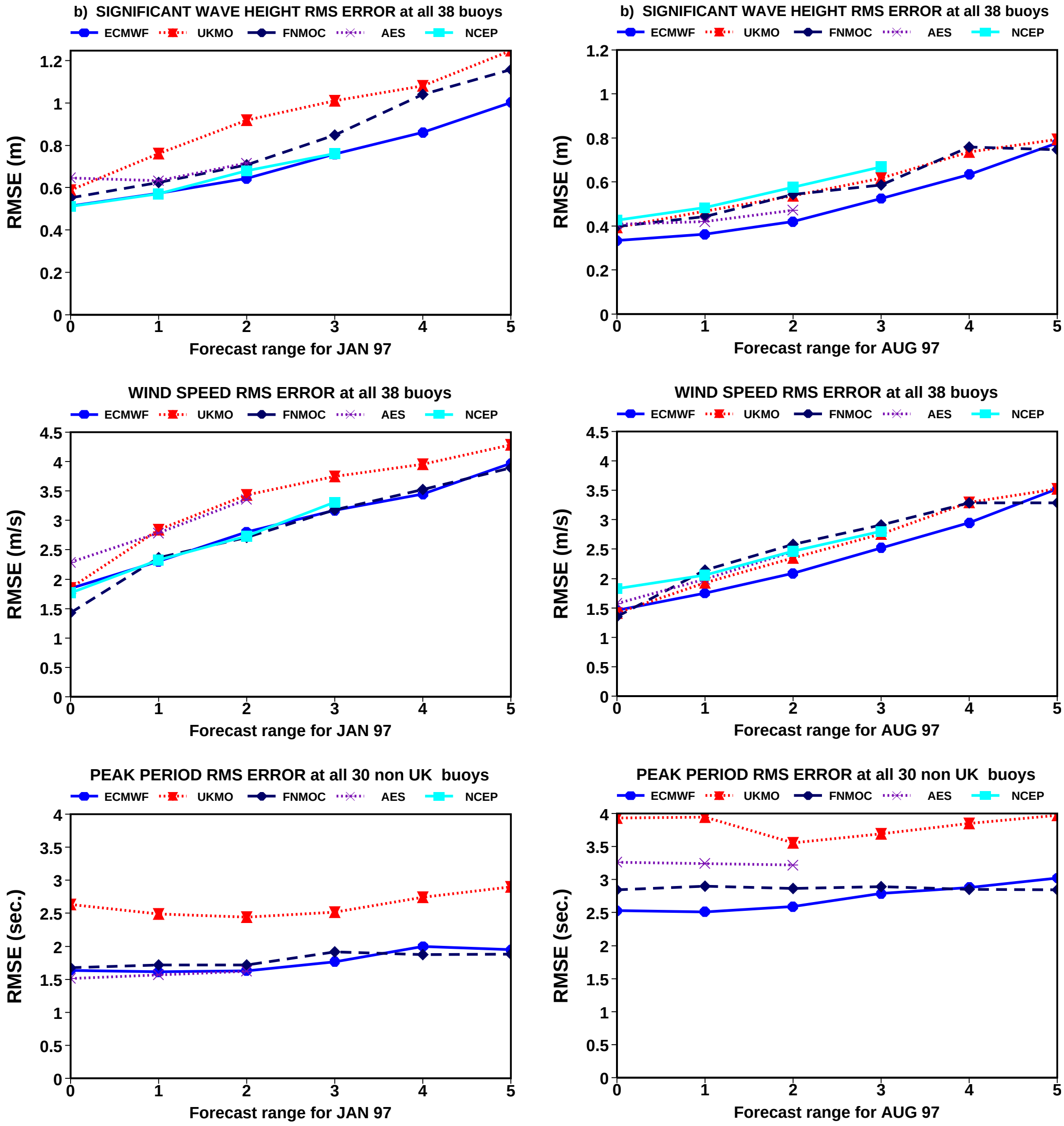


Figure 3: Root mean square error for model wave heights, 10m wind speeds and peak periods compared to all buoy observations which are common to ECMWF, UKMO, FNMOC. (a) January 1997. (b) August 1997. Peak periods are not reported by buoys from the UKMO network around the British Isles. Similarly, NCEP does not provide peak periods.

