Short Range Forecasting Division
Technical Report No. 26

A re-calibration of the Wave Model

by

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UKMO Wave Model
Re-calibration 1992

CONTENTS

1.0 Introduction

Recent work with the single gridpoint version of the UKMO wave model (Holt and Hall, 1992) raised several questions about the wave growth and equilibrium windsea characteristics of the model. Further questions arose during testing of the revised windsea/swell separation developed following the findings of the UKMO/WAM intercomparison (Gunther and Holt, 1992). This note investigates further the shortcomings of the UKMO wave model calibration, identifies some of the problems and proposes solutions to them.

Previous recalibration of the wave model, carried out by Thomas and Ephraums (1986) when developing the 'new' physics of 1986, was intended primarily to correct deficiencies in model performance in the North Sea. At that time there was no global wave model. The global wave model with the 1987 physics was assessed by Stratton (1987), who used a dissipation coefficient 5.0E-5, slightly greater than that suggested by Thomas and Ephraums (1986). Objective verification of model performance in that study was clouded by an error in the wind program, nevertheless the revised physics was implemented operationally in the global model. This study is therefore the first attempt to overhaul the wave model since the introduction of the global 1987 model.

The study falls into several parts : Section 2 discusses the equilibrium wave heights attained by the model for various windspeeds; Section 3 discusses the rate of growth of wave energy in the model and Section 4 describes an error discovered in the transition from wind-sea to swell in the case of falling windspeeds. The November 1988 case study is rerun using the revised wave model, results are discussed in Section 5. The costs and benefits of increasing the frequency range and resolution in the revised model are covered in Section 6, for both the experimental model and the November 1988 global case study. Finally Section 7 gives recommendations for operational implementation of the revised wave model.

2.0 Equilibrium wave heights.

Observations show that for a steady wind waves reach a limiting height, after which the wind input at higher frequencies is balanced by nonlinear transfer to lower frequencies and by dissipation due to whitecapping and other mechanisms. The net energy input becomes zero at all frequencies. Pierson and Moskowitz (1964) described the observed equilibrium spectra as a function of windspeed. Expressions for the peak frequency (Fpm) of the equilibrium spectrum, and for the total energy of the spectrum (Epm) and hence for the equilibrium wave height Hpm may be written as :

$$Fpm = 0.14g/U$$
$$Epm = [U/(1.4g)]^4 \qquad \text{Eqns 1.0}$$
$$Hpm = 4\sqrt{Epm}$$

where U is the windspeed from the lowest atmosphere model sigma level, here assumed to be at a height of 19.5m (Stratton, Wave Model Documentation Paper 6)

Wave models are generally calibrated so that the windsea energy at equilibrium does not exceed Epm for the windspeed. Further work (JONSWAP 1973) refined the spectral shapes for growing windseas, making them more peaked at the peak frequency, but the equilibrium wave height and energy remained limited by the PM value.

The UKMO wave model in its current form (1987-1992) does not achieve the PM limit for wave height for any windspeed. Figure 1a shows the difference between Hpm and model equilibrium height for a range of windspeeds, and Figure 1b shows the actual values of PM and model wave heights. It is clear that waves resulting from windspeeds of 6,7 and 8 m/s are not correctly represented in the wave model, and further that certain other windspeeds are poorly represented, eg 15m/s, 17m/s, 20m/s, 23m/s, 24m/s, 27m/s and 28m/s. However the shortfall at higher windspeeds is relatively unimportant, as for these seas to be generated the wind must blow steadily for several days over a fetch of several thousand kilometers. What is important is that the growth rates for these windspeeds should be correct, so that the seas developed by rapidly turning strong winds reach the correct height. The growth rates produced by the model are discussed in Section 3. It is important that windseas can achieve the PM limit at lower windspeeds where the duration and fetch requirements can be met, for example by windspeeds of 7-15m/s in the Trade Wind areas.

Wave growth in the UKMO wave model is accounted for by two terms. Wave growth from a state of rest is initiated with a linear term added to the highest model frequency component, following Hasselmann et al (1976). Wave growth is continued with an exponential form following Snyder et al (1981). Since 1987 the wave model has used a lookup table to reshape the growing windsea spectrum to a prescribed JONSWAP spectrum, parametrising the transfer of wave energy due to nonlinear wave-wave interactions. This lookup table was introduced to reduce the cost of running the model. Investigation shows that for windspeeds of 6,7 and 8 m/s the energy input by the linear growth term at the first step is such that the peak frequency of the reshaped spectrum was outside the frequency range covered by the lookup table. Consequently the model did not reshape the spectra for these windspeeds, and all the energy remained in the highest frequency bin in the model.

As the dissipation coefficient was reduced for a windspeed of 15m/s in the experimental model, there was a sudden step change in the equilibrium wave height (Figure 2). This could be explained because the source term for dissipation is a function of the spectral shape, as is the input source term to a lesser extent. Reducing dissipation allowed the energy to increase such that the next entry in the spectral lookup table was reached, and this allowed an equilibrium with a higher energy level. Altering the dissipation coefficient may also alter the growth rate of a developing windsea. Therefore the first step taken in recalibrating the wave model was to revise the lookup table, so that realistic equilibrium wave heights could be reached for the full range of windspeeds.

2.1 Revised lookup table.

2.1.1 Increased resolution of spectral peak frequency

The spectral shape lookup table in use in the model since 1987 has a maximum frequency of 0.227 Hz, the next to top frequency bin of the wave model. As described above this is too low to resolve the spectra for growing seas from 6, 7 and 8 m/s winds. Increasing this top frequency by a factor 1.1 to 0.2497 Hz allowed the spectra at these windspeeds to develop correctly. The wave model frequencies cover the range 0.04Hz to 0.324 Hz, so from Eqn 1.0 for the peak frequency of the PM spectrum, the lowest windspeed for which the peak frequency of the equilibrium spectrum lies within the model frequency range is 5.04m/s. Even the peak frequency for $u=6$m/s is such that all the energy lies in the top frequency bin.

The resolution of spectral peak frequency in the 1987 lookup table is between 0.04Hz and 0.227Hz with 55 increments, arranged logarithmically. This was first increased so that the revised lookup table covered the range 0.04Hz to 0.2497Hz, with 110 increments arranged logarithmically. This increase in peak frequency resolution allowed the equilibrium height for $u=15$m/s to move closer to the PM limit, without altering the dissipation coefficient. Figure 2b shows that the step jump in waveheight as dissipation was varied was much reduced. However even after doubling the resolution of the lookup table there remained a problem at higher windspeeds, 24m/s and 28 m/s in particular. Further investigation varying the dissipation coefficient for $u=24$m/s with the revised lookup table revealed a step jump in wave height similar to Figure 2a. Because of this the resolution of the lookup table was further increased to 220 peak frequency components. However there still remained problems at certain windspeeds. Tests of even higher frequency resolution failed to improve the equilibrium heights at these windspeeds. The difference in equilibrium waveheight between the model with the revised lookup table and the PM limit is shown in Figure 3 for a range of windspeeds.

2.1.2 Increased resolution of spectral peakedness, gamma

The JONSWAP study noted that for a developing windsea the energy at the peak of the spectrum exceeded the peak energy of the PM spectrum with that peak frequency. In the JONSWAP spectrum this enhancement of peak energy is described by the coefficient γ which is the ratio Emax(fj)/Epm(fj) where fj is the spectral peak frequency (See Figure 4 for definitions of the shape parameters). For a fully developed spectrum γ approaches 1 and the spectral shape approaches the PM spectrum. From the JONSWAP study, mean values of the shape parameters were found to be $\gamma = 3.3$, $\sigma_a = 0.07$ and $\sigma_b = 0.09$, and these values have been used in the representation of JONSWAP spectra in wave models (Hasselmann et al 1976). In the UKMO wave model, for each peak frequency specified as described in the previous section, the lookup table stores a JONSWAP spectrum with shape parameters $\sigma = \sigma_a = \sigma_b = 0.08$, for values of spectral peakedness, γ, between 1.0 and 3.3.

Accordingly, the resolution of gamma in the lookup table will determine the shape taken by the spectrum as the windsea grows, and thus will influence both the growth rates and the equilibrium spectrum and energy level, as both dissipation and input terms are functions of spectral shape. The resolution of gamma in the experimental model lookup table was increased from 24 to 96 components, however tests showed that this had only little effect on the equilibrium height achieved. In the experimental model the timeseries of source terms for a growing windsea was smoother. The resolution of γ in the global model lookup table was not changed.

2.1.3 Conclusion

Extending the frequency range of the lookup table allows the spectra for windspeeds of 7m/s and 8 m/s to be correctly represented. The spectrum for 6m/s windspeed is constrained by model frequency resolution to remain in the top bin and so the equilibrium wave height is some 25cm below the PM limit. Increasing the resolution of the extended lookup table allows the equilibrium spectrum for several values of windspeed to move closer to the PM limit. However at certain windspeeds, particularly at higher values, the equilibrium heights still fall short of the PM value, by up to 0.9m. Increasing the resolution of gamma in the lookup table does not affect these cases. Table 1 summarises the lookup table properties. The difference between PM limit and model equilibrium waveheight using the 1992 lookup table is shown in Figure 3 for a range of windspeeds.

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TABLE 1

Lookup table	Spectral peak frequency resolution	gamma resolution	top frequency
1987	55	24	f(nfreq-1)=0.227Hz
1992	220	24	1.1* f(nfreq-1)=0.2497Hz

2.2 Varying the dissipation coefficient

Figure 3 shows that whilst revising the lookup table has increased the equilibrium wave height for many windspeeds, nevertheless the PM limit is not achieved for most windspeeds, particularly windspeeds greater than 15m/s where the equilibrium wave height may still be up to 50cm below the PM limit. Reducing the dissipation coefficient will increase the equilibrium wave energy, allowing an energy balance to be reached at a higher energy level. Further, a reduction in dissipation coefficient will also improve the levels of swell energy in the model, since the dissipation term acts directly to reduce swell energy and is not balanced by the wind input term at swell frequencies. By adjusting the exponential growth coefficient and dissipation coefficient to provide a correct growth rate and energy balance for growing windsea for the smallest possible dissipation coefficient, there will be less dissipation of swell in the model. This should improve the model representation of swell. Model growth rates are discussed in Section 3.

The impact on equilibrium wave height of reducing the dissipation coefficient is shown in Figure 5 for windspeeds of 24m/s and 28m/s, using the 1992 lookup table. The sensitivity of the model equilibrium waveheight to spectral shape and dissipation coefficient is clearly shown in Figure 5b where the reduction from $4.55 * 10^{-5}$ to $4.50 * 10^{-5}$ increases the equilibrium height by over 50 cms.

