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A comparison of 2nd generation and 3rd generation wave model physics

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1 Introduction

Since the introduction of operational numerical wave modelling at the UK Met Office in 1976 the wave model used has been of the so called 'Second Generation' (2G), in which the energy transfer by nonlinear wave-wave interactions is parametrized. Inherent in this approach is the need to separate wind sea from swell in the wave energy spectrum at each gridpoint. There have of course been refinements and improvements to the model formulation over the years, but the fundamental approach has remained unchanged.

With the parallel development of numerical wave models at other national forecast centres it became clear (SWAMP, 1985) that a more complete description of the nonlinear transfer was required, in order to better approximate the underlying physics. This led to the development of the 'WAM' model (WAM group, 1988) , a so called '3rd Generation' (3G) model, which uses the Discrete Interaction Approximation (DIA) developed by Hasselmann et al (1985) to approximate the nonlinear transfer. This approach is computationally more expensive than a 2G parametrization, but is still an approximation to the exact calculation. To date the exact calculation of the nonlinear transfer has been carried out only in single point experimental models, as the computational requirement prohibits its use in any global or regional model. Indeed the global implementation of the WAM model with the DIA at ECMWF is only at 3 degrees resolution, whereas the operational global implementation with 2G physics at the Met Office is on a grid of 0.833 by 1.25 degrees.

In this paper a comparison is presented of several simple test cases run using the UK Met Office Experimental Wave Model, both with the Met Office 2nd Generation physics, and also with a version of the 3rd Generation DIA routine. The intention is to highlight any differences in performance or any points of close agreement between the two approaches and where possible suggest changes or corrections in the light of the findings. The intention is also to compare the different computational cost of the two approaches, with a view to identifying the costs and benefits from possibly implementing 3rd Generation physics in the Met Office operational wave model at some future date.

2 The Models.

2.0 Wave Growth and dissipation

A numerical wave model solves the energy balance equation (Eqn 1) for the wave energy $E(f,\theta)$.

$$\partial E/\partial t + (C_G.\nabla)\ E = S_{in} + S_{diss} + S_{nl} \qquad (1)$$

The energy $E(f,\theta)$ is discretised into frequency and direction components. The terms on the left of Eqn 1 represent the local rate of change of wave energy and the advection of wave energy by the appropriate group velocity C_G, which is frequency dependent. The right hand side of Eqn 1 represents the source terms from the various physical processes operating. S_{in} represents the energy input from the wind stress, S_{diss} represents energy loss due to turbulent dissipation and 'whitecapping' , and S_{nl} represents the transfer of wave energy through the spectrum by nonlinear wave-wave interactions. Integrated over the whole frequency and direction spectrum the term S_{nl} is zero. The terms arising through the effects of shallow water were not included in this comparison.

For the comparisons presented here both models used the same form of S_{in} and S_{diss} , although with different dissipation coefficients as described below. The term S_{nl} was represented either by the UK Met Office 2nd Generation parameterisation, or by the 3rd Generation Discrete Interaction Approximation.

2.1 UK Met Office 2nd Generation physics

Following the introduction of the CRAY computer to the Met Office the operational wave model is now written in standard Fortran. The wave growth subroutine used in the experimental model has been re-written to be an exact copy of the operational code, but applied at one grid point only. This allows a direct testing and evaluation of the operational code which was not previously possible as the code used on the Cyber contained machine dependent special calls. Indeed the test cases used here initially revealed some small errors in the CRAY operational code which would otherwise have remained undetected.

The formulation of the 2G model is described in detail in Wave Model Documentation Paper No 6 (unpublished, available from S-Division). Wave growth follows Snyder (1981), consisting of both a linear growth applied to the highest model frequency when generating windsea from zero energy, and the exponential growth term. The dissipation scheme is based on that used by the WAM model (WAM 1988), with coefficients tuned to suit the 2G physics. A parametrisation of directional relaxation in turning winds is also included (Ephraums, 1986). Operationally the model is run with a source timestep of 1 hour, with 16 direction bins and 13 frequency bins. Details of the constants used are given in Table 1. For direct comparison with the 3rd Generation model experimental runs were also made with 26 frequency bins, and with a timestep of 2 minutes.

Table 1 : values of constants used in 2G model

Number of direction components :	16
Number of frequency bins	13 or 26
Frequency range	0.04Hz to 0.324Hz
Dissipation coefficient	5×10^{-5}
Exponential growth coefficient	0.2
Directional relaxation coefficient	$4.0. \times 10^{-4}$
Source timestep	3600 sec or 120 sec

2.2 3rd Generation DIA routine

The version of the 3G code used in the Experimental Model is an early version of the code used in the WAM model amended for research use and further modified to interface with the Experimental Model. It is important to note that further development and refinement has taken place to the code used in the WAM model since this copy was taken, and any conclusions drawn relate only to the version used here.

Calculation of the full nonlinear wave-wave interaction involves an integral over all possible wave numbers, although only a small selection of the interacting resonant wavenumbers contribute significantly to the transfer. This fact forms the basis of the discrete interaction approximation (DIA) (Hasselmann et al 1985) which considers, for each wavenumber, only a single quartet of resonant interacting wavenumbers. The computation involved is greatly reduced. It is important to note that the exact calculation , against which the DIA was verified, depends on the spectral form assumed when calculating the transfer coefficients, and a different set of transfer coefficients must be calculated if the actual spectral shape becomes significantly different from that first assumed. The DIA applies one algorithm to all spectral forms, so introducing a further approximation.

The formulation of the DIA requires a high resolution in frequency, so for the 3G model a total of 26 frequency bins are used, although the frequency range is not altered from the 2G model. A correction is included in this version of the code to enforce the total integrated nonlinear term to be zero. If the model departs greatly from balance at any timestep the model may become unstable, as the nonlinear calculation may then be perfomed on an unrealistic energy spectrum. For this reason it is necessary, with the explicit finite difference scheme used for the source terms in the experimental model, to use a sufficiently short timestep. A source timestep of 120 seconds has been found suitable. The WAM model uses an implicit time scheme for the source terms, allowing a timestep of 20 minutes.

Further, because there is no artificial constraint on the spectral shape with 3G physics, the source term coefficients must be carefully tuned to give the correct asymptotic energy balance for a growing wind-sea. As the 3G physics gives rise to spectral shapes which differ in detail from 2G physics, the net dissipation applied will also differ as the dissipation function depends on certain mean parameters of the wave energy spectrum. Therefore a dissipation coefficient different from that used in the 2G model is required. The value was selected to give the correct asymptotic wave height for a wind sea growing from rest, from the tables in the WMO Manual (WMO 1987). Values used are given in Table 2.

Table 2 : values of constants used in 3G model

Number of direction components :	16
Number of frequency bins	26
Frequency range	0.04Hz to 0.324Hz
Dissipation coefficient	1.5×10^{-5}
Exponential growth coefficient	0.2
Directional relaxation coefficient	not applicable
Source timestep	120 sec

3. Model intercomparison

A series of different wind conditions are applied to the models. All the cases involve a duration limited growth, that is a wave field changing with time only. The case of a fetch limited wave field - independent of time but varying with distance offshore - is not studied here. The test cases include growing a sea from rest with a constant wind speed and direction, the response to a turning wind, the response to a falling wind and the effect of a windsea developing in opposition to existing swell. For the purpose of describing the comparison, the run with the current operational configuration (ie the 2G model with a timestep of 3600 seconds and 13 frequency bins) is taken in each case as the control.