As expected, a similar pattern can be found in figure 5 for the monthly evolution of the 10m wind speed RMSE. Note however, that the wind observations are included in the data used by atmospheric model assimilation. The agreement of the analysed winds with the observation might only reflect on how well the assimilation scheme fits the observations. It is interesting to note that the best analysis fit does not necessarily lead to a better forecast.

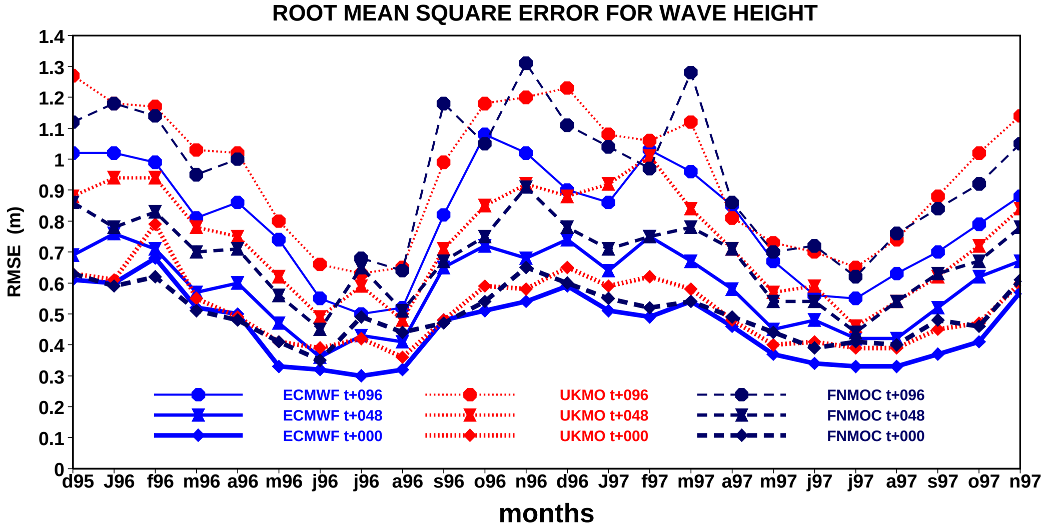


Figure 4: Monthly time series of analysis and forecast root mean square error for model wave height when compared to buoy observations which are common to ECMWF (solid lines), UKMO (dotted lines), FNMOC (dashed lines). 12Z analysis (diamons, t+000), day2 (diabolo, t+048), and day 4 (circles, t+096) forecasts are presented from December 1995 to November 1997. Note that some FNMOC day4 forecast data are missing.

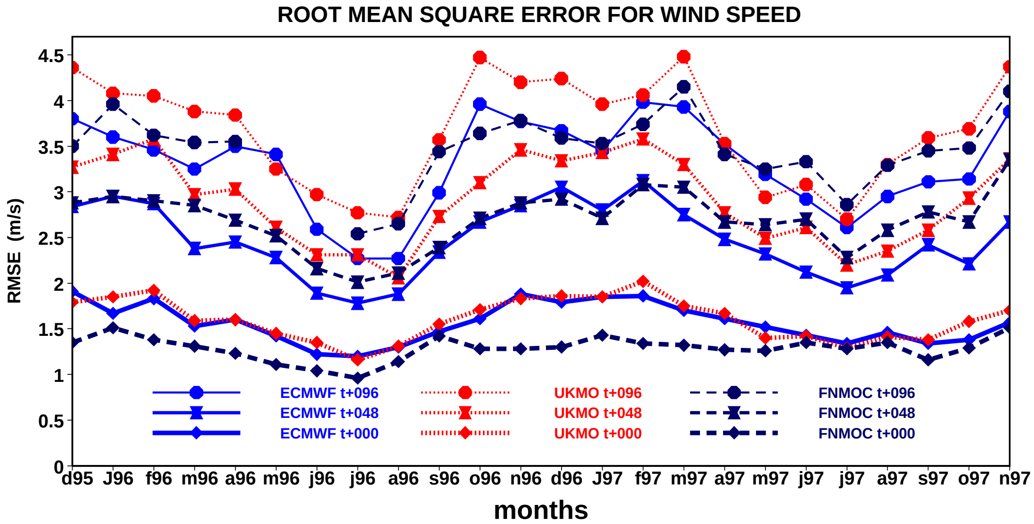


Figure 5: same as figure 4 but for 10m wind speed.