With a value for the dissipation coefficient of $4.50 * 10^{-5}$ all equilibrium heights are within 30cm of the PM limit (Figure 6) for windspeeds up to 30m/s. For any value of dissipation coefficient greater than this the PM limit is missed by up to 60cm for some windspeed.

3.0 Growth rates

The original calibration of the 1987 physics (Thomas and Ephraums, 1986) compared wave model growth rates for fetch-limited and duration-limited growth against curves obtained from the

WMO manuals and from the JONSWAP study. The fetch limited growth curves of the JONSWAP study were transformed to duration limited by Golding (1983) assuming a propagation speed of 0.85 times the group velocity of the peak frequency. Prior to 1987 the growth of wave energy in the model was tuned to fit this duration-limited line. One aim of the 1987 revision was to increase the growth rate for short duration or fetch. The resulting curve fitted the WMO values well in the early stages of growth but gave energies larger than the derived JONSWAP value. Recent studies have shown (eg Gunther and Holt, 1992) that the growth of windsea in the current global model closely followed observations, for example at the USA buoys in the Western Atlantic. It is probably correct for the model growth to be closer to the WMO values than to the JONSWAP line. It is not clear why there should be such a discrepancy between the results, as for the fetch limited conditions observed in JONSWAP the water was effectively deep for fully developed waves for all windspeeds observed. However the SWAMP study (1985) found differences between model growth curves and JONSWAP arising from the assumption of differing values of drag coefficient Cd in the reduction of winds from U10 to U*. It is not known what assumptions were made in the derivation of the JONSWAP line plotted on Figure 7, and this should be used as a guide only. In Figure 7 energy, frequency and time are non-dimensionalised as follows :

$$E^* = E\, g^2 / u^4$$

$$T^* = g\, t / u$$

$$f^* = f\, u / g$$

Figure 7 shows that, in the wave model with revised lookup table and dissipation coefficient 4.5E-5, the wave energy is greater than the JONSWAP energy for all times until the energy balance is reached. Two points are apparent. The exponential growth applied after the first timestep gives a growth rate in excess of that observed by JONSWAP, and the subsequent growth also exceeds the JONSWAP rate. Exponential growth of energy in the model top frequency bin is applied using the calculated peak frequency Fj of the corresponding JONSWAP spectrum, if this frequency is greater than f(nfreq). For the first step starting from the energy input by linear growth the value of Fj is large, hence the large growth at this timestep. Tests using the phase speed and frequency for the exponential growth corresponding to f(nfreq), which is the frequency bin containing the energy, show that the growth at timestep 2 is reduced and lies closer to the JONSWAP result. The subsequent growth however continues as before.

4.0 Decaying swell in the direction of windsea

Early tests with the revised lookup table in the global model revealed a difficulty with the way in which the current model limits windsea energy in the case of falling windspeed. Where the windspeed falls but wind direction does not change appreciably the total wave energy in the 'windsea' frequency-direction sector may exceed the PM limit; however this energy is not windsea but is 'swell'. For some windspeeds it is possible that the PM spectrum for the lower windspeed is entirely contained within the envelope of the spectrum for the higher windspeed - Figure 8 shows an example taken from the experimental wave model. In its current form the wave model would incorrectly reduce the wave energy to the PM limit in this sector, thus throwing away the residual swell energy, in the example shown corresponding to a wave height of 1.24m . (In the 1987 wave model there is a compensating error so that this does not happen for windspeeds of 9m/s or less).

Physically this is incorrect as the swell spectrum should decay gradually under the action of dissipation (and to a lesser extent nonlinear transfer) until the correct windsea envelope for the reduced windspeed is reached. This is made possible in the revised wave model by a simple check on the value of the total wave energy in the "windsea" sector at the start of each timestep - if this exceeds the PM limit then only dissipation is applied and the residual energy is not lost.

5.0 November 1988 hindcast study

The hindcast study used in the WAM intercomparison (Gunther and Holt 1992) was run using the final revised version of the wave model on the 3 degree global grid. Verification against buoy observations allowed comparison with previous versions of the UKMO wave model and with the WAM model (Cycle 3) used in the original intercomparison. Model and observed 1D spectra at Buoy 51002 (Hawaii) were also compared, for the example discussed in the WAM report (Gunther and Holt, 1992). The revisions to the wave model were : use of the 1992 lookup table, a dissipation coefficient of 4.5E-5, and the check for decaying swell described in the previous section.

Figure 9 shows that the mean bias at the buoy locations is much improved by the revised formulation. In particular the verification at Hawaii confirms that the problem with swell in the model is now greatly alleviated. There is a large improvement in the bias at the Alaskan buoys, 46001 and 46004, and tests during development of the changes show that this is mainly due to the correct treatment of swell energy with falling windspeeds.

A comparison of modelled and observed 1D spectra at 00z 26th November 1988 (Figure 10) shows that the revised model is much closer to the observation than the original model spectrum. However the "spectral gap" around 0.15Hz noted in the WAM report is still present. This should be improved by the further development of a revised swell-windsea separation, and further improvements to the formulation of swell dissipation. (This work is currently under development and will be reported elsewhere) The model simulation of swell energy at lower frequencies is greatly improved, and the 1D spectrum is closer to observed than the WAM model, which tends to form a broad single-peaked spectrum.

Global charts of wave height difference from the hindcast, for 06z 25/11/1988, are shown at Figure 11. Figure 11a shows the full impact of implementing the proposed changes - the difference in wave height between the revised model and the operational model is almost everywhere positive, and exceeds 40cms over a large area of the subtropical Pacific. Figure 11b shows the impact of simply reducing the dissipation coefficient in the current operational model. Here the difference is much less, and there are more areas where wave heights are lower than in the control run.

6.0 Increasing model frequency resolution and top frequency.

Because the equilibrium energy level reached depends critically upon the resolved spectral shape it is clear that increasing the model frequency resolution will have an impact on the model equilibrium wave heights. Tests in the experimental model for windspeeds of 28m/s and 6m/s (where the greatest differences between model and PM equilibrium wave height remain) showed that increasing the number of frequency components in the model increased the equilibrium height. For a windspeed of 28m/s this allowed the PM limit to be reached with a dissipation coefficient of $4.5 * 10^{-5}$. This is because the equilibrium spectral peak frequency is better resolved, and at coarser resolution the spectral peak frequency has to move down to the next model frequency bin to reach the PM limit.

Increasing the top model frequency to 0.42 Hz allowed, in the experimental model, a correct representation of the spectrum for windspeeds of 6m/s (Figure 12) and 5 m/s, and allowed the equilibrium heights for these and other windspeeds to approach closer to the PM limit (Figure 13). For windspeeds of 4m/s or less all the wave energy was contained in the top model frequency bin. In the experimental model with top frequency 0.42Hz and with 26 frequency components all equilibrium wave heights were within 10cm of the PM limit, and for windspeeds of 8m/s and above were within 5cm (Figure 13).

The revised wave model with 26 frequency components and a top frequency of 0.42Hz was run for the November 1988 case. Verification results (Figure 14) showed little change in mean wave height bias - a 1cm increase in wave heights at Hawaii, and a 7cm increase at the NW

Atlantic buoys, where windsea dominates. Verification of wave period (Figure 14b) was made worse. These results may be explained because the main impact of extending frequency range and resolution is to improve representation of wind sea at low windspeeds. This will modify the mean spectral parameters, increasing the spectral mean frequency where there are light winds, and thus increasing dissipation of the whole spectrum there, including swell frequencies. The mean period will be shorter. Before increasing frequency range and resolution operationally, further work is required on the formulation of swell dissipation used in the model. Increasing frequency range and resolution in the current model benefits only those areas dominated by windsea and lacking swell.

Increasing the number of frequency components also increases the model run time and disk space requirements, and if implemented operationally will destroy continuity of the wave model archives of E(f) which are of use commercially. Table 2 shows that the increase in run time and elapsed time (in batch) is approximately proportional to the increase in number of frequency components. At the present time the benefits of increasing frequency resolution are small compared to the costs involved.

Table 2

Cost of a 6 day model integration on 3° global grid :

	Elapsed time	Run time CPU
a) Nfreq=13	102 sec	502 sec
b) Nfreq=26	223 sec	1229 sec

7.0 Summary and Recommendations

1 A revision of the spectral shape lookup table to increase the top frequency and increase the resolution of peak frequency is necessary to improve the representation of spectra in the model for all wind speeds. This does not alter any other characteristics of the model.

2 To achieve the PM limiting wave height for those windspeeds for which the limit may reasonably be achieved it is further necessary to reduce the dissipation coefficient.

3 The incorrect loss of swell energy in falling windspeeds but unchanging wind direction may be corrected by comparing the total wave energy in the 'windsea' sector with the PM limit at the start of the timestep, and only applying the appropriate source terms at that point.

4 Increasing the frequency resolution and increasing the top model frequency to 0.42Hz both help to improve the representation of spectra at low windspeeds. In a global model this can increase dissipation of the whole spectrum, including swell, thus worsening the verification figures at some locations.

RECOMMENDATION:

It is proposed to implement the following changes in the operational wave model:

a) Implement the revised '1992' lookup table.

b) Use the coefficients 0.2 for exponential growth (no change) and 4.5 E-5 for dissipation (reduced from 5.0E-5)

c) Check for "windsea" greater than EPM at the start of each timestep and then apply only the appropriate source terms.

These changes will allow the correct representation of windspeeds of 6,7 and 8 m/s in the model, and will improve the representation of wave height for windspeeds of 15m/s, 17m/s and higher. The reduction of dissipation coefficient will benefit the swell energy in the model. The check on "windsea" will ensure that wave energy is not thrown away in the case of falling windspeeds at constant direction.

The large costs and relatively small benefits of increasing model frequency range and resolution are noted. The decision to implement this change should be taken separately from the above recommendations, possibly at the time of the next computer upgrade.

Further improvement of swell in the model will come from the improved windsea/swell separation currently being developed, and from refinements to the formulation of swell dissipation in the model, and from an increase in directional resolution.

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Figures

Figure 1a	Pierson-Moskowitz equilibrium wave height (Hpm) minus model equilibrium wave height (current wave model).
1b	Pierson-Moskowitz equilibrium wave height and model equilibrium wave height (current model)
Figure 2	model equilibrium height and pierson-moskowitz equilibrium height for u=15m/s. Varying dissipation coefficient. a) 1987 lookup table. b) 1992 lookup table.
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Figure 4	Jonswap spectrum definitions.
Figure 5	Equilibrium wave heights from integrations of the experimental wave model with revised lookup table, varying dissipation coefficient. a) u=24m/s b) u=28m/s
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Figure 8	Model 1D spectra for U=7m/s and U=12m/s showing the amount of wave energy incorrectly lost in falling winds by the old model, by assuming that all energy with frequency $> 0.8\ f_{pm}$ is windsea.
Figure 9	November 1988 case study. Mean wave height bias at buoy locations.
Figure 10	November 1988 case study. Modelled and observed 1D spectra at Buoy 51002, Hawaii, on 00z 26th November 1988

Figure 11 November 1988 case study: Charts of wave height difference:
Contour interval 0.2m. Positive differences shaded, with shading density increasing every 0.4m
a) Revised model minus current operational model.
b) Current operational model with dissipation coefficient $4.5*10^{-5}$ minus current model with dissipation coefficient $5.0*10^{-5}$.