3.1 Growing wind-sea :

With a wind of constant strength and direction blowing over an initially calm sea the wave height grows until eventually an equilibrium is reached, when the contributions from all three source terms balance to give zero net energy input in each frequency bin. Initially growth is represented in the model by the linear term, and after the first couple of timesteps by the exponential growth term. Energy is input to the waves at high frequencies, and transferred to lower frequencies by the nonlinear transfer - this controls the evolving shape of the energy spectrum. In the following it is useful to consider the time evolution of the source terms, as well as the distribution of source term with frequency at a given instant. The timeseries shows each source term integrated with respect to both frequency and direction, that is the total source or sink of energy due to that process at each timestep.

Integration with a 20 m/s wind blowing for 60 hours.

a) 2G model with 13 frequency bins and timestep of 3600 seconds.

Figure 1a shows a time series of the energy source terms integrated over the spectrum. The top dashed line is the exponential growth term, the solid line is the total resultant source term, incuding the linear term in the first timestep, and the lower dashed line picked out with crosses is the dissipation term. The integrated nonlinear term is zero. There is an apparent mismatch in magnitude as the linear term switches off and is replaced by exponential growth - this is shown by the drop in the total energy input after the first step. The exponential growth reachs 0.35 m^2s^{-1} after 3 hours and grows in a jerky manner until it reaches a steady value of 0.56 m^2s^{-1} . The jerkiness is caused by the 2G parameterisation reshaping the spectrum - as the wave energy increases, eventually a given frequency bin will be flooded and the re-shaping will spread the energy to include the next lowest frequency bin, whilst conserving the total energy of the spectrum. This results in slightly less energy in each existing frequency component and so a reduction in the exponential growth term. Equilibrium is achieved after 30 hours with a wave height of 7.8 metres. The plot of the 2-D energy spectrum shows a number of peaks which are symmetric about the wind direction, as well as the principal peak along the wind direction. This is an artifact of the interpolation and contouring procedure. After 60 hours the very low energies spread through 80 degrees on either side of the wind direction, while the 0.2 contour (which represents an energy of 1.58 m^2/rad/Hz) spreads through 22.5 degrees. (Fig 1b)

b) 2G model with 26 frequency bins and timestep of 3600 seconds

The timeseries of energy source terms (not shown) shows that the linear growth term is higher than in the run with only 13 frequency components. There is still the apparent mismatch between linear and exponential growth terms. After 3 hours the resultant term has a value of 0.21 m^2s^{-1} increasing to a peak of 0.24m^2s^{-1} . At 30 hours there is still a small residual energy input which decays to zero by 37 hours. This is some 7 hours longer than in the control run. The wave height is 6.7 m after 15 hours and reaches an equilibrium height of 8 metres, 20 cm higher than the control. Comparison of the equilibrium normalised 1-D spectra shows that with a higher frequency resolution the spectral peak is resolved (Fig 2b). With 13 bins the spectral peak falls between two frequency components and consequently is missed (Fig 2a). The timeseries of wave height follows the WMO values well.

c) 2G model with 13 frequency bins and a timestep of 120 seconds

As in the previous examples there is an apparent mismatch in magnitude of the total source term as the initial linear growth switches over to exponential growth. There are many more oscillations in this time series than in the control. This is caused by the reshaping algorithm as energy spreads to lower frequency bands as the spectrum grows. With a smaller timestep the reshaping is carried out more often, at spectral energy levels between those present in the runs with a longer timestep. These differences are however superficial as equilibrium is reached within an hour of the time taken by the control run. The wave height reaches 7.8 metres, as in the control. The 2-D energy spectra are virtually identical but this version has less noise at 0.05 Hz. The 1-D energy spectrum shows a difference at 10 hours, as the 120 second run has slightly more energy in a lower frequency resulting in a flatter spectral peak, but the spectra settle down to the same shape after 20 hours. At 10 hours the peak is at 0.08 Hz with a value of 0.44 times the Pierson Moskowitz limit (EPM) for the windspeed, compared to a peak energy of 0.53 EPM at 0.095 Hz in the control.

d) 3G model with timestep of 120 seconds

The evolution in the 3G model is much smoother due to the continuous nature of the model. The normalised 1-D spectrum has a smaller peak than in the 2G model, but is spread out over greater frequency range. The energy - source terms (Fig 3a) show a much smoother evolution than in the 2G models, as there is no jerkiness caused by energy moving into new bins on reshaping. The significant wave height reaches 6.9 metres after 15 hours and 8 metres after 60 hours. The wave height is still growing very slowly but appears to be tending to a value of about 8.2 m (Fig 3b). The 2-D spectrum is similar to that of the 2G model except the spectral shape is more spread out with some of the very low energies spread 135 degrees from the direction of the wind (Fig 3c). The peak energy is situated along the wind direction. The 0.2 contour (which represents an energy of 1.58 m^2/rad/Hz) is spread about 100 degrees each side of the wind direction, at a frequency of 0.13Hz.

Integrations with a 10 m/s wind blowing for 60 hours

Qualitatively the description of the previous section also applies when a windspeed of 10m/s is applied to each of the models. In the control 2G model equilibrium is reached after 25 hours, with a wave height of 1.8m. This is lower than the empirically derived WMO value of 2.2m, suggesting that the value of the dissipation coefficient used in the 2G model was too high. The 2-D spectral shape has a 75 degree spread from the wind direction for low energies and a 20 degree spread for 0.2 contour. In the 3G model equilibrium is also reached after 25 hours, but with a wave height 2m, closer to the WMO value. As was the case with the 20m/s windsea, the spectrum in the 3G model is broader than in 2G model.

Conclusions from this section

For the growth of a 20m/s windsea all models followed the WMO values for wave height growth well with only slight differences. The 3G model and the 2G model with 26 frequencies reach 8.0 m after 60 hours while the 2G models with 13 frequencies, both for 1 hour and 2 minute timesteps reach 7.8 m after the same time. The angle through which the energy spreads from the mean direction is markedly larger for the 3G than for the 2G integrations, suggesting that the version of the 3G model code used may be spreading the energy through too great a range of directions. This point may require further investigation.

From the integrations with 10 m/s wind generating a windsea for 60 hours it was noted that the wave heights differed significantly between the models. This suggests that the constant for dissipation in the 2G model has been set for a 20 m/s wind. The dissipation coefficient was reduced by 10 % in the 2G model and the integration was performed again, resulting in an increase in the waveheight to 2.0 m.

■ For a given windspeed the spectral shape and total energy in the 2G model depends on the number of frequency components used. Higher resolution in frequency better locates the spectral peak frequency.

■ For windspeeds of 15m/s or lower the equilibrium wave height in the current 2G model is less than that in the WMO tables.

■ The mismatch in magnitude of the source terms at the transition between linear and exponential growth is not likely to have serious consequences, but nevertheless deserves investigation.

■ The spread of even low wave energy levels to more than 90° from the wind direction by this version of the 3G model is unrealistic and needs further investigation.

