METEOROLOGICAL OFFICE

Forecasting Research

Forecasting Research Division
Technical Report No. 119

Improvements to the UKMO wave model swell dissipation and performance in light winds

by

M.W. Holt

October 1994

Meteorological Office
London Road
Bracknell
Berkshire
RG12 2SZ
United Kingdom

Introduction

Recent comparisons between the third generation WAM (WAM group 1988) and second generation UK Met Office wave models, run using UKMO winds at the Met Office, have identified two areas where the performance of the UKMO wave model may be readily improved. This report is written in two sections, describing in turn each of these revisions. First, the wave model performance in low windspeeds is examined, and secondly the amount of dissipation applied to swell is re-assessed in the light of current knowledge of the energy input term.

1 Wave model performance in low windspeeds

1.1 Preliminaries

The UKMO wave model uses a top frequency of 0.324Hz, and a total of 13 frequency components. In the 1992 recalibration (Holt,1992) it was noted that growth of waves would not be adequately represented for windspeeds less than 6m/s. This was because the energy for these waves was entirely contained within the top frequency bin of the wave model. However a trial extending the frequency range and resolution, run for November 1988, showed only small differences from the control run. Since 1988 however verification of model windspeeds against buoy observations has shown a reduction in the positive bias, leading us to suspect (Foreman et al 1992) that as the buoy measurements are at some height less than the model level one nominal height, the model windspeeds are underestimated in the operational global Unified Model. It is probable that in the model a greater area of the ocean surface is now covered by windspeeds lower than 6m/s, compared to the Cyber model before 1991, and that this is contributing to the overall negative bias in wave height in the operational UKMO wave model, of around 40cm in winter months. The global mean wind speed is of the order of 6m/s, so it is important that a wave model can perform well for such wind speeds. Any improvements possible to the wave model response to low windspeeds will indirectly increase wave heights for stronger winds also: in the case of increasing windspeeds there will be more initial wave energy, and the growth from this is exponential. This could lead to the generation of higher waves in storms, and higher swell in the model.

This section firstly compares wave growth from rest in both UKMO and WAM wave models. It was this that first drew attention once again to the poor performance of the UKMO wave model in light winds. Secondly, wave growth in light winds is explored in the experimental model, using UKMO wave model physics, and the range of parameter values necessary to better represent waves for low windspeeds is determined. Thirdly, the results of extending frequency range and resolution in the UKMO model on the January 1992 case (Unified Model winds) are described. The remainder of this first section describes tests of a parametric growth term for low windspeeds, both in the single gridpoint experimental model, and in the global model for the winter case study of 1-19 January 1992 and the summer case of 1-19 June 1994.

1.2 The Problem

During tests developing output fields of wave stress it was noted that when spinning up from rest, even after only 6 hours, the wave heights from UKMO model can be as much as 50cm lower than those from WAM. Because this is only after 6 hours, it is unlikely to be associated with deficiencies in representation of swell, which is already known to be a difficulty with the UKMO model. The areas of greatest difference in wave height at 6 hours correlated with areas of windspeeds less than 6m/s.

The results of preliminary trials extending the range and resolution of frequency in the UKMO wave model are summarised below. All runs started from zero wave energy, and ran for 6 hours with the same UKMO hindcast wind dataset (winds for WAM were scaled to 10m by a factor of 0.91). Runs were on the operational 'Cray' wave model grid - resolution 0.833° latitude by 1.25° longitude. The standard WAM model uses 25 frequencies between 0.04Hz and 0.4177Hz with a logarithmic increment. The standard UKMO model uses 13 frequencies between 0.04Hz and 0.324 Hz, also with a logarithmic increment.

MODEL	Max frequency (Hz)	# frequencies	mean wave height (m)	pointwise maximum
WAM	0.417	25	1.22	5.43
UKMO	0.620	26	0.830	5.90
UKMO	0.520	26	0.814	5.87
UKMO	0.420	26	0.785	5.81
UKMO	0.324	26	0.747	5.75
UKMO Oper	0.324	13	0.735	5.75

After 6 hours growth from calm, the global mean wave height in the operational UKMO wave model is 39cm lower than in WAM. However the pointwise maximum wave height in UKMO is 32cm greater than in WAM. This is in line with results from the first case study intercomparison of WAM and UKMO wave models (Holt, 1994) in which for a particular storm, UKMO model wave height was some 2m greater than WAM, and closer to observed. The UK Met Office wave model has no problem with windsea generation in moderate or strong winds.

The impact of extending frequency range and resolution was to increase mean wave heights in the UKMO wave model by only several cm, not by the tens of cm required. Also the pointwise maximum wave height increased with increasing frequency range, suggesting that the model growth for moderate or strong winds would need re-tuning in order to retain the present adequate growth rates. Simply extending frequency range and resolution in the UKMO model to be comparable with the WAM resolution does not help with wave growth in light winds.