Buoy measurements of the period at the wave spectral peak (peak period) are harder to compare to model estimates because of the different uncertainties in its determination. For example the UKMO model has only 13 frequency components, and the method for calculating the peak period is simply to choose the component with maximum energy. In contrast, the FNMOC model fits a spline to the spectrum before calculating the peak period. The other models are also limited by the model frequency resolution (25 bins). Nevertheless, it is interesting to note that peak period errors are largest during the northern hemisphere summer (figure 6) and do not increase much in the forecasts. This increase in error may possibly be related to swell which has propagated over large distances from southern hemisphere storms.

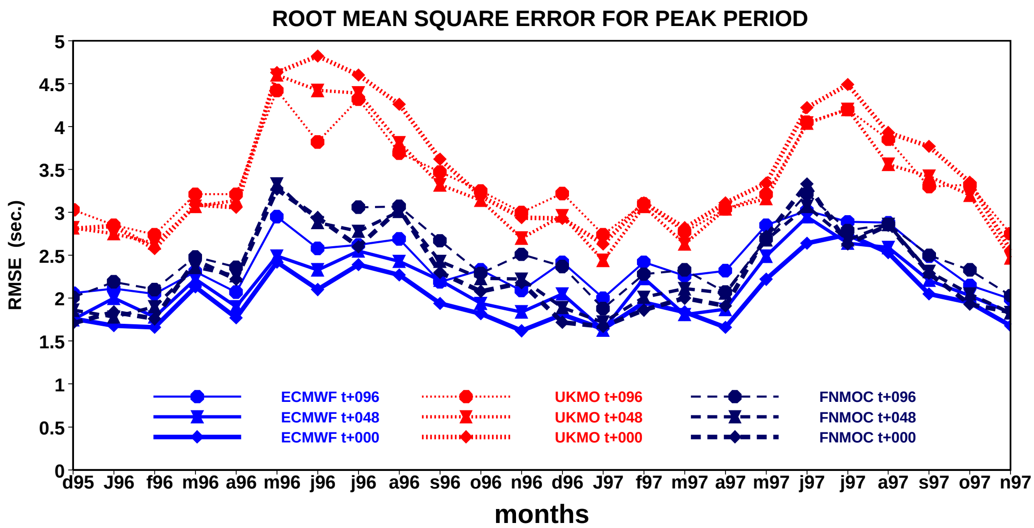


Figure 6: same as figure 4 but for peak period.

Generally, as indicated in figure 7, wave height biases (model - observation) tend to become more positive with forecast range. ECMWF wave height analysis has the largest negative bias. Interestingly, the sharp reduction in bias between April and May 1996 occurred as ECMWF and UKMO switched from using ERS-1 to ERS-2 altimeter data in their respective wave analysis (see also Holt 1997). It is believed that ERS-1 wave height measurements were generally too low, especially over the tropical areas, resulting in an underestimation of swell energy in the analysis (Janssen et al. 1997).