Figure 12 Experimental model 1D spectra for u=6m/s, increasing frequency range and resolution.

Figure 13 Equilibrium wave height difference from PM limit, with top frequency 0.42Hz and 26 frequency components.

Figure 14 November 1988 case study: Extended frequency range and resolution.
a) Wave height mean bias at buoy locations.
b) Wave period mean bias at buoy locations.

Figure 1a

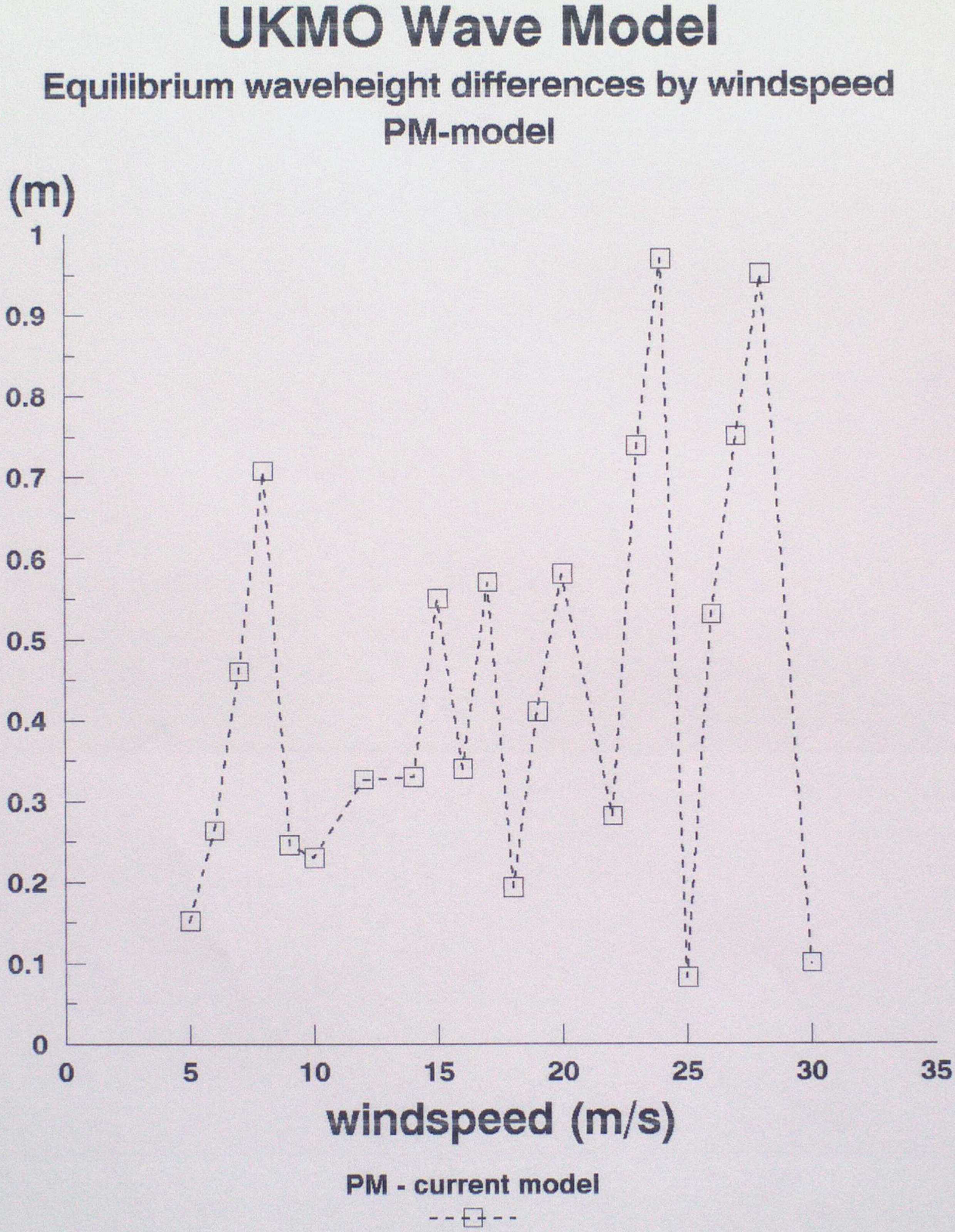

UKMO Wave Model
Equilibrium waveheight differences by windspeed
PM-model
(m)
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
5
10
15
20
25
30
35
windspeed (m/s)
PM - current model

Figure 1b UKMO Wave Model

Equilibrium waveheights by windspeed

Current model

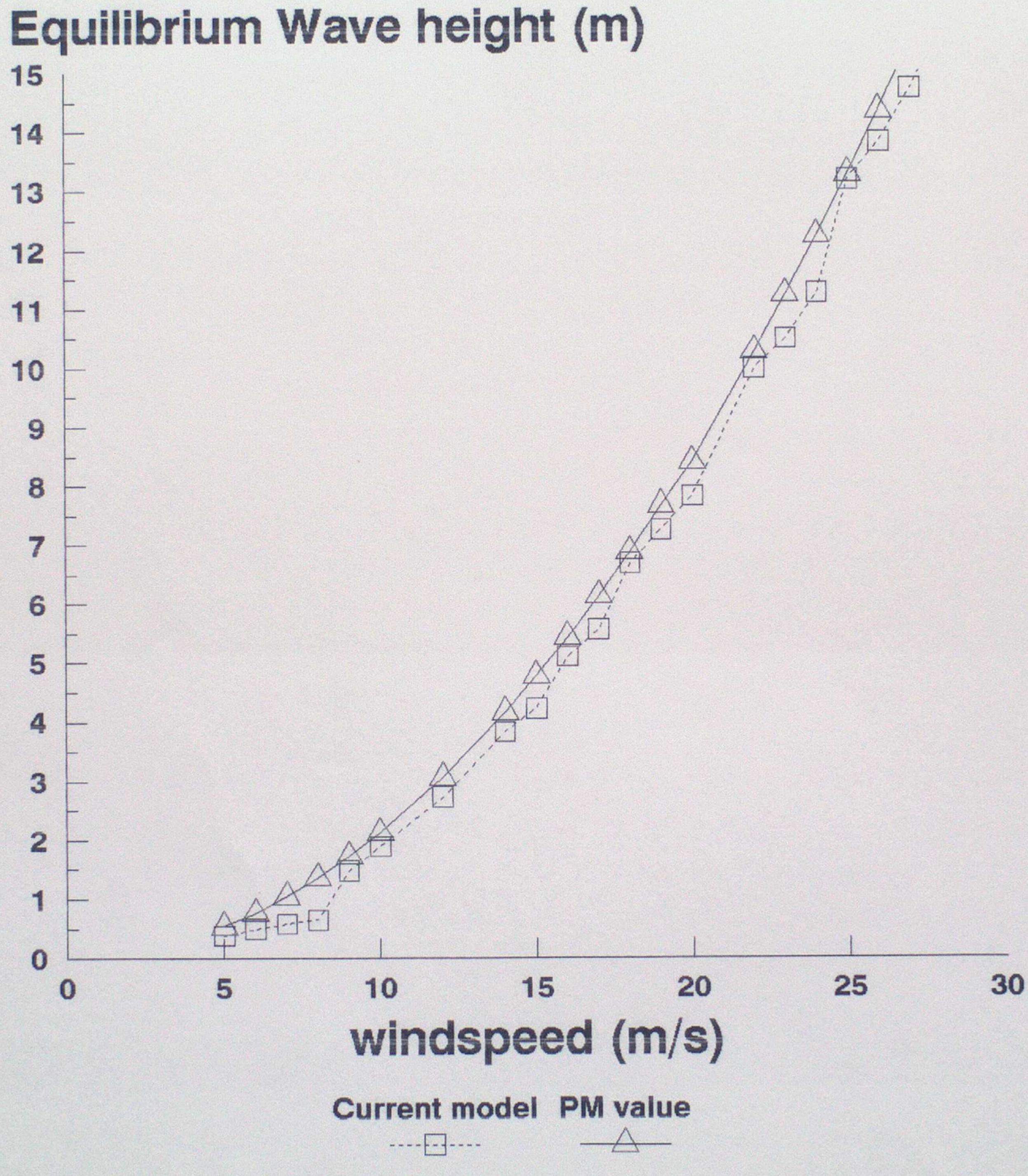
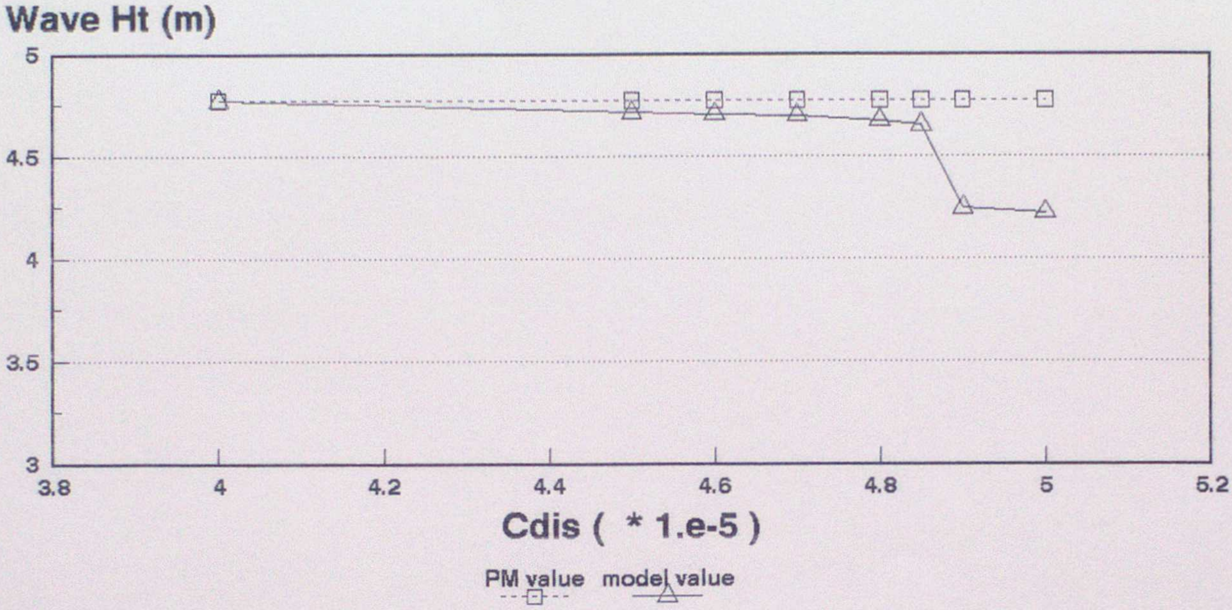