1.3 Tests with the UKMO single gridpoint model: Fully developed waves for a windspeed of 5m/s.

For different frequency configurations in the single gridpoint wave model, the limiting waveheight was calculated for a constant windspeed of 5m/s. The significant wave height of the fully developed Pierson-Moskowitz (PM) spectrum (Pierson and Moskowitz, 1964) is 0.53m for this windspeed, and the wave model equilibrium height should be close to this.

Table 2: Equilibrium wave heights for various frequency configurations of the UKMO single gridpoint wave model, all with Fmin=0.04Hz.

# frequencies	max frequency (Hz)	limiting wave height (M)
13	0.324	0.38
26	0.324	0.38
26	0.420	0.45
26	0.580	0.49
62	0.580	0.51

For the wave model limiting height to approach the PM value requires a top frequency of at least 0.58Hz and 62 frequency components. The corresponding spectra are shown in Figure 1.

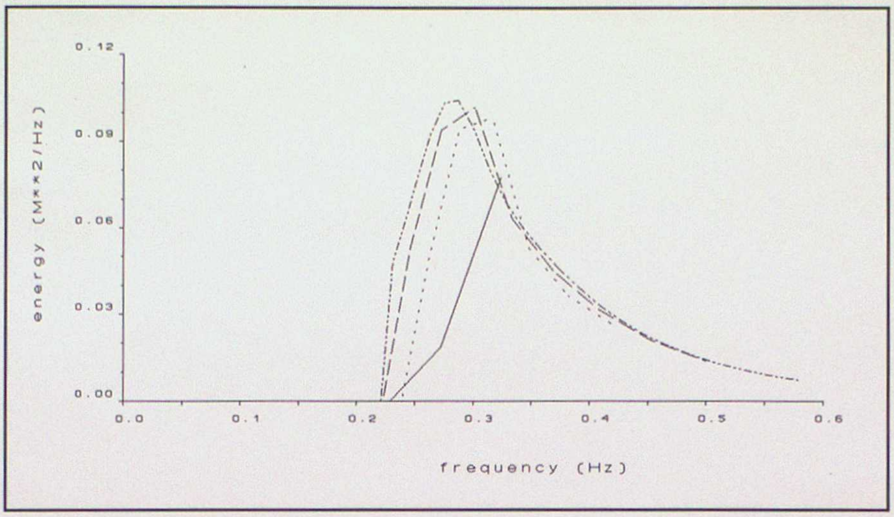


Figure 1. 1D spectra for u=5m/s, for various frequency ranges and resolutions.The solid line shows the spectrum obtained in the current operational model. The dotted line shows the spectrum with Fmax 0.42Hz and 26 frequencies, the dashed line shows the spectrum for Fmax 0.58Hz with 26 frequencies, and the dashed-dotted line for Fmax 0.58Hz with 62 frequencies.

However it is clearly undesirable to have 62 frequencies when most lie below the peak frequency for a windspeed of 6m/s and so do not contribute to wave growth for this windspeed. Wave spectra from the experimental model using 13 frequency components, but with a frequency range from 0.1Hz to 0.58Hz are shown in Figure 2.

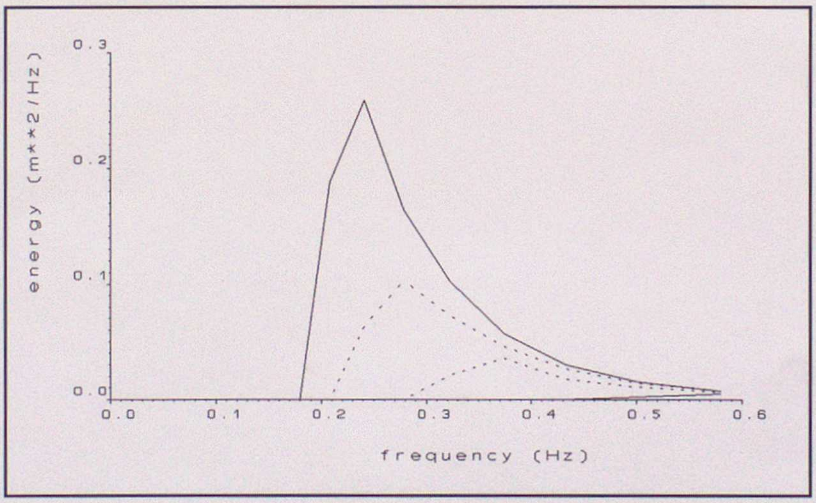


Figure 2: 1D spectra with 13 frequency components, for windspeeds of 6m/s (solid); 5m/s (dashed), 4m/s (dotted) and 3m/s (barely visible at 0.4-0.5Hz). Model frequency range 0.1Hz - 0.58Hz

1.4 Case study with maximum frequency 0.42Hz and 26 frequencies:

The case study of 1-19 January 1992 has been rerun using the UKMO model at Cray global resolution (0.833 latitude by 1.25 longitude) with a top frequency of 0.42Hz and 26 components, broadly similar to the frequency resolution of WAM. Figure 3 shows the impact on wave height verification at representative moored buoys.