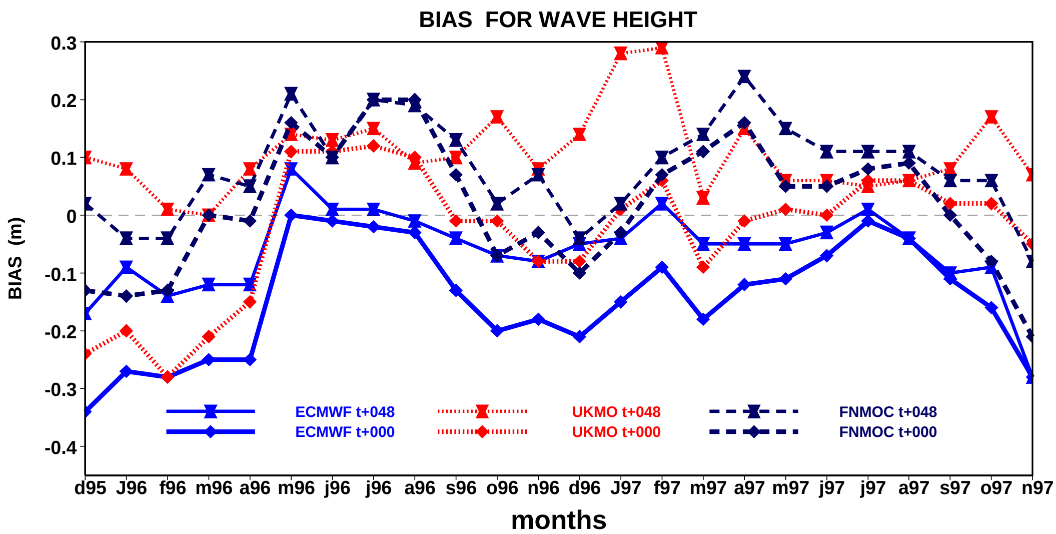


Figure 7: Monthly time series of analysis and day 2 forecast bias for model wave height when compared to buoy observations which are common to ECMWF, UKMO, FNMOC (model - obs). The time series run from December 1995 to November 1997.

All statistics presented so far were for all buoys combined, the same can be done by selecting a subset of buoys which are in a region with similar climatological conditions. There are quite some regional differences in analysis performance, as shown in all figures 8. Only buoy data common to all global WAM users are considered for the statistical collocations. Generally speaking, wave models perform relatively better at the eastern side of the ocean basin (8b,f) than on the western side (8a,d,e). In particular, by comparing figure 8a and 8b, it is clear that the ECMWF wave height for the East Coast of the US is not as good as the West Coast in absolute terms as well as with respect to the other centers. Looking at a typical time series for winds and waves for the East Coast of the US and Canada (figure 9), it is clear that the ECMWF model has some difficulty in reproducing the wave height peaks. Such behaviour is much less pronounced for all other regions. Based on this information, ECMWF is currently investigating the possible reason for such discrepancy. The better performance of the other WAM models would seem to point to either the winds used by ECMWF or to the implementation of WAM at ECMWF.

The performance of the AES model can also be compared with the other centres (figure 8a,b,e). Note that in late 1995, AES were still tuning their models, this comparison provided them with an independent tool to assess their progress (figure 8b). The AES wave model statistics are also used to assess the impact of the wind forcing by the different AES atmospheric models over the Pacific and the Atlantic oceans. For example, figures 8a and 8e indicate that the AES wave model produced some what higher wave height scatter index for the Canadian and US East Coast after February 1997. This increase can be linked to the introduction of a new atmospheric model (Global Multiscale Environmental) at AES for the Atlantic region. It is indicated by the degradations of the wind statistics at the buoy locations (not shown).

This comparison was also very helpful in pointing out the operational problem encountered by NCEP in which the model run had to be interrupted and restarted from a cold start in which all knowledge of swell is absent. This had an adverse impact on the wave analysis, especially for regions which are known to be dominated by swell (Hawaii, US West Coast, figure 8c,b).

Finally, the comparison of the model results with buoy data off Japan, illustrated the current inability of most operational weather centres to analyse intensity of tropical cyclones. Consequently, the resulting wave analysis of most centres is relatively poor for months in which one or more of those events take place (figure 8a,d). For example, figure 10 shows how all centres did not resolve the eye of Typhoon Rosie off the coast of Japan in July 1997. It is interesting to notice that in the case of typhoon Rosie, all model winds are similar and the wave models responded in a similar fashion to their respective winds. This contrasts with the behaviour of the ECMWF wave model for the American east coast where local winds show similar characteristics for most models but not for waves (figure 9).