3.2 Turning winds

One of the major differences between 2G and 3G physics identified by the SWAMP report (SWAMP 1985) was in the response of the spectrum to a turning wind. Immediately following the SWAMP report a parameterisation of directional relaxation of the spectrum was included in the UK Met Office 2G model (Ephraums, 1986). At that time the scheme was compared against such observational studies as were available. The experiments reported here are the first comparison between the 2G parameterisation and the exact calculation of a 3G model.

Young et al (1987) compared the 3G WAM model with the exact nonlinear calculation for various turning wind situations. They found that for windshifts up to 60° the spectrum remains coherent and adjusts smoothly to the new direction. For windshifts greater than about 60° a new windsea develops separately from the old windsea which then decays.

A 20 m/s wind turning 30° in two steps over 30 hours.

a) 2G model with 1 hour timestep and 13 frequencies

The evolution of source terms in this run closely follows the development in the control run of the previous experiment (without turning the winds), with minor differences as equilibrium is reached. Small reductions in the exponential and resultant terms occur when the wind turns, though after about 90 minutes the source terms have returned to their previous values. Equilibrium is reached with a wave height of 7.8m (the same as for a constant wind direction). Following the turn in wind direction the wave energy at lower frequencies turns more slowly than the energy at higher frequencies (Table 3). The spectrum reaches equilibrium some 10 hours after the angle change.

		time (hours)		
		18	30	60
frequency	0.15	14°	15°	30°
(Hz)	0.14	13°	15°	30°
	0.10	7°	15°	30°
	0.08	5°	13°	28°

Table 3: Angle turned through by particular frequencies at certain times. 2G model

b) 2G model with 26 frequencies, timestep 120 seconds.

The timeseries of energy source terms follows the control run with minor differences after the second turn in wind direction. There is no change in wave height evolution or 1-D spectral shape.The rate of turn of energy in a particular frequency bin (Table 4) was similar to the control.

		time (hours)		
		18	30	60
frequency	0.15	14°	15°	30°
(Hz)	0.14	14°	15°	30°
	0.10	9°	15°	30°
	0.08	5°	13°	28°

Table 4: Rate of turn of wave energy in particular frequency components, in the 2G model with 2 minute timestep, 26 frequencies.

c) 3G model with timestep 120 seconds, 26 frequency bins.

The timeseries of energy source terms show very little deviation from the run with wind at a constant direction. Small reductions occur in the exponential and resultant terms when the wind turns. This is because the waves in the direction of the wind are of smaller amplitude after the wind turns. The terms take about 90 minutes to return to their previous levels. The resultant drops by 20 % at 15 hours and goes to zero at 30 hours as equilibrium is reached. As in the control run, the significant wave height reaches 8.0 metres after 60 hours. The rate of turn of energy in a particular frequency component is displayed in Table 5. Energy at higher frequencies turns more quickly than at lower frequencies, where the spectral peak is located. After 60 hours the spectrum has nearly reached equilibrium. The peak value is the same as the previous experiment after 20 hours, falling to a lower value after 40 hours before recovering after 60 hours. Virtually all of the spectrum has turned through 30 degrees after 60 hours.

		time (hours)		
		18	30	60
frequency	0.15	12°	15°	30°
(Hz)	0.14	12°	15°	30°
	0.10	5°	15°	30°
	0.08	1°	7°	25°

Table 5: Rate of turn of energy in a particular frequency component for the 3G run

Conclusion from this section

The directional relaxation parameterisation in the 2G model gives a result close to the rate of turn of windsea calculated by the 3G model.

3.3 Falling winds

In the 2G model the reshaping of the spectrum by the parametrization of nonlinear transfer takes place only when the windsea energy is less than the theoretical value of the Pierson-Moskowitz spectrum for that windspeed. The reshaping is thus most effective with a growing windsea. In the case of a falling wind, particularly for example falling from a speed of 20m/s, it is possible that the windsea spectrum for the lower windspeed will be entirely contained within the envelope of the spectrum for the higher windspeed. Thus for some considerable time in the 2G model, until dissipation has sufficiently reduced the energy levels, there will be no calculation of the nonlinear transfer. Further, when the nonlinear transfer is calculated it is restricted in the 2G model to the range of frequencies covered by the windsea part of the spectrum. In the 3G model however the nonlinear transfer is a function of the entire spectrum, and so with a falling wind we may expect the nonlinear transfer of wave energy to continue, and to occur over the full frequency range of the spectrum, not simply over those frequencies covered by the windsea. For these reasons it is expected that experiments with a falling windspeed will provide important insight into the differences between 2G and 3G wave model physics.

Experiments were carried out generating a fully developed windsea, then allowing the windspeed to fall without change in direction. The windspeed either fell to zero, or to some value less than the original windspeed.

20 m/s windsea with windspeed falling to zero.

a) 2G model, 1 hour timestep

Initially the only source term acting is the dissipation. The amount of dissipation decreases quite rapidly in the first couple of hours. After the change in windspeed the waveheight falls from 7.8m initially to 5.6 m after 60 hours, a peak energy of 0.6 times the EPM limit. The 1D spectrum is fairly broad, with energy close to the peak value in a range of frequencies around the peak. (Figure 4a)

b) 3G model 2 minute timestep

After 30 hours the peak energy had fallen to 60 % of the initial value and the peak of the spectrum had moved down to 0.07 Hz. The wave height fell from 7.6 m after 30 hours to 5.5 m after 60 hours. The 1D spectrum (Figure 4b) is more peaked than in the 2G model. More of the swell energy is concentrated at the peak frequency, and there is less energy at frequencies higher than the peak. Figure 4c shows that the 3G formulation continues to transfer swell energy to lower frequencies even after 60 hours. This transfer does not occur in the 2G model, and so the spectra differ. This also implies a difference in the dissipation applied in each case, as the dissipation depends on the spectral form.

20 m/s windsea with windspeed falling to 10 m/s.

After a 20 m/s windsea had been generated the wind speed was reduced to 10 m/s without any change in direction. In the 2G model the wave height fell from 7.8m initially to 5.70m after 10 hours. The dissipation was initially -0.40 m^2s^{-1}, decreasing slowly to -0.02 m^2s^{-1} after sixty hours. The wave height continues to fall, reaching 4.8m after 60 hours. **This is lower than in the case with windspeed falling to zero.** The separate windsea and swell peaks are clearly shown in the 1d spectrum, Fig 4(d), which compared to Fig 4A shows the swell energy much reduced. The peak swell energy reduced to 0.4 times EPM after 60 hours whilst the windsea peak remained constant. Figure 4e shows that the instantaneous peak value of dissipation after 60 hours is doubled when a 10m/s wind is blowing, and also that once the windsea is fully developed the dissipation acts only on the swell energy.

Similarly in the 3G model the swell height was lower than the case without any windsea present.

Conclusions from this section:

In the 3G model continued nonlinear transfer of energy to lower frequencies sharpens the peak of the swell spectrum. This is not present in the 2G model. A consequence of this is that, although the wave energy is conserved during the transfer so total wave height remains unaffected, the propagation of swell will be affected as the group velocity is frequency dependent. With a more peaked swell spectrum there will be less dispersion of swell energy.