For the general case of mixed windsea and swell the impact is difficult to predict in advance. A better representation of windsea at low wind speeds could lead to more dissipation being applied to the entire spectrum, and hence extra dissipation of swell acting to reduce wave heights. Figure 3 shows a clear benefit at the mixed windsea-swell buoys in the N Pacific - 46001 and 46004. There is only a small impact in the central Pacific at 51001 and 51004 (these are dominated by swell), and a modest improvement at Buoys 41001 and 44011 in the western Atlantic. However from the results of Section 1.3 it is clear that to correctly represent waves for winds of 5m/s or less, the frequency resolution at high frequencies should be greater than used here, and also the top frequency should be greater than 0.42Hz.

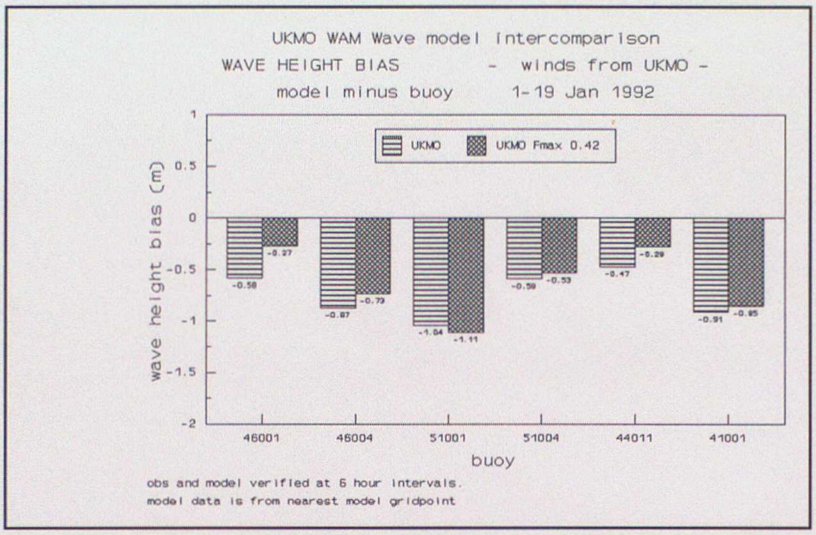


Figure 3 Wave height verification for the standard (1992) UKMO wave model (horizontal lines), and for the model with top frequency 0.42Hz and 26 frequencies (shaded), for 1-19 January 1992, at representative moored buoys.

Buoy	Lat	Long	location
51001	23.39N	162.3W	central Pacific
51004	17.5N	152.6W	central Pacific
46001	56.3N	148.3W	NE Pacific
46004	50.9N	135.6W	NE Pacific
41001	34.9N	73.0W	W Atlantic
44011	41.1N	66.6W	W Atlantic

Table 3. locations of buoys used for model verification

The increased cost is proportional to the increase in number of frequencies, and the model file size is also increased in proportion, so the cost of the run described above is twice that of the model run operationally at the time of the tests.

1.5 A parametric windsea growth term for low windspeeds

The previous sections have demonstrated the need for better representation of waves at low windspeeds within the UKMO wave model. However for winds greater than approximately 7m/s the existing schemes are adequate. Simply extending the frequency range and resolution is not sufficient to significantly improve wave model performance, and increasing the number of frequency bins increases the cost of the model.

One option could be to include a spectral sub-model covering a high frequency range, for use at low windspeeds. If this is attempted the memory required to run the wave model is greatly increased. An alternative approach is to use a 'parametric' growth expression for developing windsea. In a parametric model, the windsea spectrum is described by only a few parameters, and the evolution of these parameters is predicted. An example of such a model is the second generation Dutch wave model GONO (GOlven NOrdsee), Janssen *et al* 1984. This was developed and run operationally at KNMI during the 1980s, and uses an expression for windsea growth depending on the windspeed and the existing windsea. This algorithm has been coded into a trial version of the UKMO wave model physics routine. For windspeeds less than a pre-determined critical value this expression is used to calculate the windsea growth over a timestep, rather than explicitly determining the exponential growth and dissipation terms from the wave spectrum. Once the windsea growth is determined this extra energy may be added on to the existing spectrum using the current look-up tables to reshape the spectrum, or placed in the highest frequency bin of the spectral wave model as appropriate. The approach was first tested in the single gridpoint experimental model.