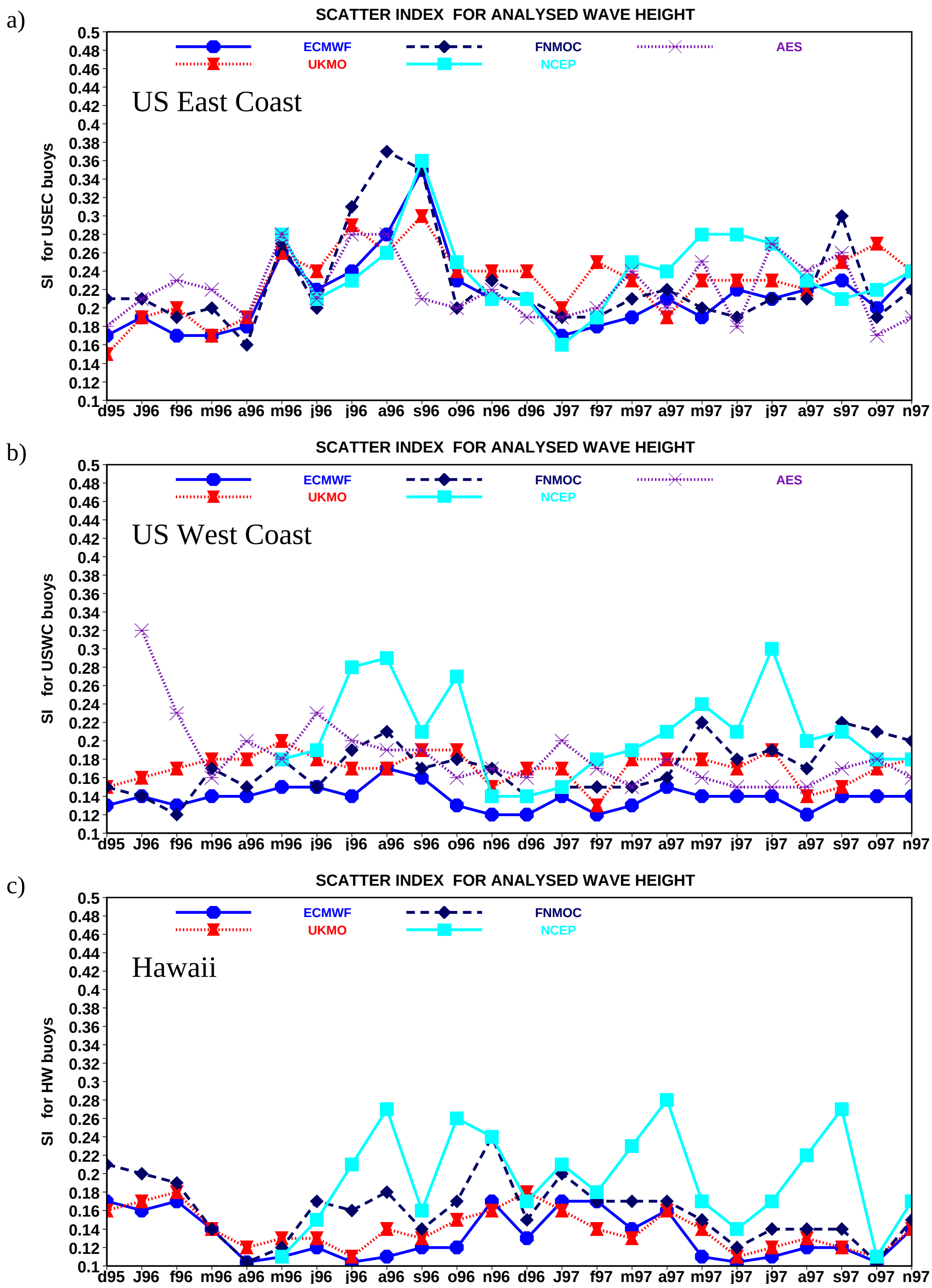
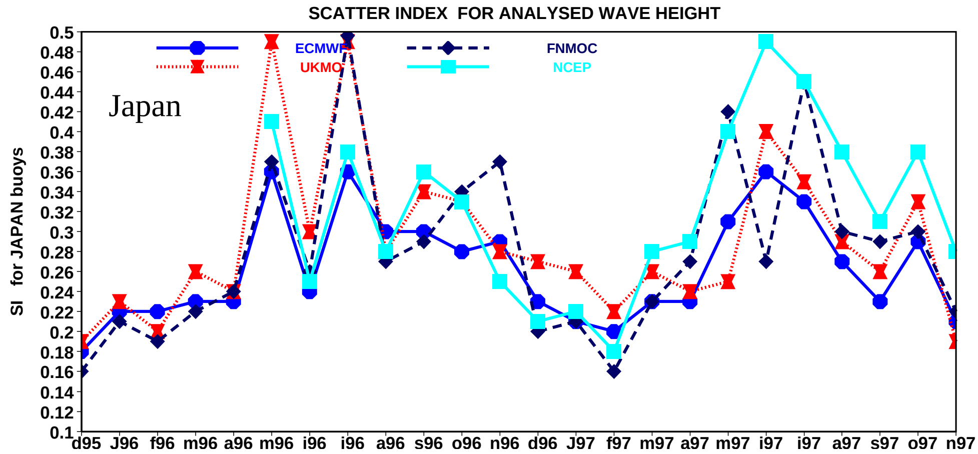