The effect of using mean spectral parameters in the formulation of the dissipation is shown, as in both models swell heights fall more rapidly when any windsea is present. This is because the presence of the windsea greatly increases the mean frequency of the spectrum, and the dissipation is proportional to the square of the mean frequency.

3.4 Windsea opposing swell

The previous experiment demonstrated the effect of even a following windsea in increasing the dissipation of swell. The Ships Routing bench have noted over several years a tendency for swell in the central Pacific within the UK wave model to die down very quickly when meeting an opposing wind. The experiments in this section seek to examine which of the source terms may be responsible for this unduly rapid decay of swell.

20 m/s wind turning 180 degrees after 30 hours.

a) 2G model, 1 hour timestep.

The 1-D spectral shape developed a double peak after 30 hours as fresh windsea was generated in the new direction. The windsea peak was 0.65 of the Pierson Moskowitz limit (EPM) for the windspeed and the swell peak energy was 0.56 EPM after 40 hours. After 50 hours of integration this double peak had evolved into a single peak, reaching a value of 1.11 EPM, which decayed to 1.07 EPM by 60 hours. The dissipation term was least prominent at 33 hours, immediately following the windshift, then became more important again. Both the exponential growth and resultant terms increased and the resultant became positive after 35 hours as the new windsea developed. Equilibrium appeared to have been reached after 60 hours. Immediately following the change of wind direction the wave height fell to 7m before growing again and reaching 7.8 m after 60 hours as the windsea became fully developed in the new direction.

b) 3G model.

After the wind turned the wave height fell to 7m, increasing again to 7.9 metres after 60 hours. This was 10 cm less than in the control run. After 40 hours there were two peaks: the swell peak at 0.085 Hz in the original direction with a value of 1.2 EPM, and the windsea peak with value 1.4 EPM was located at 0.10 Hz in the new wind direction. After 60 hours the swell peak in the original direction had fallen to 0.4 EPM at 0.08 Hz and the peak at 180 degrees had increased to 1.6 EPM at 0.09 Hz.
The peaks were less sharp than in the 2G model but the energy levels at higher frequencies were greater, perhaps owing to the greater directional spread of energy in this version of the 3G model. This could account for greater nonlinear transfer from the original direction to the new direction than was experienced by the 2-G model.

Conclusions of this section

The reduction of swell energy through the action of the dissipation scheme is enhanced, in both 2G and 3G models, when windsea, however slight, is opposing the swell.

3.5 Costs

The cost penalty of using third generation rather than second generation physics is threefold :

Firstly the 3G scheme requires a higher resolution in frequency, as the interaction between wavenumbers is explicitly calculated. The WAM model with the discrete interaction approximation uses 26 frequency components, compared to 13 in the UKMO 2G model.

Secondly, because the nonlinear interaction is calculated explicitly the timestep must be sufficiently short to allow a physical balance with the input and dissipation terms. Using the explicit source timescheme of the UK experimental model, a timestep of 120 seconds is required. The WAM model uses an implicit timescheme for the source terms, allowing a timestep of 20 minutes. The use of such a scheme and timestep in the UK model would further have some effect on the costs of the advection scheme, as the advection timesteps (frequency dependent) are divisors of the source timestep.

Thirdly, the actual DIA code is computationally more expensive than the UK 2G code, even when run at the same frequency resolution and timestep.

A high resolution in direction should also be required by a 3G model, particularly when the nonlinear interaction is calculated in the case of turning winds. The WAM model however uses 12 direction bins, which is considered adequate. The test runs of the DIA in the UK experimental model used 16 direction bins in all cases, as in the current UK operational model. The impact of increasing direction resolution on the 3G calculation is not explored here, but should be considered if in the future a 3G model is to implemented. An increase in direction resolution will further increase the cost of implementing a 3G model.

The costs for a simple model comparison at one gridpoint are shown in Table 6.

Table 6

Costs of running the 2G and 3G models

Model	Δt (sec)	n steps	n freq	GO step CPU seconds (IBM)
a) 3G	120	1800	26	10.55
b) 2G	120	1800	26	6.03
c) 2G	120	1800	13	3.25
d) 2G	3600	60	26	0.43
e) 2G	3600	60	13	0.25

■ From (a) and (b) the 3G DIA code, for the same number of timesteps and frequency components, is almost twice as expensive as the UKMO 2G code.

■ With development of an implicit source term timescheme allowing a timestep of 20 minutes, the model will require 3 times as many steps as the current operational 2G.

■ From (b) and (c) , and from (d) and (e), doubling the number of frequencies doubles the work.

Therefore at a single gridpoint the expected cost penalty of a 3G model, compared to the current 2G model, is

Increase to 26 frequencies	2 x cost
Shorter timestep (20 min)	3 x cost
Code more expensive	2 x cost

In total therefore the discrete interaction approximation Third Generation wave model is approximately 12 times more expensive than the current UKMO second generation wave model.

4 Summary and Conclusions

The study has compared an early version of the 3rd generation DIA code with the UKMO 2nd generation code, in several idealised wind situations for duration limited wave growth at a single gridpoint. Fetch limited growth has not been studied, nor has the impact on model performance of other factors such as grid resolution or direction resolution.

In a growing windsea 1D spectra from both versions of the model are similar. There is a difference between UKMO 2G run with 13 and with 26 frequency components - the higher frequency resolution better resolves the spectral peak. In a simple case of turning winds the models agree closely and there is no cause for concern regarding the UKMO parametrisation of directional relaxation. This is in line with the findings of Gunther and Holt (1992) who present a 2G/3G model intercomparison example of turning winds from a hindcast study using real data. Both versions of the experimental code used here suffer from excessive dissipation of swell energy,when any windsea, however slight, is present. This is a shortcoming of the dissipation formulation used, and is only indirectly affected by the treatment of nonlinear terms, in that the dissipation is a function of spectral shape and spectral mean parameters, which may differ slightly between a 2G and 3G evolution.

The third generation code is more expensive to run than the UKMO second generation scheme, and requires a shorter timestep and higher frequency resolution. Overall the third generation scheme, applied at a single gridpoint, will use approximately twelve times the CPU time taken by the second generation scheme, once an implicit source timescheme is developed.

Conclusions

- The UKMO 2G scheme may benefit from an increased resolution in frequency.

- The growth curves and energy balance within the UKMO 2G model should be re-examined following the development of the Cray model.

- The growth curves and energy balance within the version of 3G code used also need further study, as the values selected were not optimal for all windspeeds.

- The parametrisation of directional relaxation following turning winds is effective in the 2G model.

- The dissipation formulation, common to both models, excessively reduces swell energy when any windsea is present.

- The 3G code continues to transfer swell energy to lower frequencies after the wind drops. The 2G code does not. However this is unlikely to be important in practice, as other factors will reduce the swell energy over the timescale required to transfer a significant amount of energy to the next lowest frequency bin. Gunther and Holt (1992) found in a 2G / 3G model intercomparison that both models correctly matched the observed Central Pacific swell at the lowest frequencies.

■ The 3G code, after development of an implicit timescheme, will be 12 times more expensive to run than the 2G code.