Figure 2

a)

UKMO Wave model calibration

windspeed 15 m/s (1987 lookup table)
vary dissipation coefficient



b)

UKMO Wave model calibration

windspeed 15 m/s REVISED LOOKUP
vary dissipation coefficient

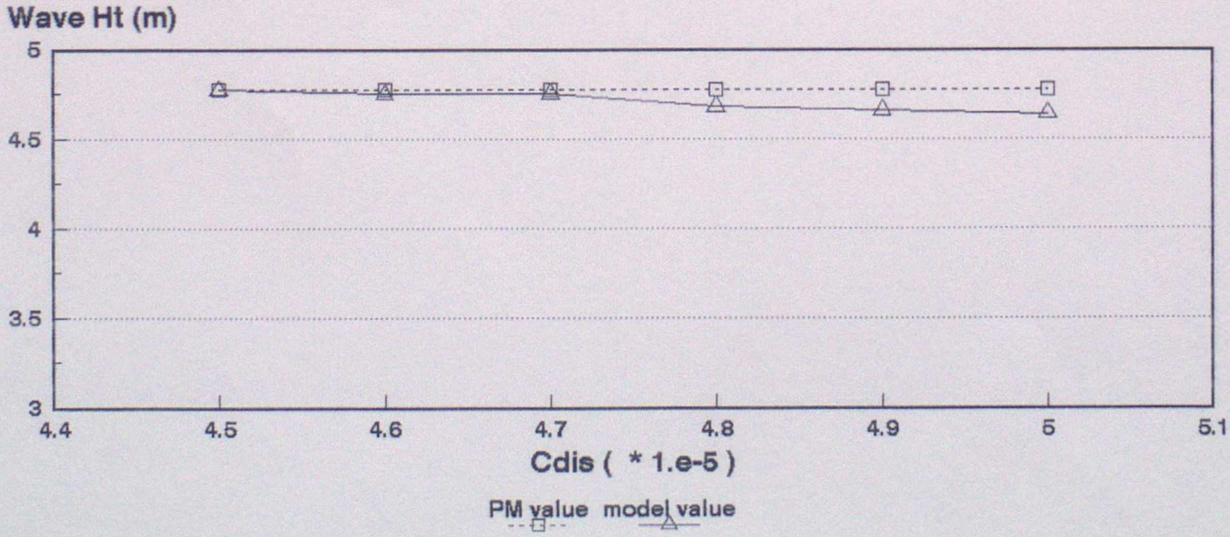


Figure 3

UKMO Wave Model

Equilibrium waveheight differences by windspeed
PM - revised lookup (Cdis 5.0 e-5)

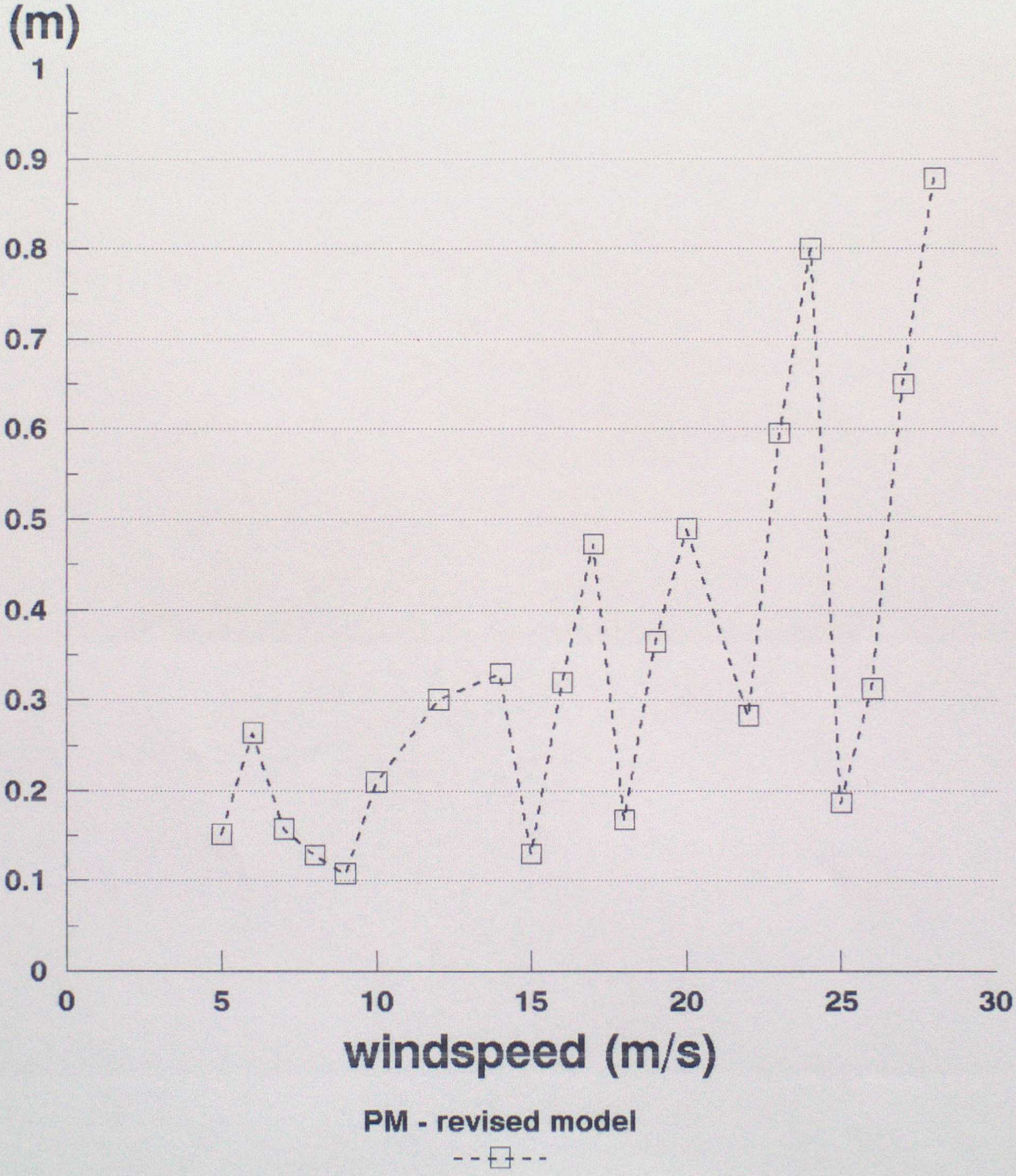


Figure 4

Hasselmann et al., JONSWAP

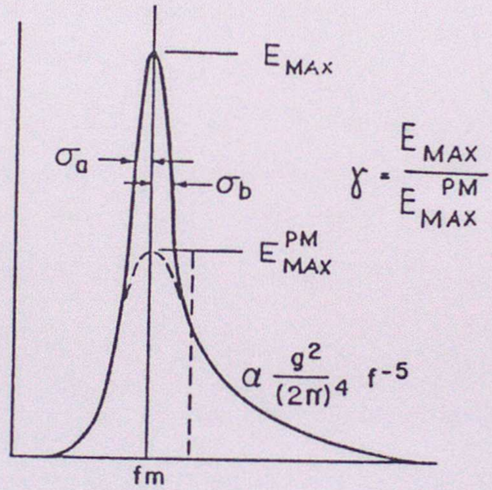
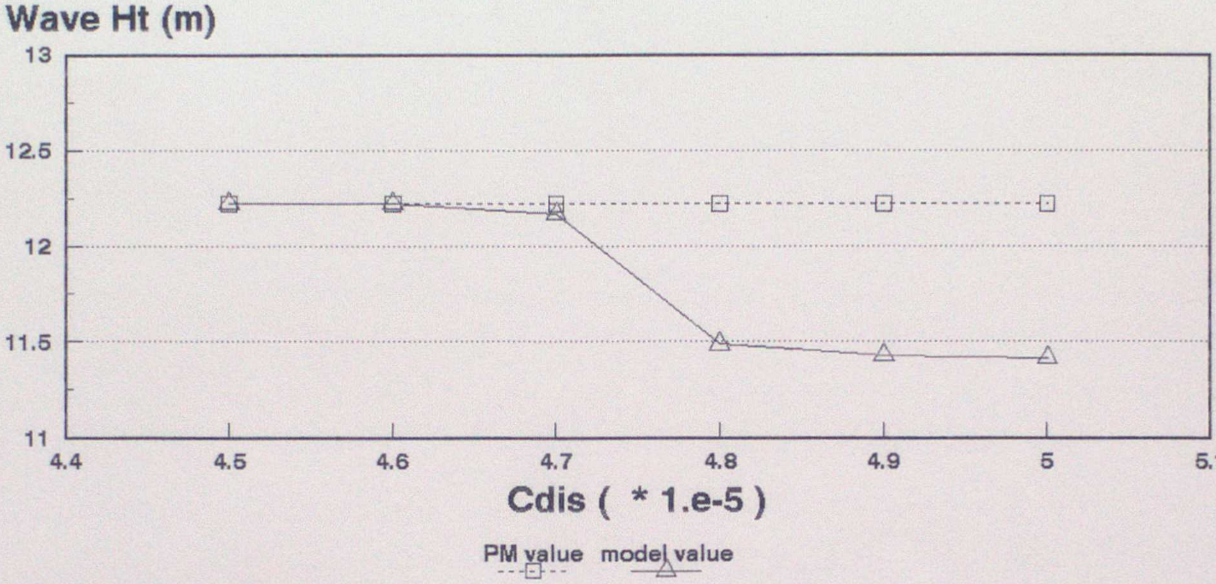