The expression for the non-dimensional rate of change of windsea energy is, using the notation of the GONO model (equation 18 in Janssen *et al* 1984)

$$B = ab/8\ \beta^2\ \xi^2\ (1-\xi^4)\ \{1/2a\ \ln[(1+\xi^2)/(1-\xi^2)]\}^{(b-1)/b} \qquad \text{Eqn (1)}$$

Where the coefficients a,b and β are determined empirically as:

$$a=6.1 * 10^{-4}$$
$$b=0.75 \qquad \text{Eqn (2)}$$
$$\beta= 4\ g\ (E_{pm})^{0.5}\ /\ (U_{10}{}^2) = 0.2512$$

(In the GONO model a value of $\beta=0.22$ was taken, however evaluating the expression determining this constant using E_{pm} as calculated in the experimental model [Eqn(6) in section 2 of this paper], and taking $U_{10}=0.91\ U_{19.5}$, with $g=9.81 m/s^2$, gave a value of 0.2512 for consistency)

and

$$\xi = (16\epsilon\ /\ \beta^2)^{1/4}$$
$$\epsilon = g^2\, EWS\ /\ (U_{10})^4 \qquad \text{Eqn (3)}$$

where ϵ is the non-dimensional total windsea energy, with g the acceleration due to gravity, U_{10} the 10m windspeed and EWS the model windsea energy.

When multiplied by the non-dimensional timestep, and then re-normalised, Eqn 1 gives the wave energy ΔE which is to be added on to the existing wave energy for this timestep.

$$\Delta E = B\ \Delta t\ (U_{10})^3\ /\ g \qquad \text{Eqn (4)}$$

Figure 4 shows the result of using this expression to calculate windsea growth at low windspeeds. From a comparison with the current UKMO model it was found that for windspeeds below 7.3m/s it was necessary to use the parametric growth term in order to achieve a limiting wave height close to the PM value.

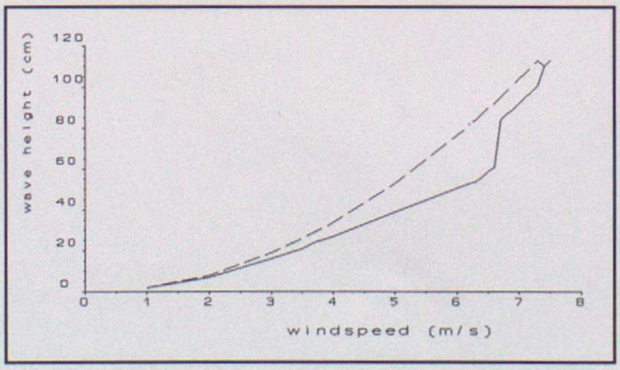


Figure 4 Model equilibrium wave height (cm) as a function of windspeed. The solid line is the 1992 UKMO spectral wave model; the dashed line is the wave height using the parametric expression for windsea growth for (model level one) windspeeds below 7.3m/s

1.6 Case study reruns:

The 'parametric' version of the UKMO wave model has been run on two case studies: the winter case of 1-19 January 1992, and a summer case of 1-19 June 1994. In both cases there was only a small impact on wave heights. There was no noticeable impact on wave period, which remains much shorter than observed.

All the buoys used in verification are in the northern hemisphere, so the summer case may be expected to have a greater incidence of light winds. Two buoys are chosen in each of the central Pacific, NE Pacific and the NW Atlantic, representative of three different wave climates. These are a subset of the buoys used for operational verification, and are chosen to give equal weight in the assessment to the wave model performance in each distinct wave climate.

The mean windspeed at the six buoys used is shown in Figure 6. The model mean wind was close to observed at all buoys except 44011 in the western Atlantic, where the model winds were stronger than observed in June.

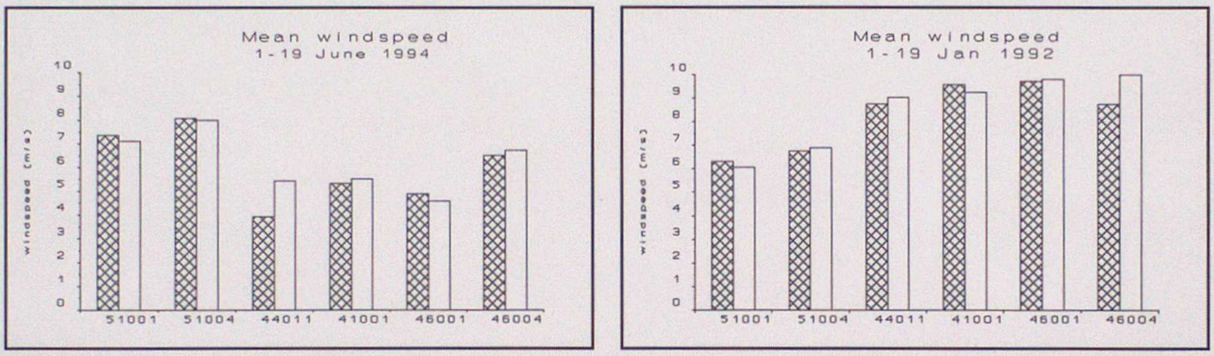


Figure 6 Mean windspeeds (m/s) at representative buoys. (left) 1-19 June 1994. (right) 1-19 January 1992. Observed values are cross hatched. The model level 1 windspeeds are uncorrected for height. The buoy windspeeds are measured at an anemometer height of around 5m.