Recommendations

Before further considering third generation code at the UK Met Office we must:

a) Develop an implicit time scheme for the source terms, allowing a timestep of 20 minutes in the 3G experimental model.

b) Obtain the code for the current version of the WAM model DIA routine.

c) Develop the Exact-NL code within the Experimental Model, to allow comparison with the exact calculation of nonlinear transfer, thus giving a complete test bed of wave model formulations. (2G, 3G, exact nonlinear)

References

Ephraums, J	1986	Directional relaxation of the wave energy spectrum in turning winds. Met O 2b Technical Note 105. Unpublished document , available from Met Office Library.
Gunther, H and Holt, M	1992	WAM / UKMO wind wave model intercomparison : Summary report. (available from ECMWF and as UKMO S Division Technical Report No 8)
Hasselmann, S, Hasselmann K, Allender, J H and Barnett, T P	1985	Computations and parameterizations of the nonlinear energy transfer in a gravity wave spectrum. Part II: Parameterizations of the nonlinear energy transfer for applications in wave models. J Phys Oceanogr **15**. pp 1378-1391

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** 1-59.
SWAMP group	1985	An intercomparison study of wind-wave prediction models. Part 1: Principal results and conclusions. Ocean Wave Modelling. Plenum Press. 256pp
WAM group	1988	The WAM model - A third generation ocean wave prediction model. J Phys Oceanogr. **18** pp1775-1810
Wave Model Documentation Paper Number 6	1991	Wave model forecast program 'qxglwmodel'. (unpublished; available from S Division, UK Met Office)
WMO	1988	Guide to wave analysis and forecasting. WMO-No 702
Young, I R Hasselmann S and Hasselmann K	1987	Computations of the response of a wave spectrum to a sudden change in the wind direction. J Phys Oceanogr **17** 1317-1338

Figures

Figure 1 Windsea growth in the 2G model, 13 frequencies, 1 hour timestep, with a windspeed of 20m/s

a) Timeseries of energy source terms ($\int S\, df\, d\theta$). (Units m^2/sec)

b) Fully developed 2D spectrum, after 60 hours. (Contour plot of Log10(E(f,θ), contour interval 0.2)

Figure 2 Windsea growth in the 2G model, windspeed 20m/s

a) Normalised 1D spectrum E(f), using 13 frequency bins.
b) Normalised 1D spectrum E(f), using 26 frequency bins (Plots of energy normalised by peak Pierson-Moskowitz energy for windspeed 20m/s, Epm = 95 m^2/Hz))

Figure 3 Windsea growth in the 3G model, windspeed 20m/s

a) Timeseries of energy source terms ($\int S\, df\, d\theta$). (Units m^2/sec)
b) Timeseries of wave height. Crosses mark values from WMO manual

Figure 3 Windsea growth in the 3G model, windspeed 20m/s

c) Fully developed 2D spectrum, after 60 hours. (Contours as Fig 1b).

Figure 4 Falling winds: fully developed windsea 20m/s falling to zero.

a) Normalised 1D spectrum E(f) from 2G model with 13 frequencies and 1 hour timestep. (Normalised by Epm=95m^2/Hz, for u=20m/s)

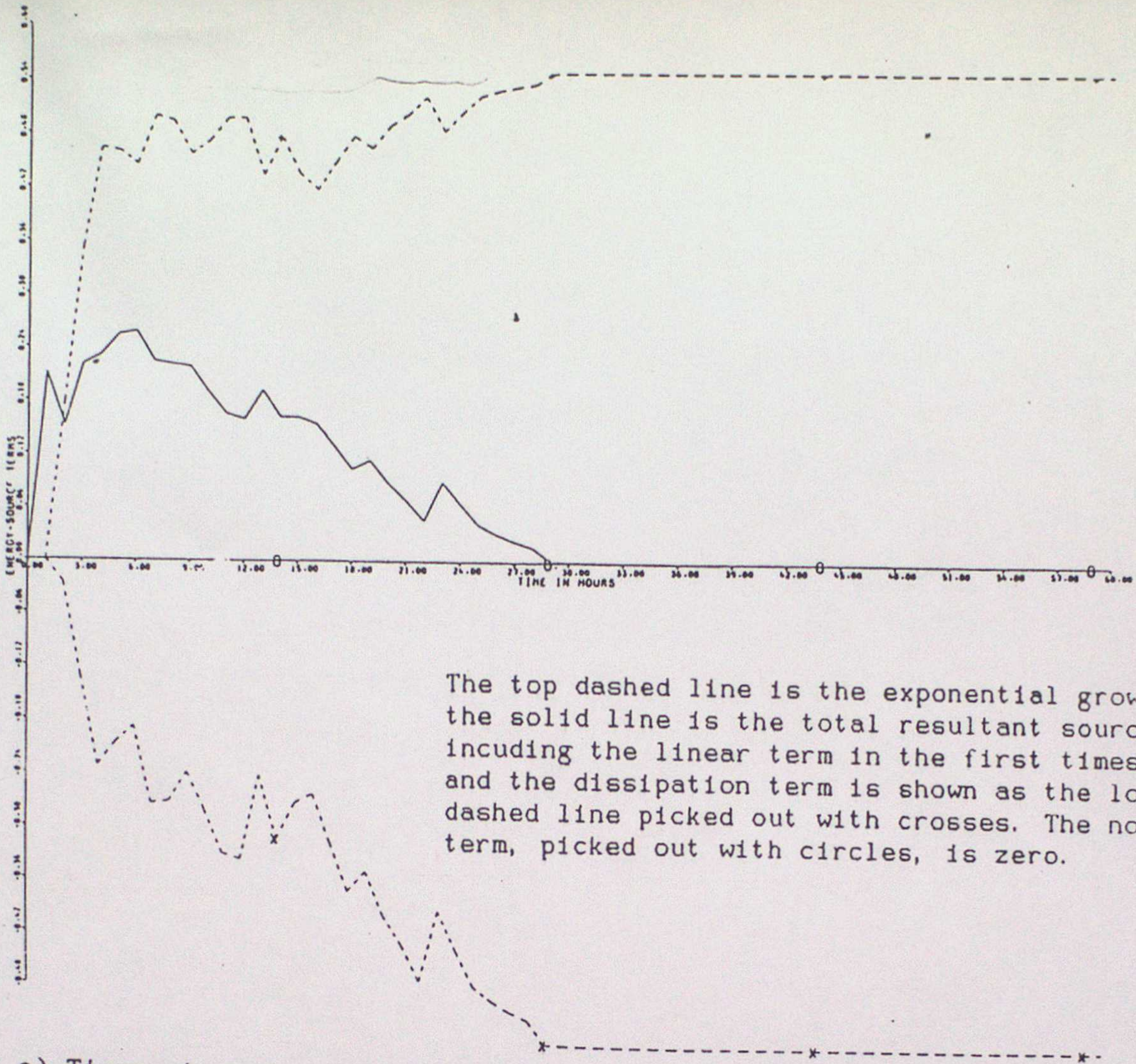
b) Normalised 1D spectrum E(f) from 3G model.

c) Source terms as a function of frequency in the 3G model, after 60 hours. Units m^2/sec.

d) Normalised 1D Spectrum at 60 hours in the 2G model; wind falling from 20m/s to 10m/s.