Figure 5 UKMO Wave model calibration

a) windspeed 24 m/s REVISED LOOKUP

vary dissipation coefficient



revised lookup (1) resolution 110

UKMO Wave model calibration

b) windspeed 28 m/s REVISED LOOKUP 220/96

vary dissipation coefficient

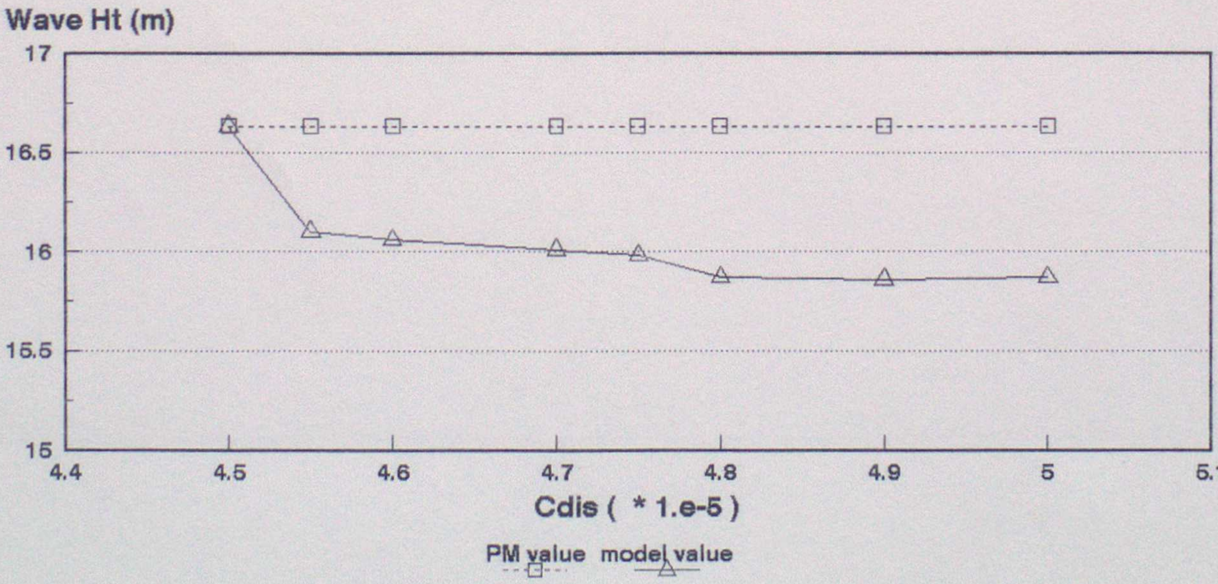


Figure 6 UKMO Wave Model

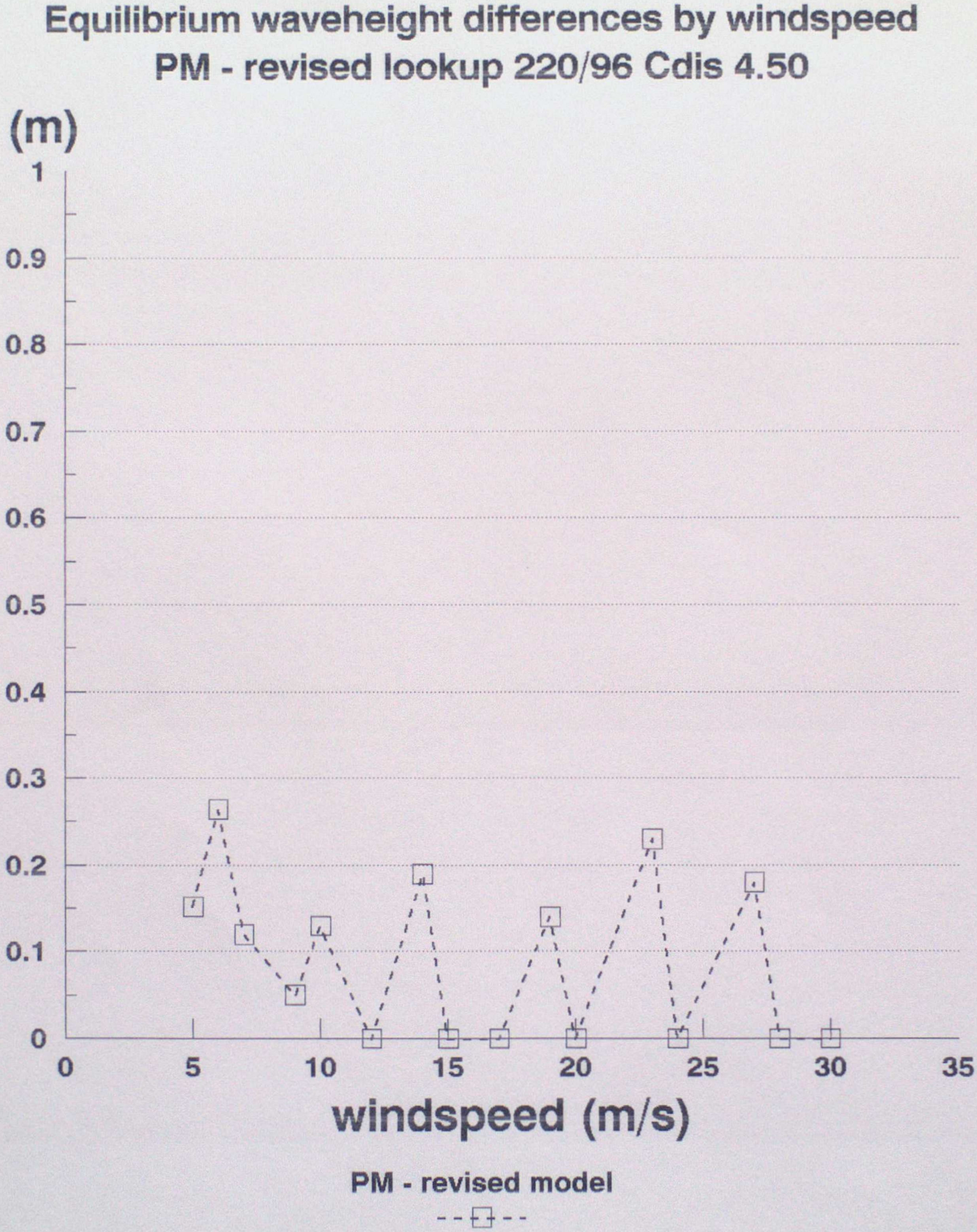
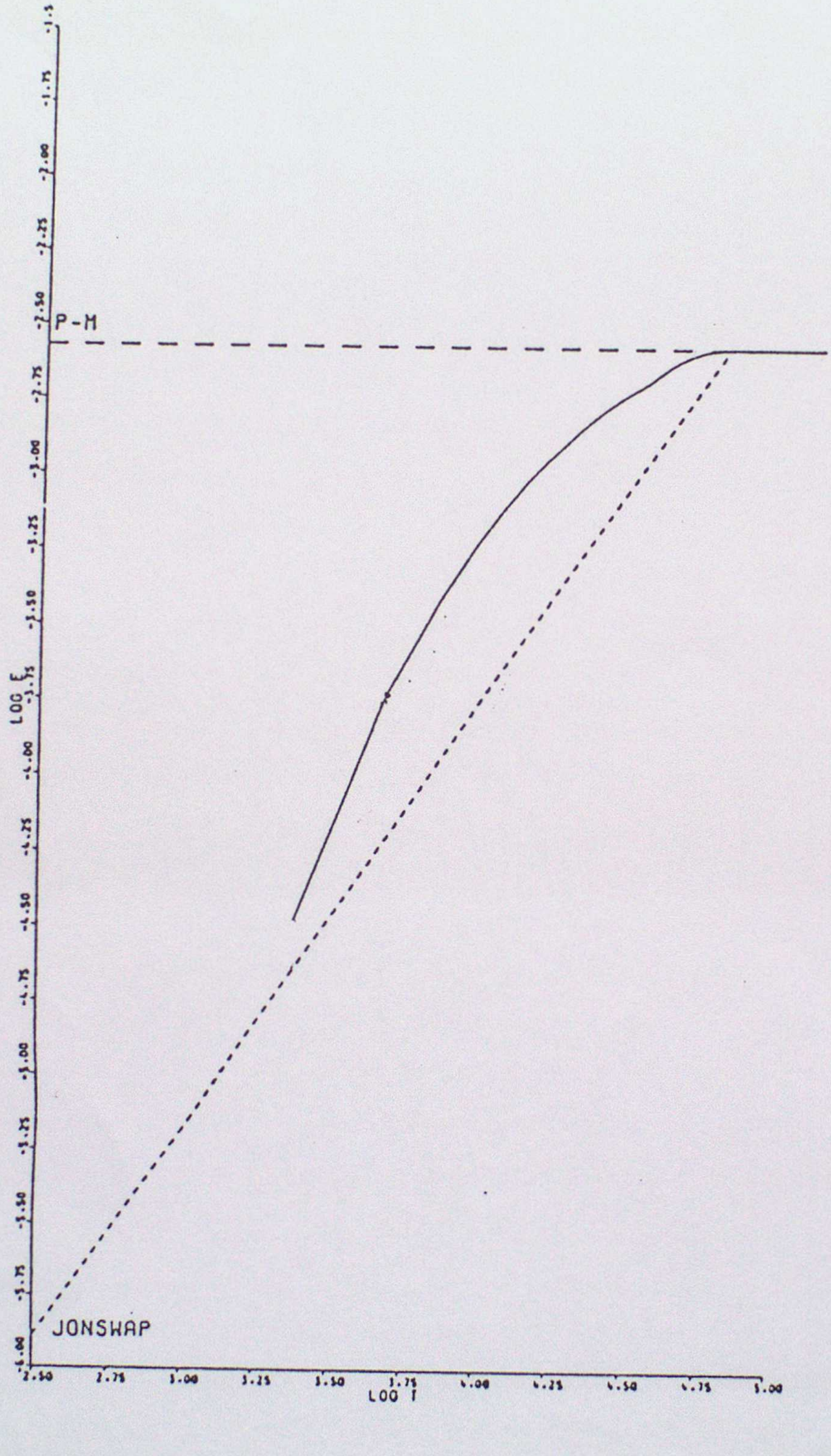