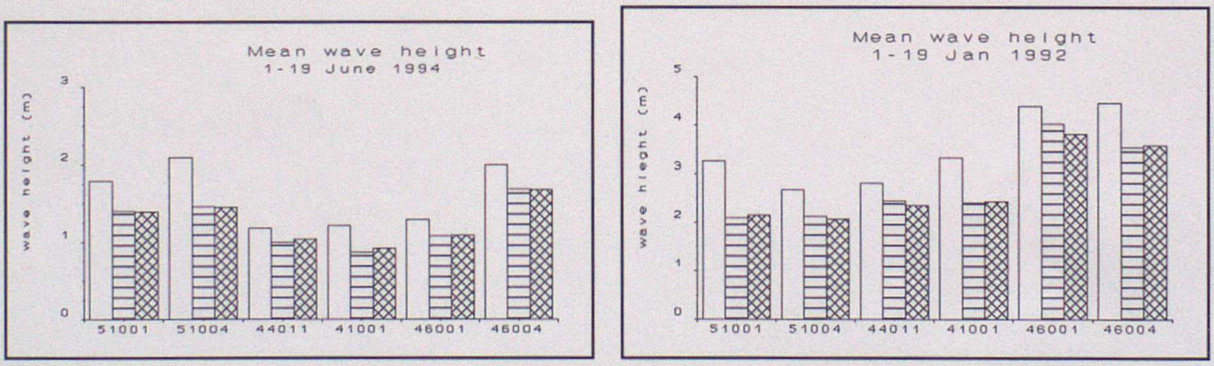


Figure 7 Mean wave heights (m) at representative buoys for (left) 1-19 June 1994 and (right) 1-19 January 1992. Observed values are shown blank; values from the current operational wave model are lined, and from the 'parametric' model, cross hatched.

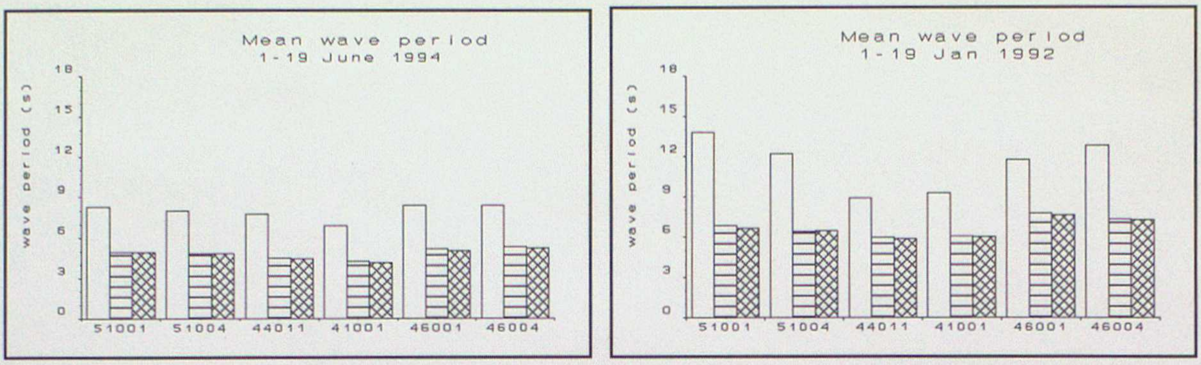


Figure 8: Mean wave periods (seconds) at representative buoys for (left) 1-19 June 1994 and (right) 1-19 January 1992. Observed values are shown cross hatched; values from the current operational wave model are lined, and from the 'parametric' model, blank. Model output is of the 'zero-upcrossing' period.

In both June and January cases the wave period in both models is much lower than observed, and there is little difference in wave period between the trial and control runs. If anything, increasing the high frequency energy present at low windspeeds causes the mean wave period to be shorter in the trial run, as at Buoy 46001 in June. The observed periods are much longer in the winter case, some 14 seconds in the mean at Buoy 51001. This may reflect more longer period swell present in the winter hemisphere. The time-mean of the upcrossing period in the models is also longer in the January case, but is not increased as much as in the observations.

Although there is little impact on total significant wave height, a comparison of charts of separate windsea and swell shows that in areas of light winds the windsea height is increased, but swell height is decreased. This may be expected as the dissipation is proportional to the mean frequency of the spectrum to the power seven, so an increase in the wave energy present at higher frequencies will lead to a greater level of dissipation. This is applied to the entire spectrum, so increasing the dissipation of swell energy. Although direct measurements of dissipation of swell energy are not available, it is thought that the dissipation applied in the UKMO model is too great by a factor of two to three, following recent work on coupling wave and atmosphere models [Chalikov & Makin(1991), Burgers and Makin(1993), Janssen(1991)]. This is explored in Section 2 of this report.