Figure 8: Monthly time series of analysis scatter index (normalised standard deviation of error) for model wave heights compared to buoy observations. Statistics are produced for groups of buoys located in given areas (figure 1): (a) US East Coast (3, 4, 5, 6, 10, 11, 12), (b) US West Coast (19, 22, 23, 25, 26), (b) Hawaii (28, 29, 30, 31), (d) Japan (1,2), (e) Canadian East Coast (13, 14, 15, 16, 17) and (f) west of the British Isles (32, 33, 34, 35, 36, 37, 39). Statistics were produced from December 1995 to November 1997 by only using collocations for which ECMWF, FNMOC, and NCEP have provided analysis data.

d)



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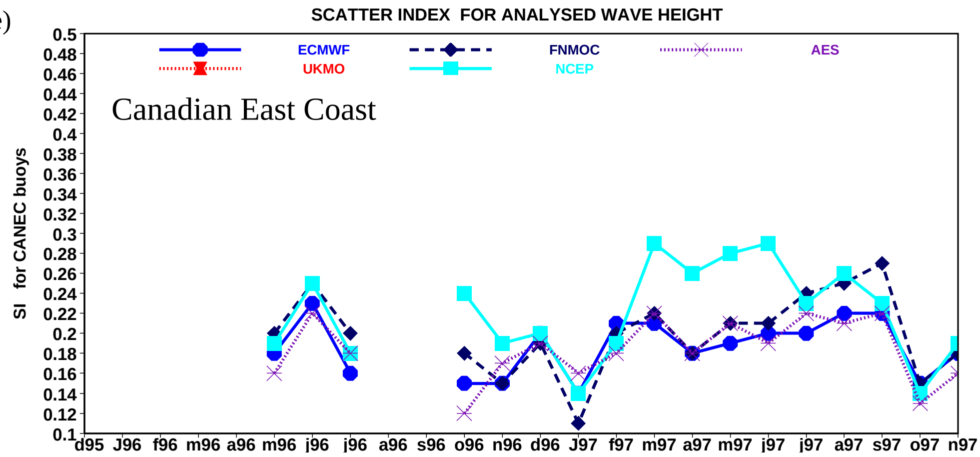