Figure 7



UKMO Experimental Wave Model

Equilibrium model 1D spectra

1992 Ikup CDIS 4.5 for U=7m/s and U=12 m/s

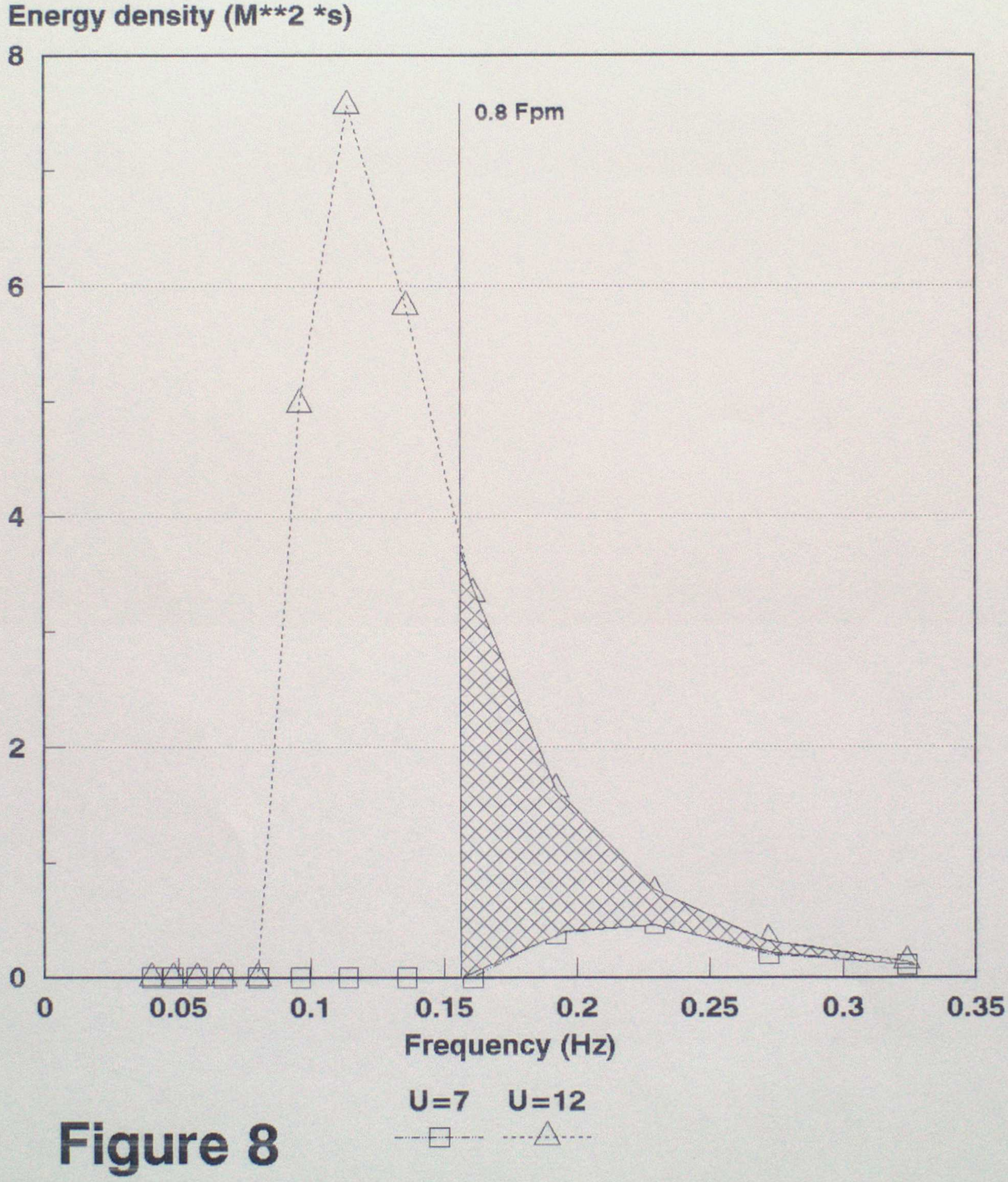


Figure 8

Figure 9

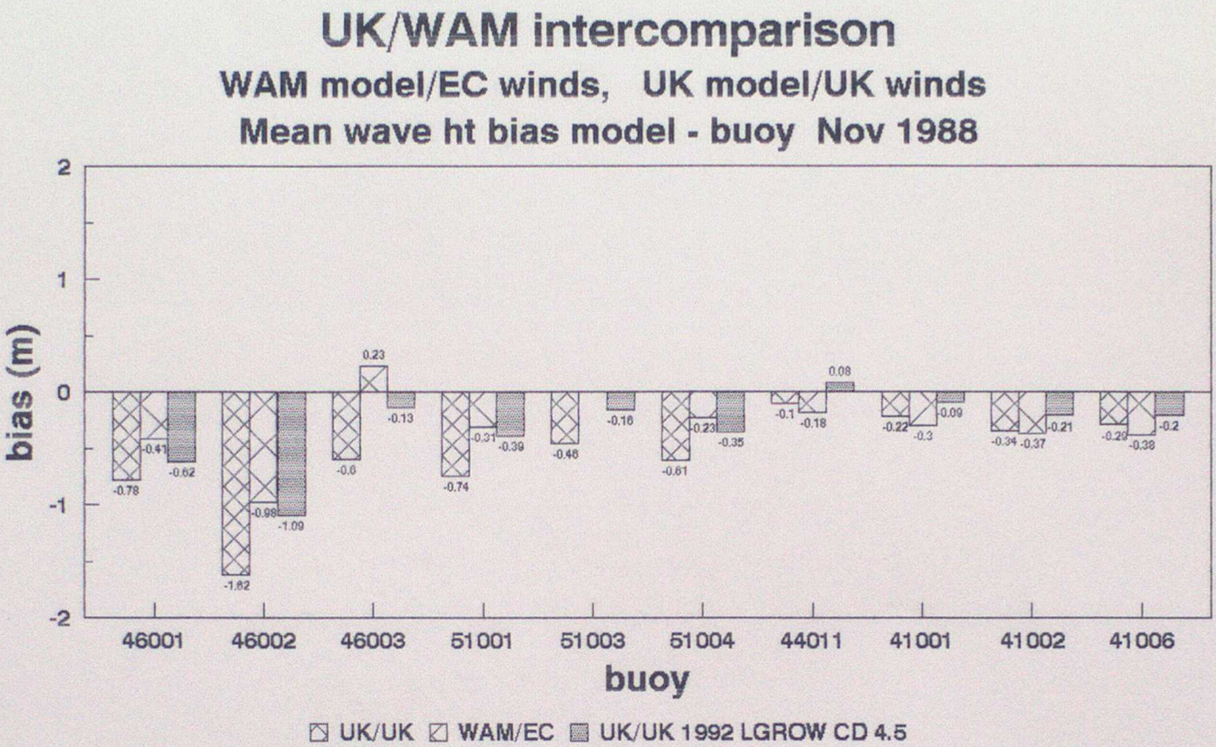

UK/WAM intercomparison
WAM model/EC winds, UK model/UK winds
Mean wave ht bias model - buoy Nov 1988
bias (m)
2
1
0
-1
-2
46001
46002
46003
51001
51003
51004
44011
41001
41002
41006
buoy
UK/UK
WAM/EC
UK/UK 1992 LGROW CD 4.5

Figure 10

WAM hindcast study

1D Spectrum at Buoy 51002 00z 26th November 1988
UK model : 1987 and 1992 lkup CDIS 4.5

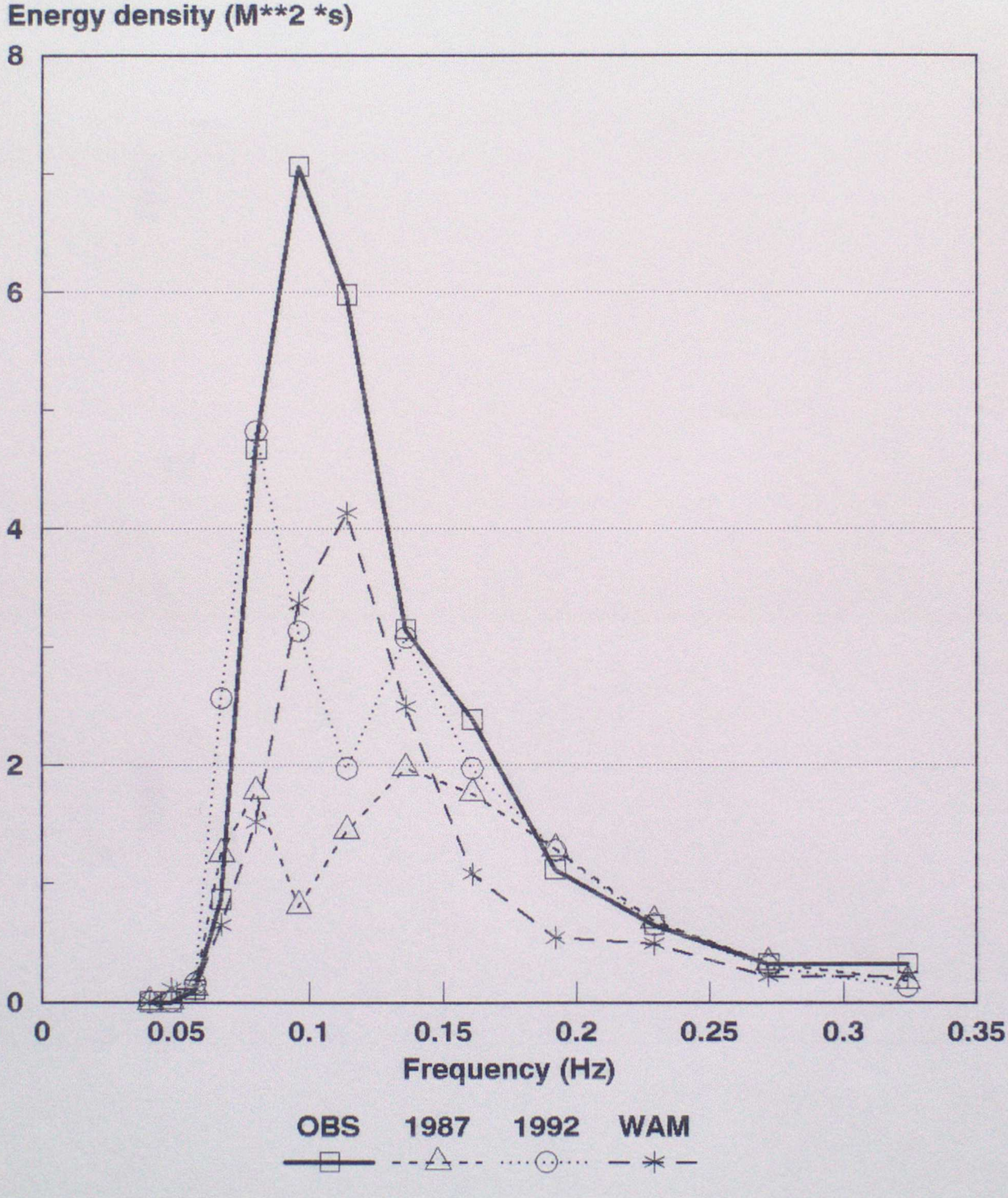
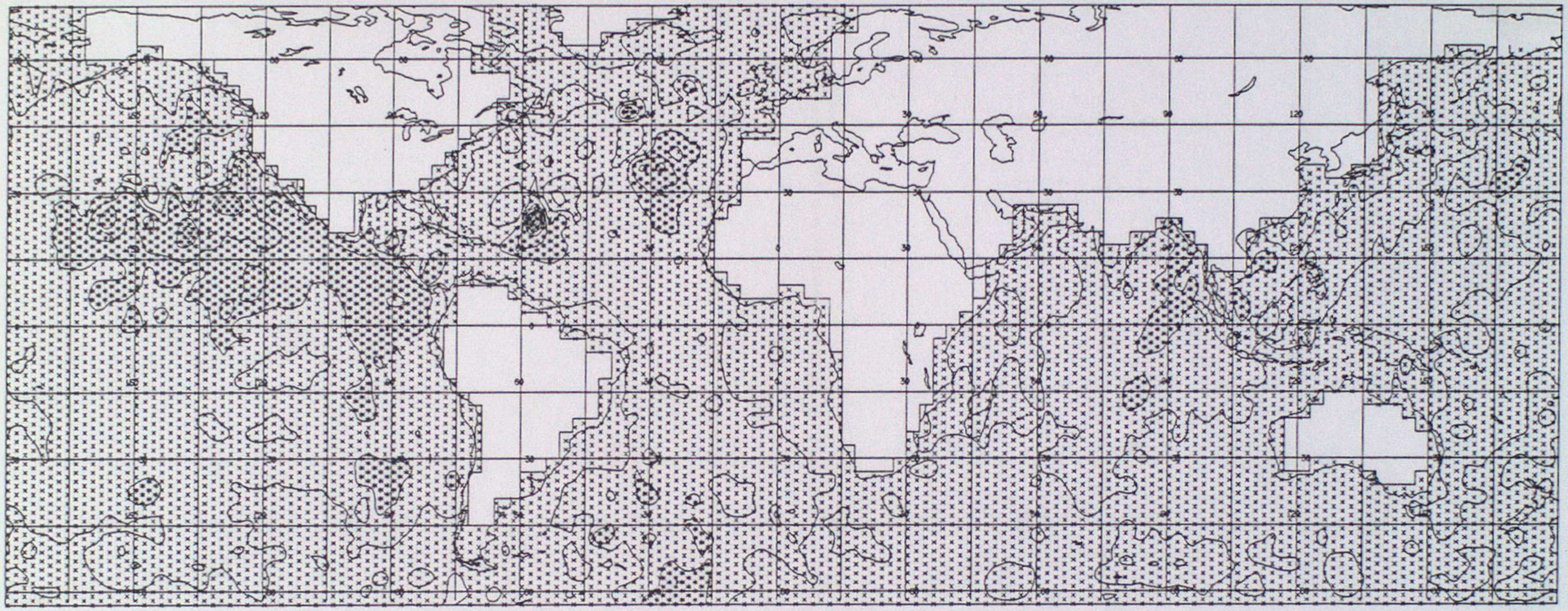