1.7 Costs

File sizes for the 'parametric' version of the model are identical to the operational model, the only difference between the two models lies in the extra calculations and checks carried out in the physics routine. From a run carried out in batch,using approximately 25% of the available C90, the 'parametric' model required an extra 41 seconds CPU for a 3 day run (an increase of 6%). The elapsed time increased by 4 seconds (ie an increase of 13 seconds CPU or 1.33 seconds elapsed per model day).

1.8 Conclusions

Improving wave model performance in light wind speeds served to increase the amount of windsea present. However in two hindcast studies in the global wave model there was only a small impact on total wave height, as swell heights were reduced in these areas. There was no noticable impact on wave period, which remained much shorter than observed.

2 Swell dissipation

2.1 Dissipation

In preparation for future work coupling wave and atmosphere models, a review of the present understanding has been carried out. This revealed that the expression for wave growth due to Snyder (1981), used in the UKMO model and early versions of WAM, overestimates the wave energy growth by a factor of between three and four compared to latest results from boundary layer coupled models [Chalikov and Makin (1991), Burgers and Makin (1993), Janssen(1991)]. However this is compensated by a tunable constant in the dissipation term, so that the residual term (S_{exp} - S_{diss}), which drives wave growth in the model, is approximately correct.

Because of this overestimate all waves other than actively growing windsea will suffer excessive dissipation in the UKMO wave model: in particular we are dissipating too much swell compared to the WAM model. Direct measurements of swell dissipation are unavailable, preventing an absolute assessment of this term.

Ideally this problem should be addressed by reformulating the growth term in the wave model: this is a major exercise and will be tackled as part of the planned work on coupling wave and atmosphere models. A simpler approach suitable for immediate application is to reduce the dissipation of all but actively growing windsea, multiplying by a suitable factor. In this approach the windsea growth is unaltered, but the dissipation of swell is re-tuned to be in line with that expected from latest theoretical and modelling results. Tests have shown a factor 0.5 to be appropriate. The expression used to calculate energy loss due to 'whitecapping' and other dissipation is given by :

$$S_{dis}(f,\theta) = A\ [\sigma/\sigma_{pm}]^m\ [\omega/\varpi]^n\ \varpi\ E(f,\theta) \qquad \text{Eqn (5)}$$

where A is a tunable constant (present value=$4.5*10^{-5}$) and the constants n,m are set to n=m=2. $E(f,\theta)$ is the wave energy spectrum, and ϖ is the mean frequency of the wave spectrum. The mean wave steepness is given by $\sigma=E_{tot}\ \varpi^4/g^2$ (with E_{tot} the total energy contained in the spectrum and g acceleration due to gravity), and σ_{pm} (=$4.57*10^{-3}$) is the integral wave steepness for the Pierson Moskowitz spectrum.

In the revised model, for all except actively growing windsea, the expression given in Eqn(5) is multiplied by 0.5. 'Windsea' in the model is defined as that wave energy within 90 ° of the wind direction, and at a frequency greater than 0.8 times the Pierson Moskowitz peak frequency (Eqn 6) for that windspeed. The windsea is actively growing if the calculated value is less than the Pierson Moskowitz limiting value E_{pm} for the windspeed (Eqn 6).

$$f_{pm} = 0.14\ g\ /\ U_{19.5m} \qquad E_{pm} = (U_{19.5m}\ /\ 1.4g)^4 \qquad \text{Eqn (6)}$$

2.1 Hindcast studies:

Two further hindcasts were run, adding the reduced swell dissipation to the changes in wave growth formulation described in Section 1. The trial resulted in a significant improvement in both wave height bias and standard deviation of errors. Verification statistics are shown below. For January 1992 the mean bias was reduced from -0.71m to -0.33m, an increase in wave height of 0.38m; for June 1994 the wave height bias was reduced from -0.35m to -0.06m, an increase of 0.29m in wave height. Standard deviation of wave height error was also substantially reduced by the revised model.