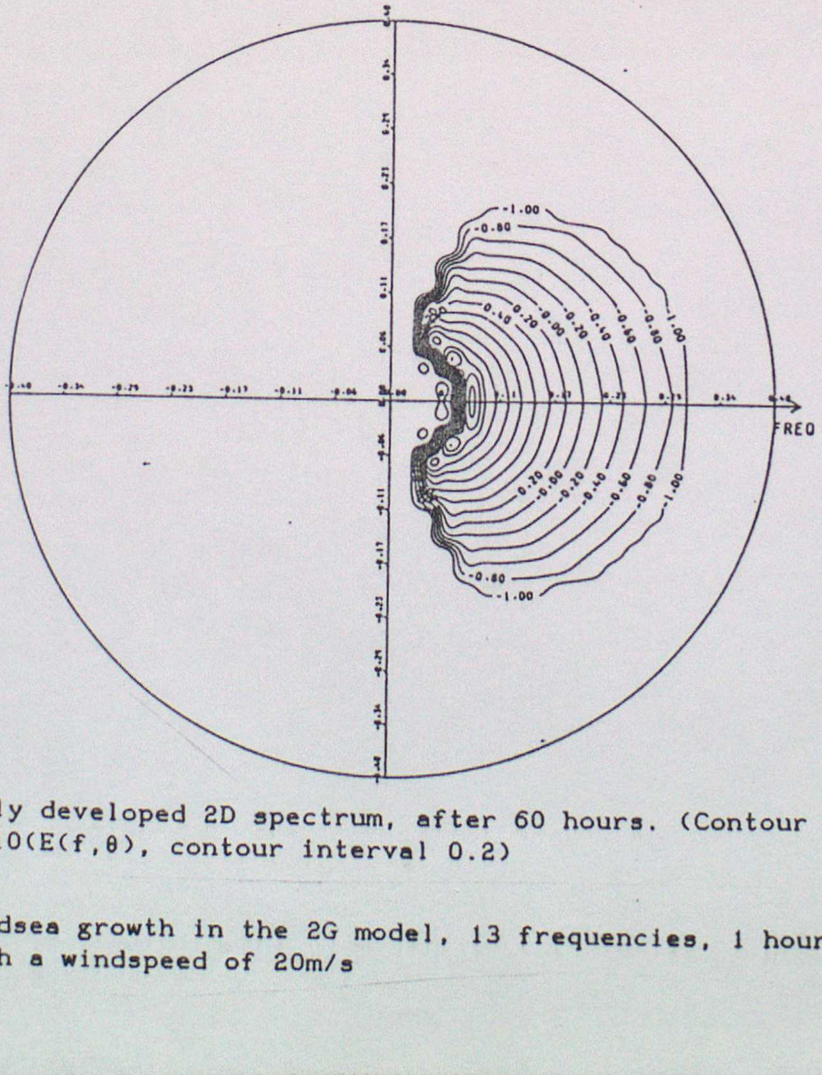
Figure 5 Falling winds: Source terms in the 2G model as a function of frequency, after 60 hours. (Units m^2/sec)

a) Windsea 20m/s; wind falling to zero.
b) Windsea 20m/s; wind falling to 10m/s.



The top dashed line is the exponential growth term, the solid line is the total resultant source term, incuding the linear term in the first timestep, and the dissipation term is shown as the lower dashed line picked out with crosses. The nonlinear term, picked out with circles, is zero.

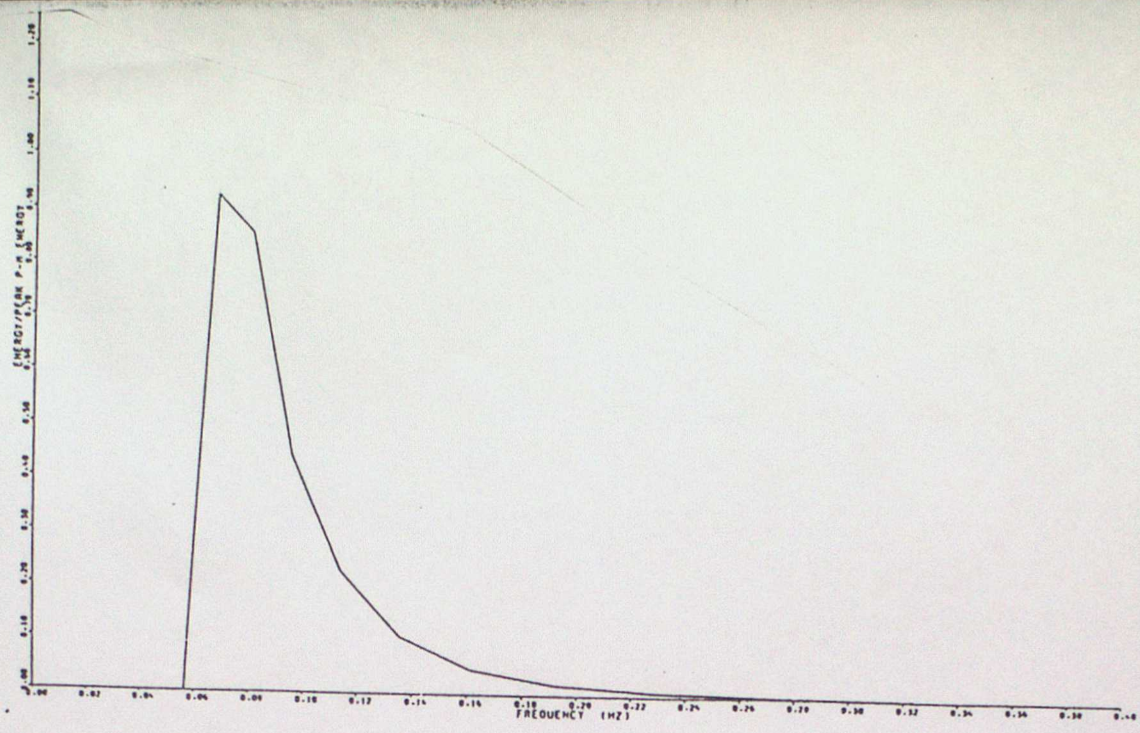
a) Timeseries of energy source terms ($\int S\, df\, d\theta$). (Units m²/sec)



b) Fully developed 2D spectrum, after 60 hours. (Contour plot of Log10(E(f,θ), contour interval 0.2)

Figure 1 Windsea growth in the 2G model, 13 frequencies, 1 hour timestep, with a windspeed of 20m/s

a)



b)