Figure 11 a)

VALID AT 6Z ON 25/11/1988



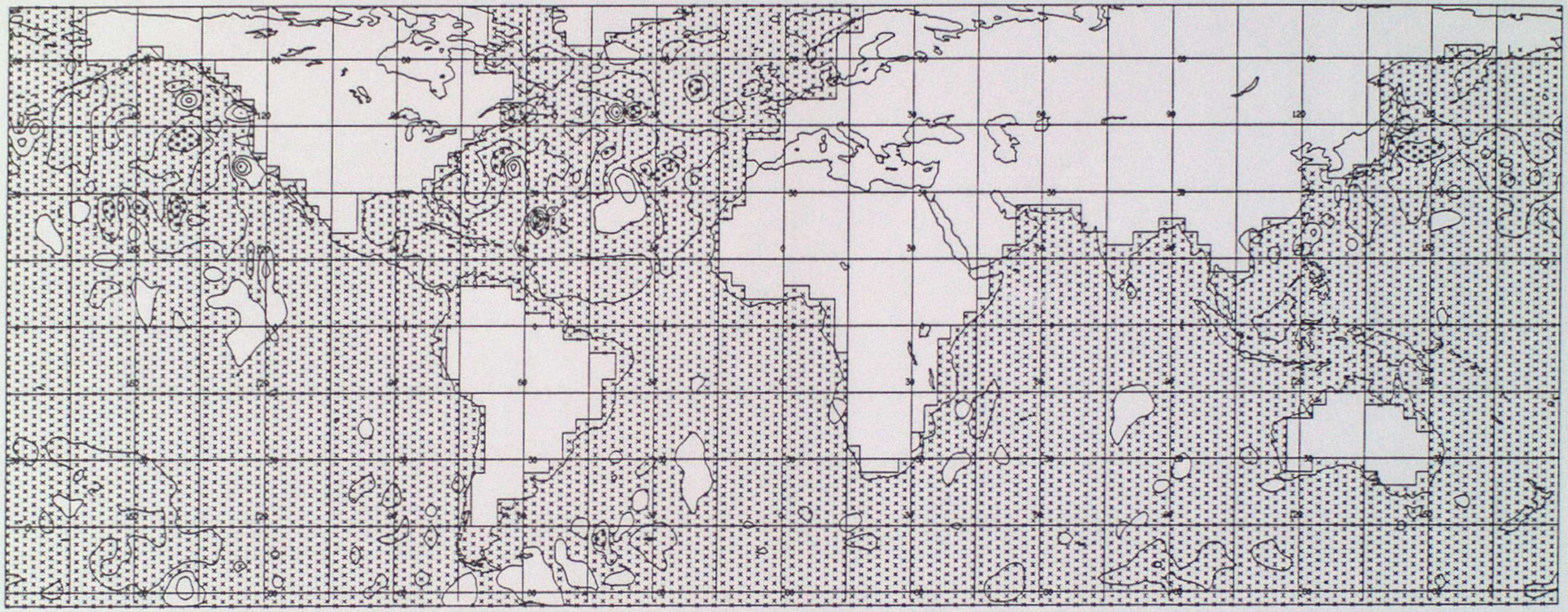
CONTOUR INTERVAL: 0.2 MKS UNITS

November 1988 case study: Charts of wave height difference:
Contour interval 0.2m. Positive differences shaded, with shading density increasing every 0.4m

a) Revised model minus current operational model.

Figure 11 b)

VALID AT 6Z ON 25/11/1988



CONTOUR INTERVAL: 0.2 MKS UNITS

November 1988 case study: Charts of wave height difference:
Contour interval 0.2m. Positive differences shaded, with shading density increasing every 0.4m

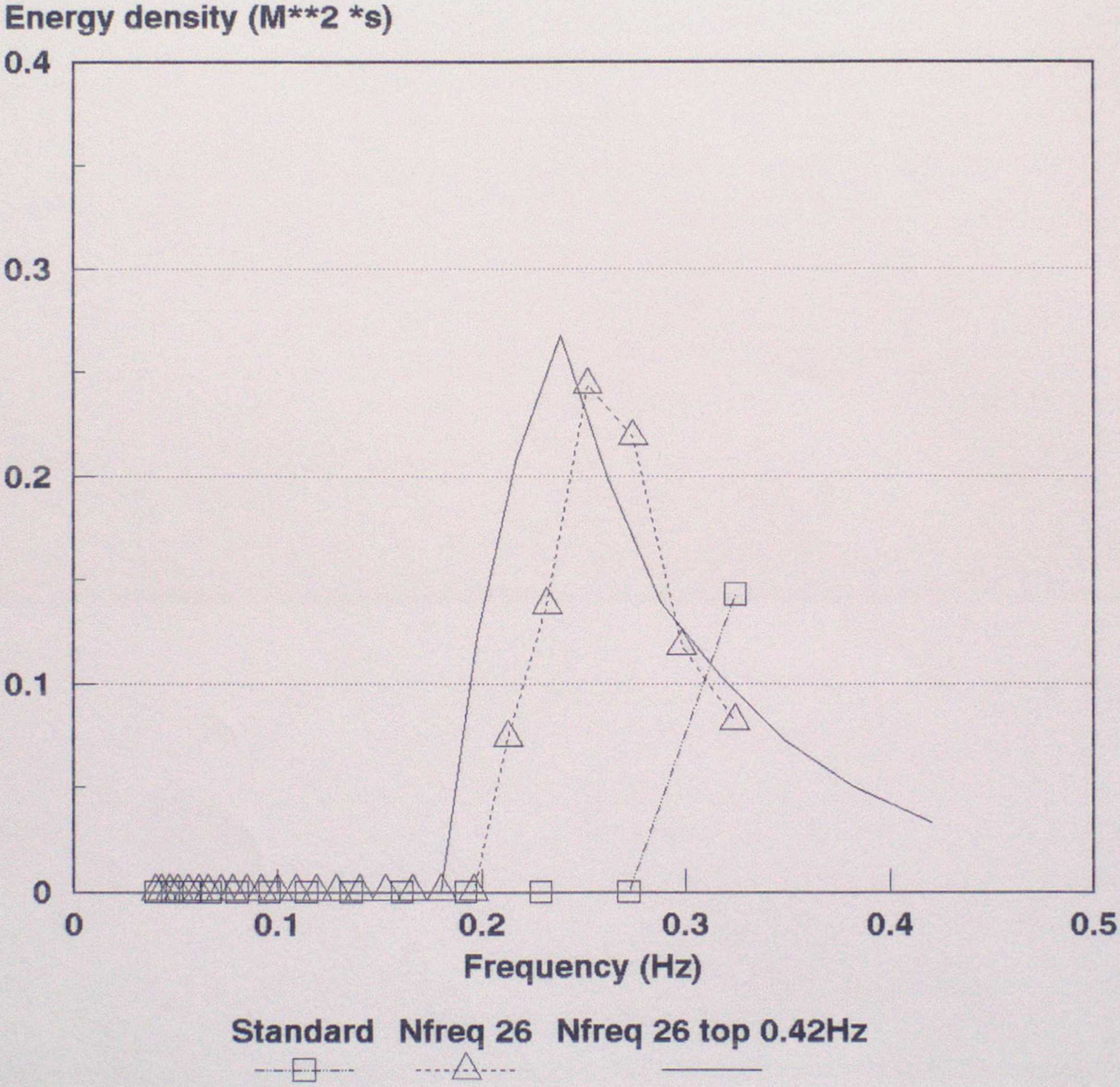
b) Current operational model with dissipation coefficient $4.5*10^{-5}$ minus current model with dissipation coefficient $5.0*10^{-5}$.