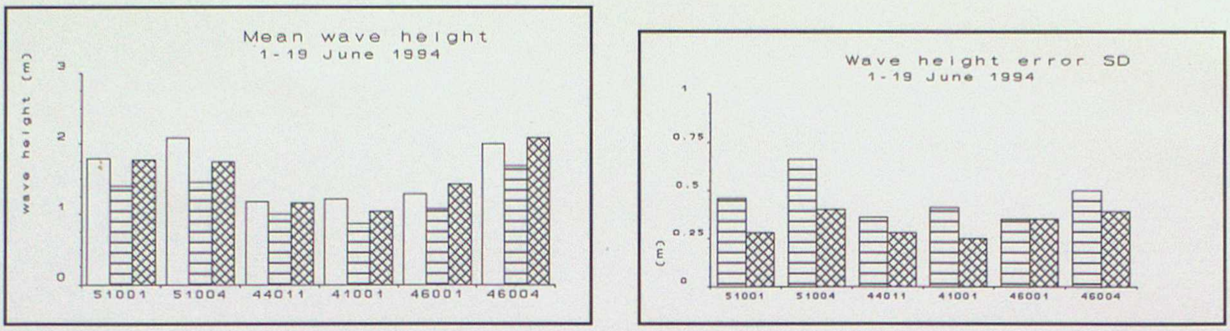
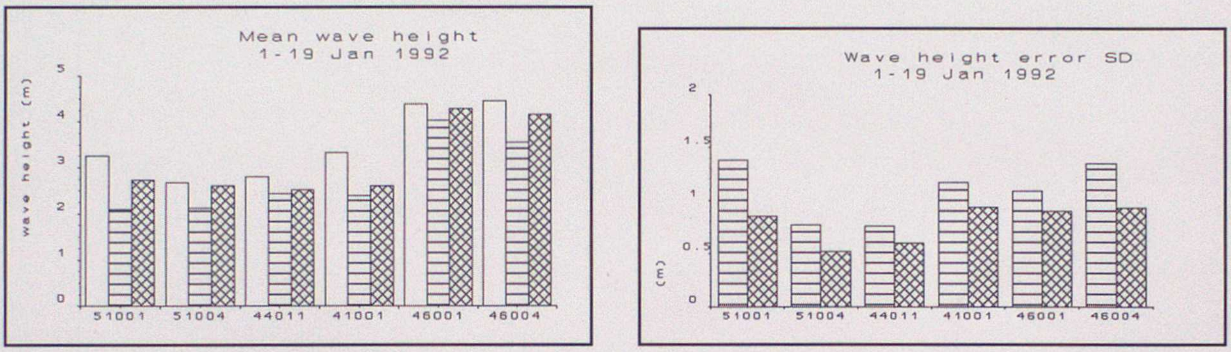


Figure 9 Mean wave heights: observed (blank); current operational (lines) and revised model (cross hatch). Standard deviation of errors: operational model (lines) and revised model (crosshatch)



Timeseries of observed (solid), operational (dotted line) and revised model (dashed line) values of wave height for one buoy in each representative area, from the June 1994 hindcast, are shown below in Figure 10. This clearly shows the increase in swell height at Hawaii (Buoy 51004); at Buoy 46004 there is a smaller increase in swell height from time to time, and consequent increase in some wave height maxima in the model, and at Buoy 41001 maximum wave heights in storms were not altered by the revision. The timeseries at Buoy 41001 shows an increase in wave height in the revised wave model towards the end of the period, when both observed and modelled windspeeds fell below 5m/s for several days.