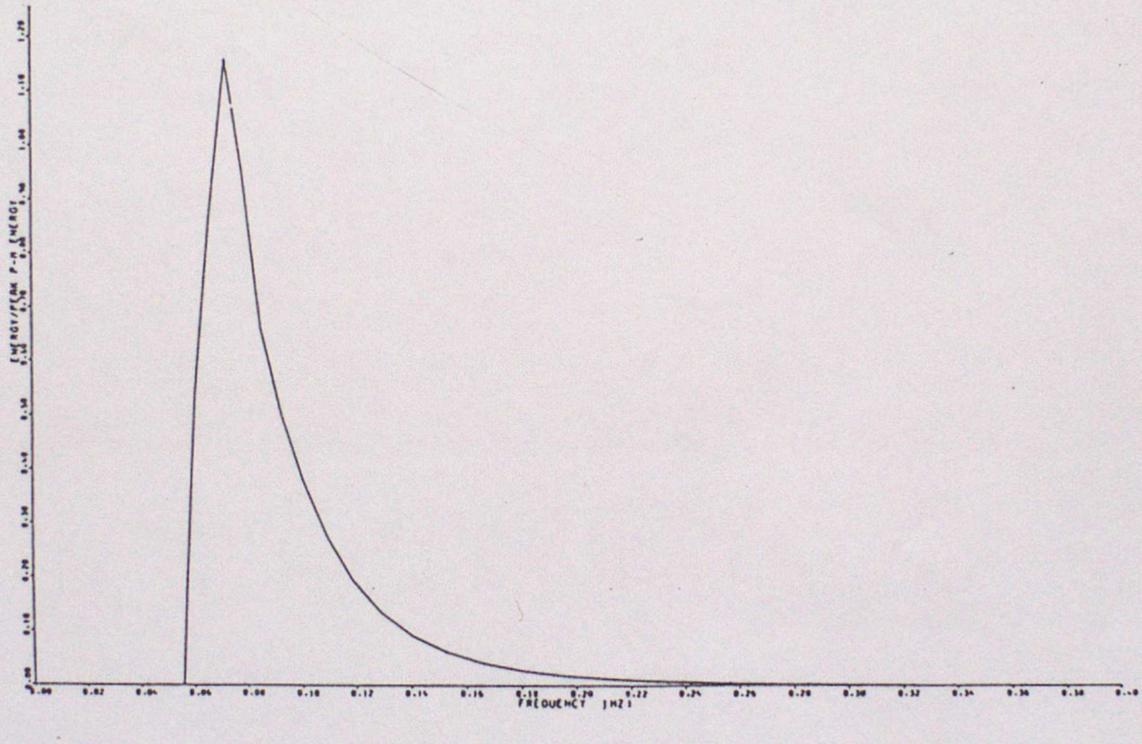
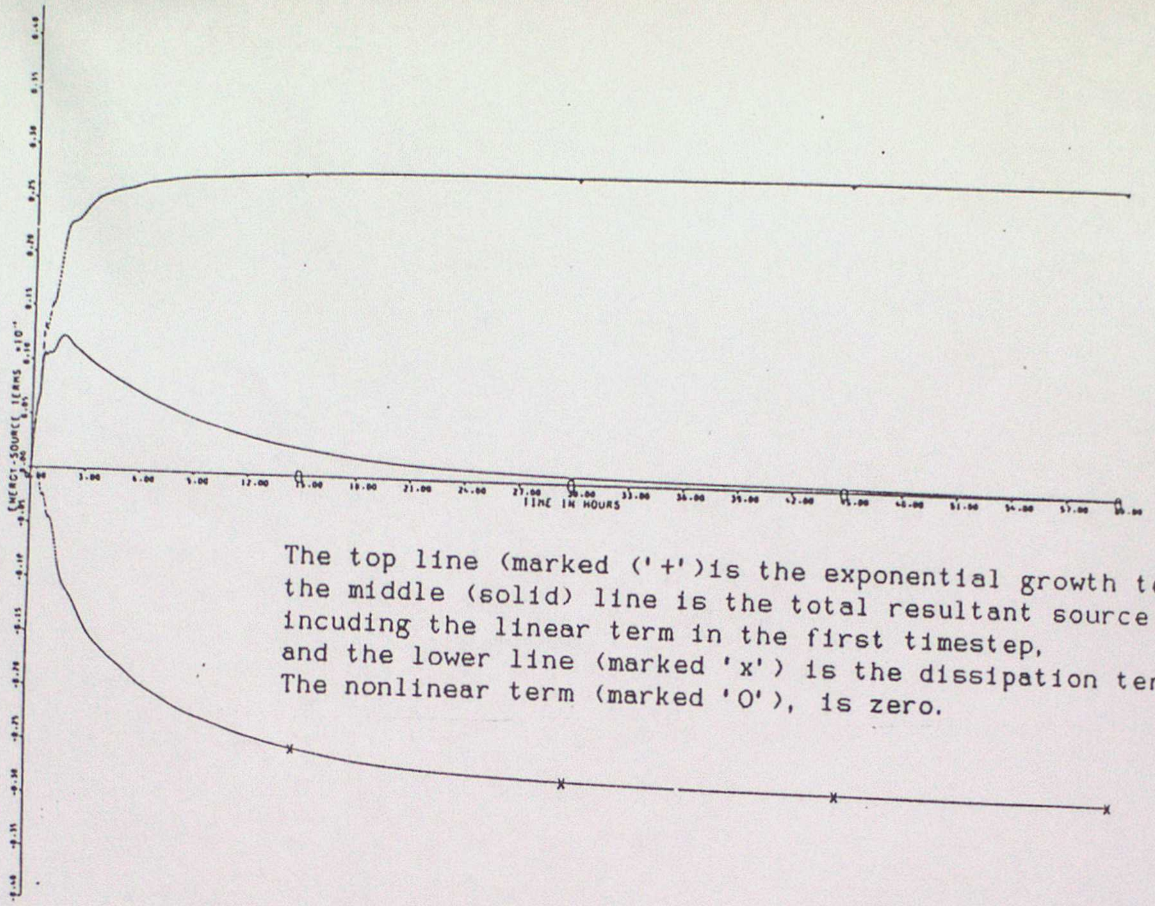


Figure 2 Windsea growth in the 2G model, windspeed 20m/s
a) Normalised 1D spectrum E(f), using 13 frequency bins.
b) Normalised 1D spectrum E(f), using 26 frequency bins
(Plots of energy normalised by peak Pierson-Moskowitz energy for windspeed 20m/s, Epm = 95 m²/Hz))

a)



b)