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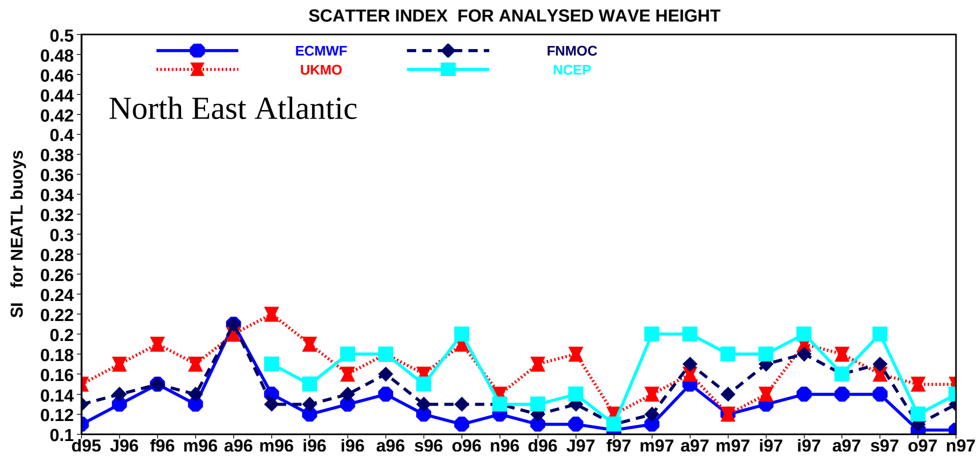

Figure 8: continued

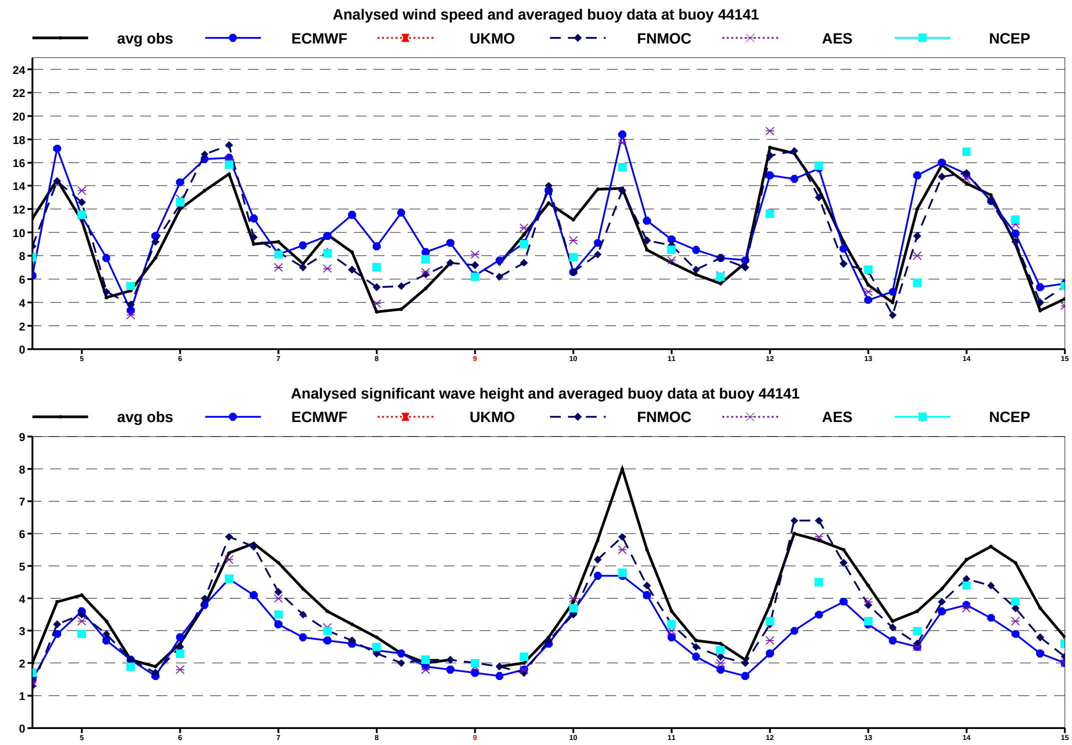

Figure 9:Time series of 10m wind speed (m/s) and wave height (m) at buoy 44141 south of Newfoundland from the 4th to the 15th of February 1997. There are no data from UKMO.