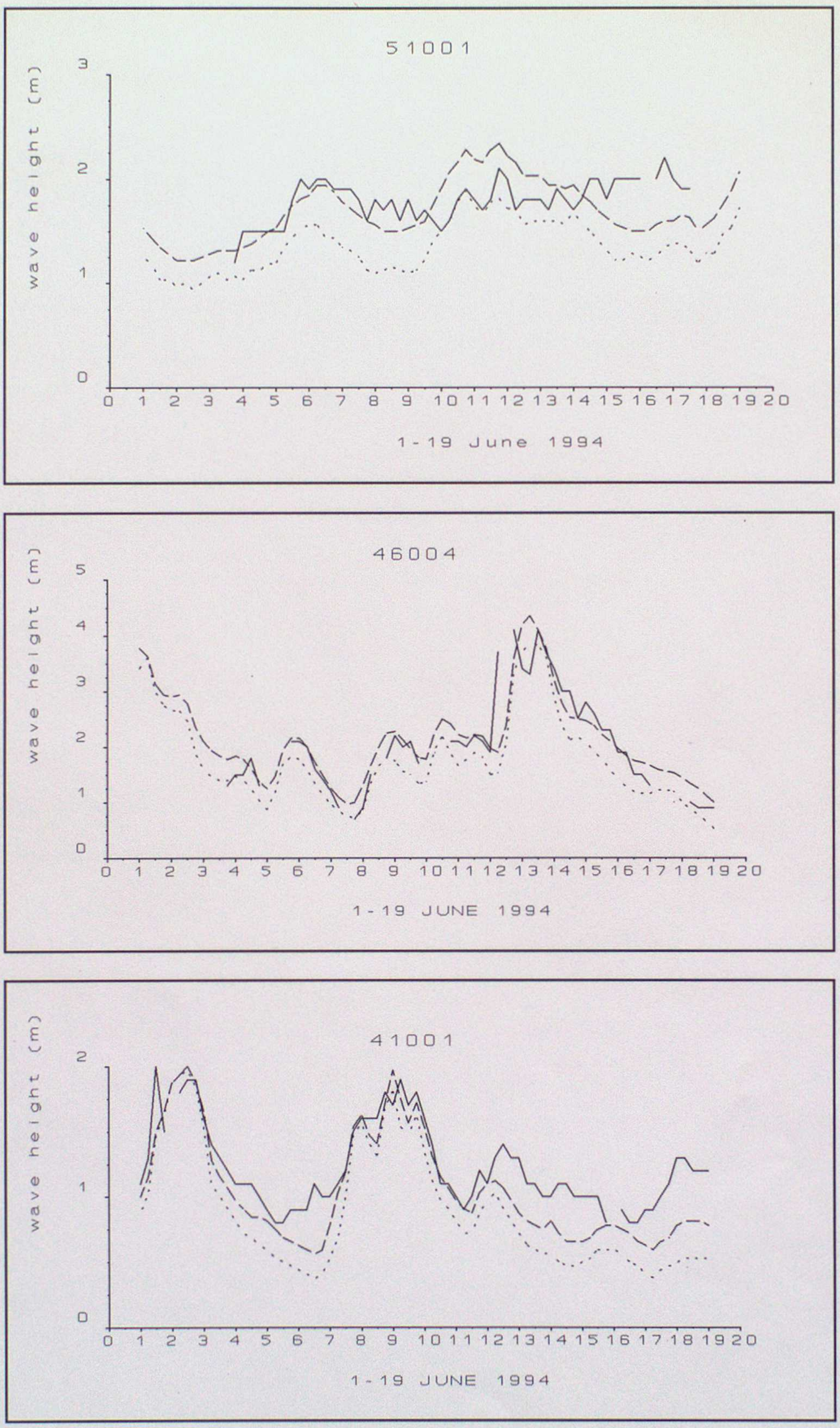


Figure 10 Timeseries of observed (solid), operational model [as at early 1994] (dotted) and revised model (dashed) wave heights for 1-19 June 1994. (a) at Buoy 51001 (b) at Buoy 46004 and (c) at Buoy 41001.

2.3 Costs and filesizes

File sizes are unaltered, and as the model frequencies are unchanged there will be no impact on the structure of the wave model archives used by Commercial Services, although the data quality should improve following operational implementation. For runs in batch the cost of a typical 3-day forecast increased from 676s CPU to 743s CPU (10%), with an increase in elapsed time of 20 seconds (11%), using 24% of the C90. For the operational global wave model this would be an increase of approximately 140 seconds CPU and 40 seconds elapsed per run.

3 Summary

The combined package of changes described above improves the response of the wave model to light winds, and sets the dissipation of swell at a level that is in agreement with current understanding of wave energy source terms. It is planned to implement this version of the wave model operationally in the autumn of 1994.

This revised version of the UKMO wave model has been compared against WAM cycle 4, run at the UKMO. The intercomparison is described in Forecasting Research Technical Report 120.

Further improvement to the UKMO wave model could come from a full revision of the wave energy growth term, following the work of Burgers and Makin (1993), Chalikov and Makin (1991) and Janssen (1991), including a full retuning of the dissipation term. This will need to take place before planned development of a coupled wave-atmosphere model. It should also be possible to further refine details of the separation of windsea from swell in the model spectrum.

References

Burgers G and Makin, V — 1993 — Boundary-layer model results for wind-sea growth. JPO **23** pp 372-385

Chalikov D and Makin V — 1991 — Models of the wave boundary layer. Boundary Layer Met **56** pp 83-99

Foreman S J, Holt M W and Kelsall S — 1992 — Assessment of the bias of significant wave height in the Met Office global wave model. FR Division Technical Report 34

Holt M W — 1992 — A re-calibration of the wave model. Short Range Forecasting Division Technical Report 26.

Holt M W — 1994 — Preliminary results of running the WAM wave model at the UK Met Office. FR Division Technical Report 92.

Janssen P A E M, Komen G J and de Voogt W J P — 1984 — An operational coupled hybrid wave prediction model. JGR C3, pp 3635-3654.

Janssen P A E M — 1991 — Quasi linear theory of wind-wave generation applied to wave forecasting. JPO **21** pp 1631-1642

Pierson W J and Moskowitz L — 1964 — A proposed spectral form for a fully developed wind sea based on the similarity theory of S Kitaigorodskii. JGR **69** pp 5181-5190

Snyder R L, Dobson F W Elliott J A and Long R B. — 1981 — Array measurements of atmospheric pressure fluctuations above surface gravity waves. J Fluid Mech **102** p 1-60

WAM group — 1988 — The WAM model - a third generation ocean wave prediction model. JPO **18** No 12 pp 1775-1810