Figure 12

UKMO Experimental Wave Model

Equilibrium model 1D spectra

U=6m/s various Nfreq



Wave Heights :
a) 0.499m b) 0.631m c) 0.722m Hpm= 0.758m

Figure 13

UKMO Wave Model

Equilibrium waveheight differences by windspeed
Hpm-H model. 1992 lkup Cdis 4.5

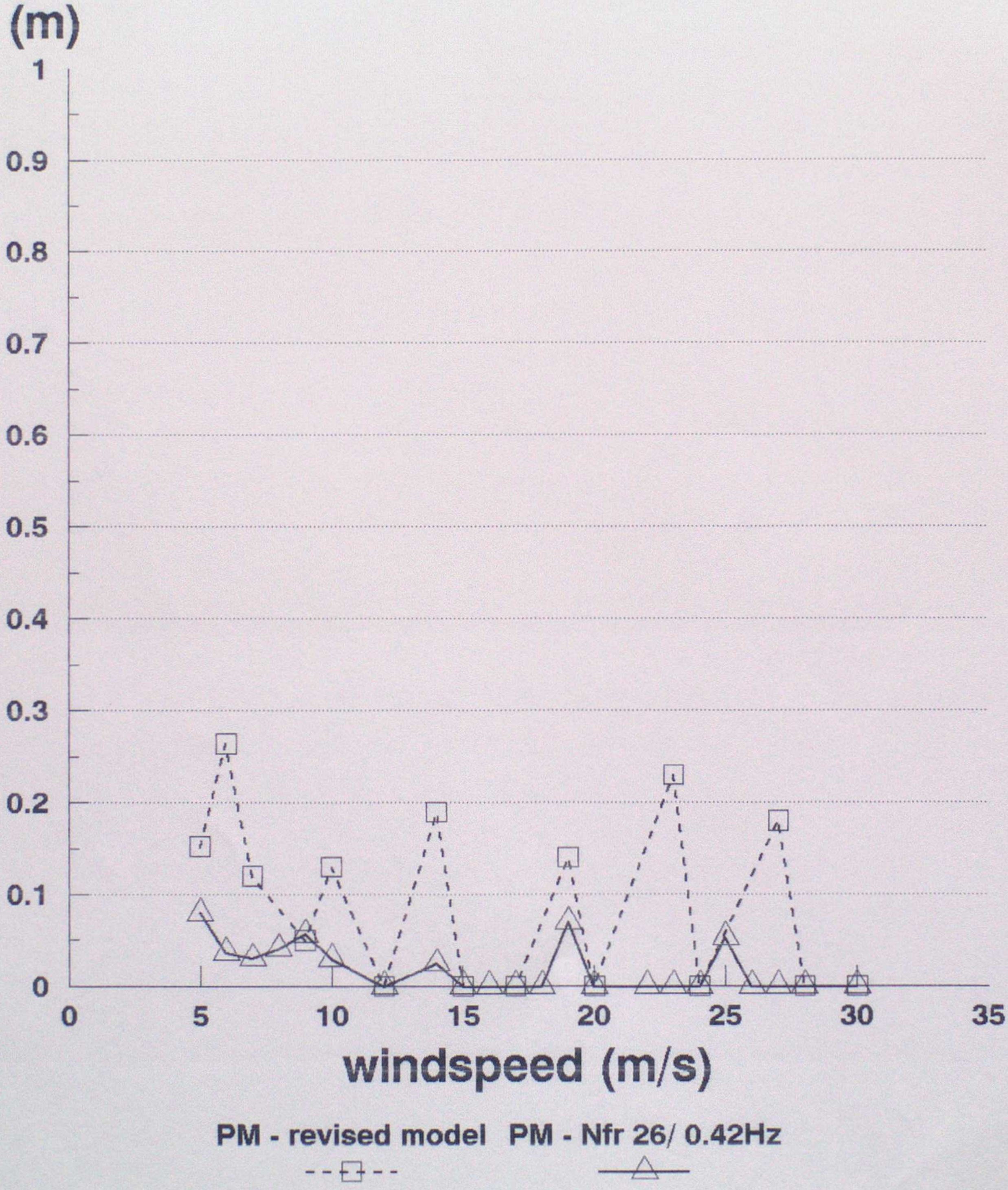
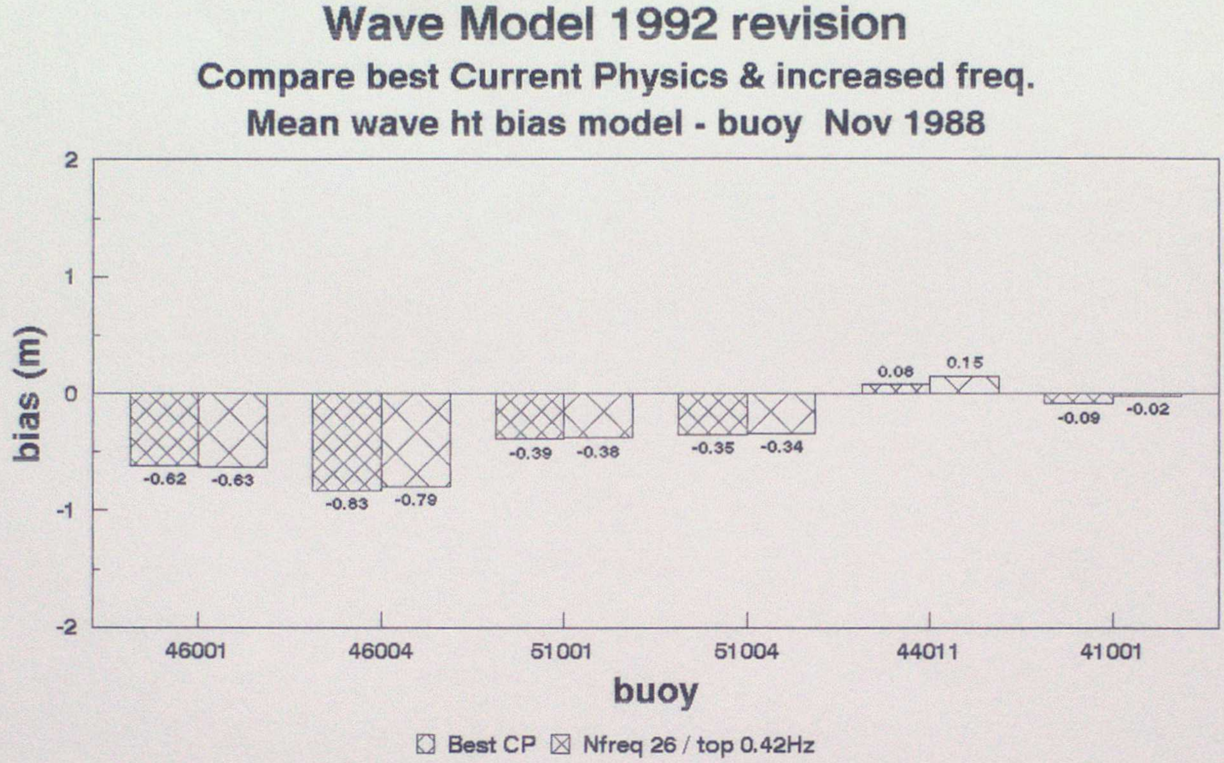
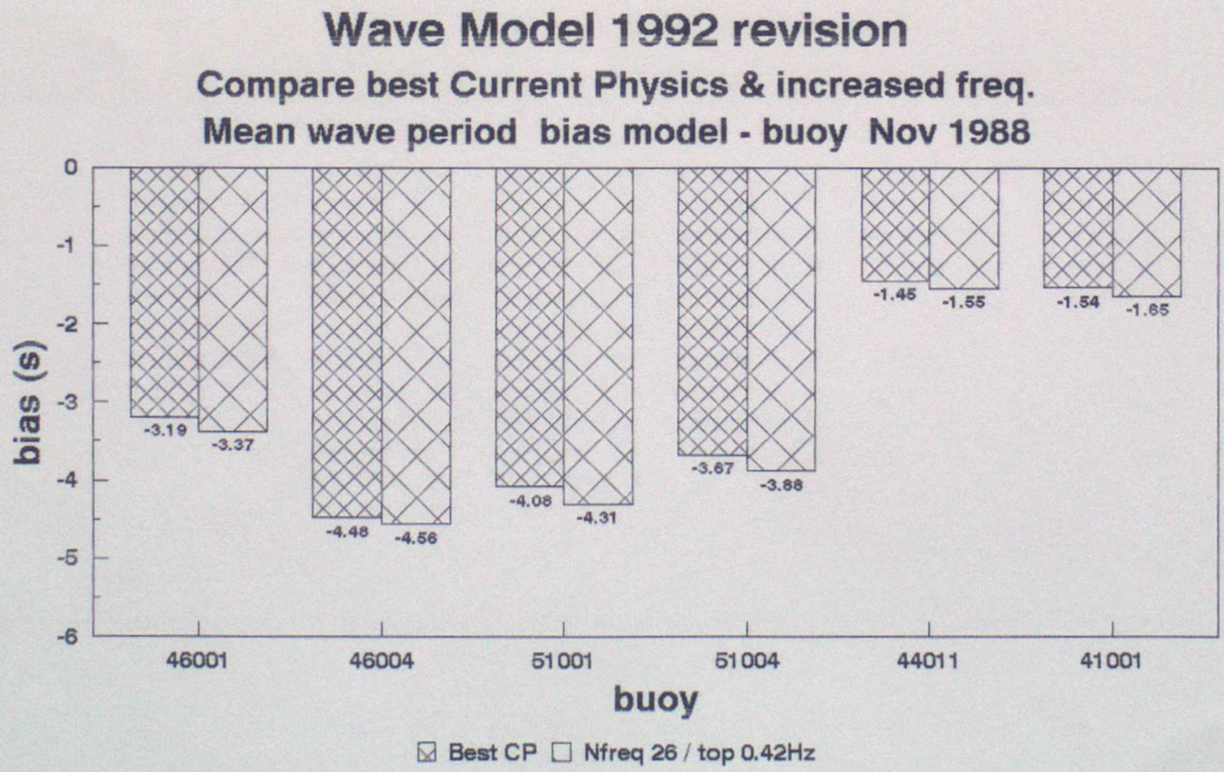


Figure 14


Wave Model 1992 revision
Compare best Current Physics & increased freq.
Mean wave ht bias model - buoy Nov 1988
bias (m)
2
1
0
-1
-2
-0.62
-0.63
-0.83
-0.79
-0.39
-0.38
-0.35
-0.34
0.08
0.15
-0.09
-0.02
46001
46004
51001
51004
44011
41001
buoy
Best CP
Nfreq 26 / top 0.42Hz


Wave Model 1992 revision
Compare best Current Physics & increased freq.
Mean wave period bias model - buoy Nov 1988
bias (s)
0
-1
-2
-3
-4
-5
-6
-3.19
-3.37
-4.48
-4.56
-4.08
-4.31
-3.67
-3.88
-1.45
-1.55
-1.54
-1.65
46001
46004
51001
51004
44011
41001
buoy
Best CP
Nfreq 26 / top 0.42Hz

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