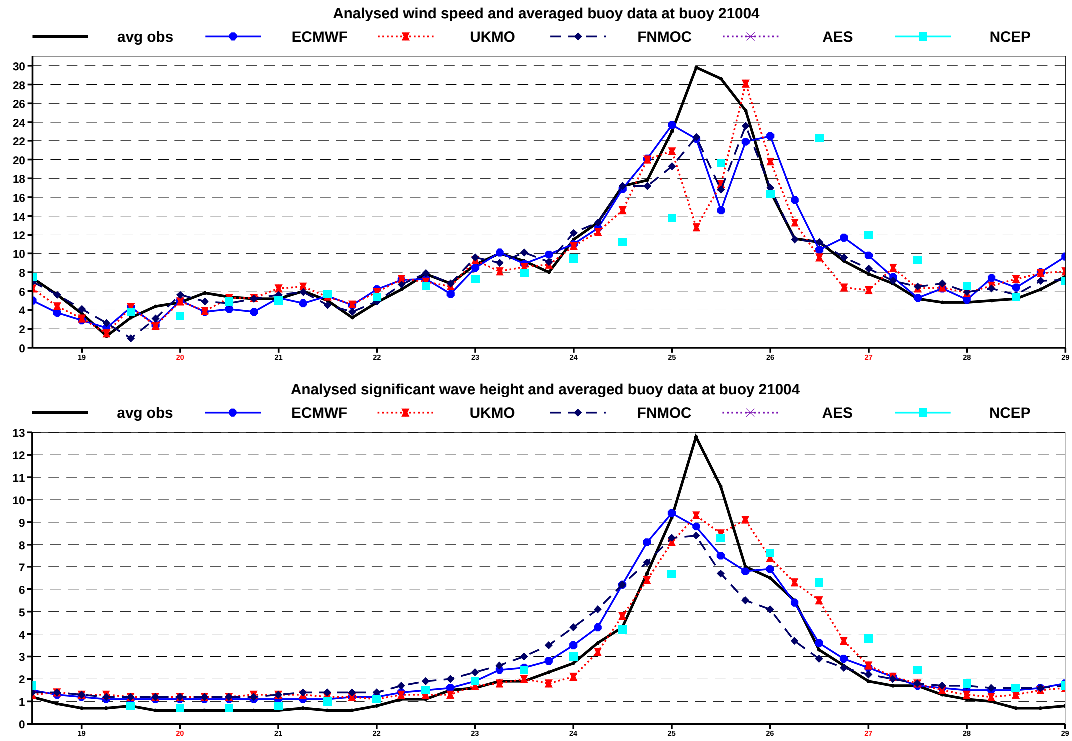

Figure 10:Time series of 10m wind speed (m/s) and wave height (m) at buoy 21004 off the south eastern coast of Japan from the 18th to the 29th of July 1997. There are no data from AES.

5. CONCLUSIONS

Every month, wave model analysis and forecasts from the participating centres are compared with buoy observations at selected locations. The buoy data are obtained from the GTS and a basic quality control and averaging procedure is used to produce observations which can be compared to the equivalent model values. The resulting comparison serves as an additional validation tool for the operational wave forecasting system of each collaborating centre (winds and waves). The comparison provides an independent reference for operational changes or problems which could otherwise go unnoticed. This information is also being used to identify wave modelling shortcomings and ultimately it should lead to improvements of future wave models.

It is believed that centres engaged in wave forecasting will benefit from this activity in the same way as weather centres benefit from the exchange of forecast verification scores. In that matter, everyone involved in the project knows the actual skill of the model forecasts, and sees what kind of errors should be tackled first.

The wave buoy data set is not included in the operational wave data assimilation scheme of any centre, it therefore constitutes an independent reference. Its geographical coverage is however very limited. In the future, the collaboration could be extended to include other types of wave data (satellites) as well as model forecast scores verified against their own analysis as it is done with numerical weather prediction models. In that case, greater geographical coverage will be gained at the cost of totally independent data.

We also hope that by making the information widely available, it will stimulate a larger wave data exchange with organisations which collect wave data but do not make them available on GTS.

6. REFERENCES

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