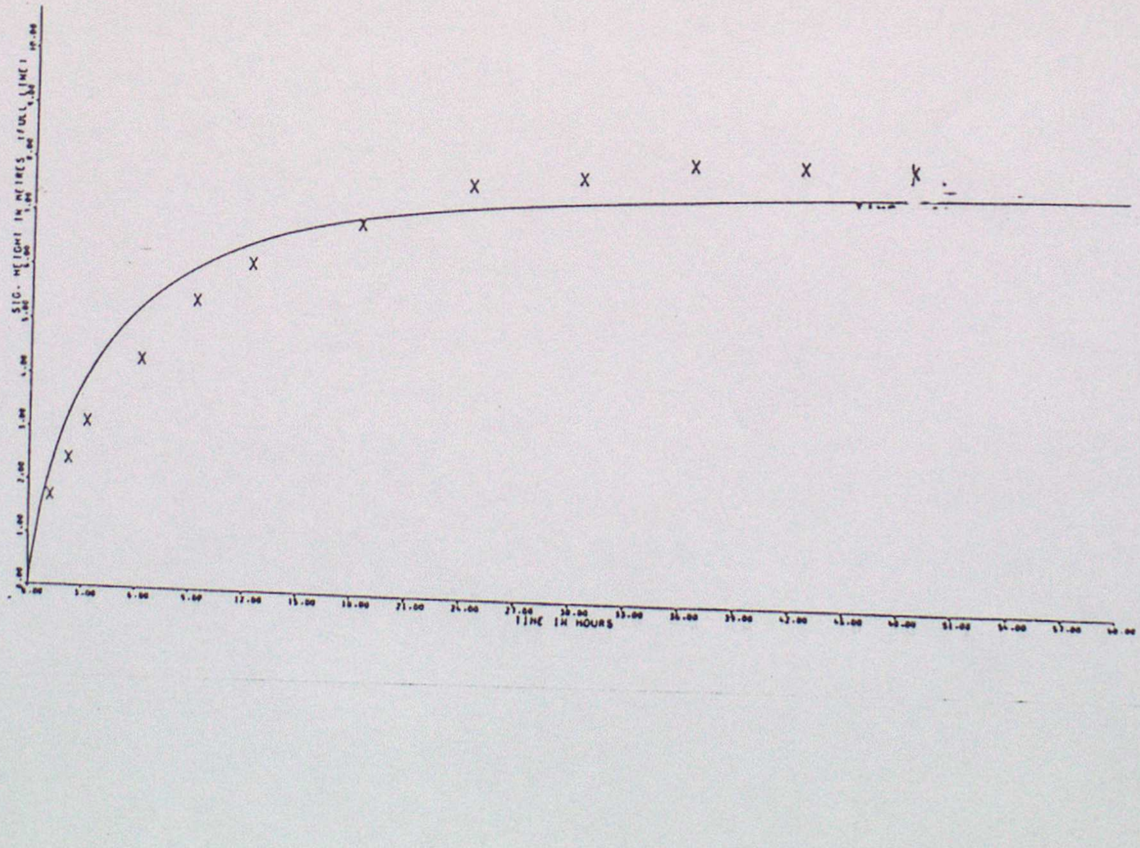
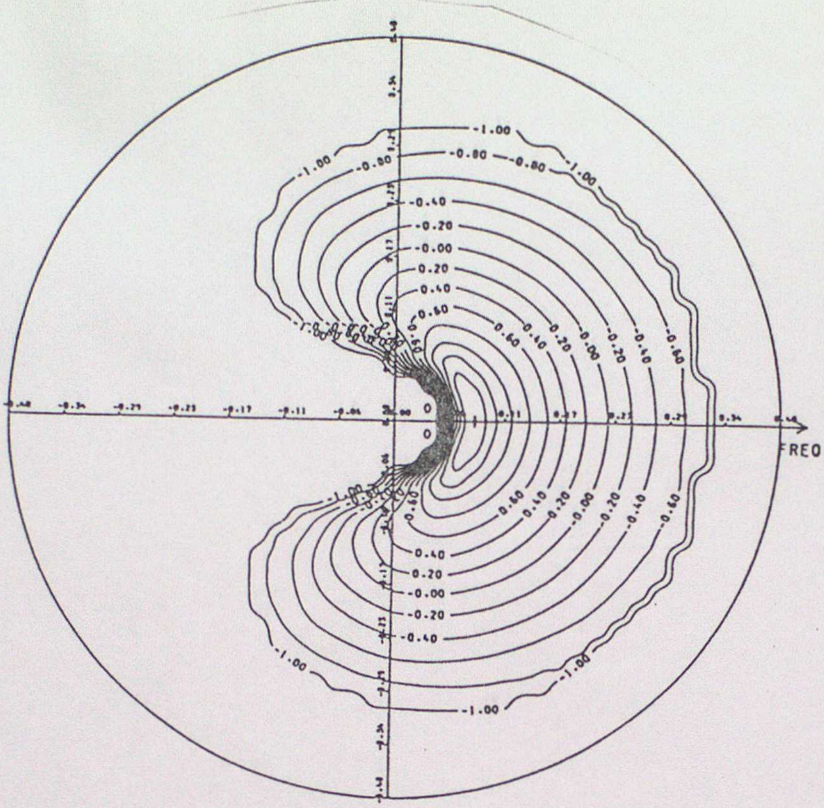


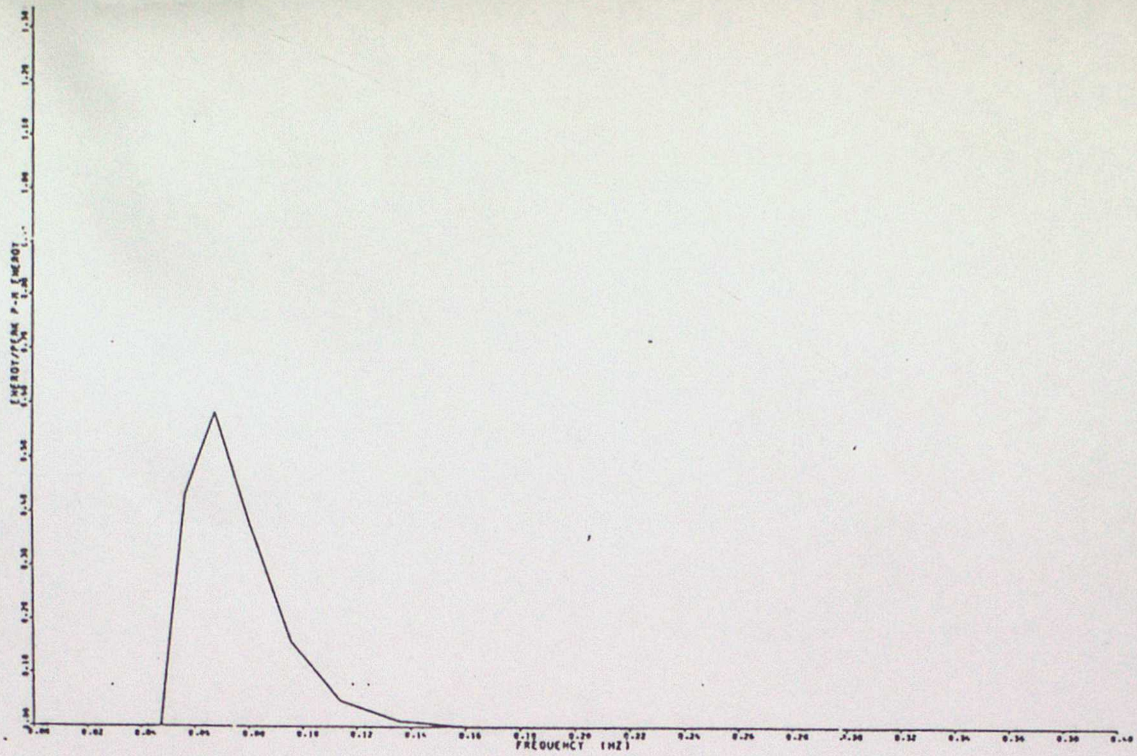
Figure 3 Windsea growth in the 3G model, windspeed 20m/s
a) Timeseries of energy source terms ($\int S \, df \, d\theta$). (Units m^2/sec)
b) Timeseries of wave height.
Crosses mark values from WMO manual



c) Fully developed 2D spectrum, after 60 hours.
(Contours as Fig 1b).

Figure 3 Windsea growth in the 3G model : windspeed 20m/s.

a)



b)

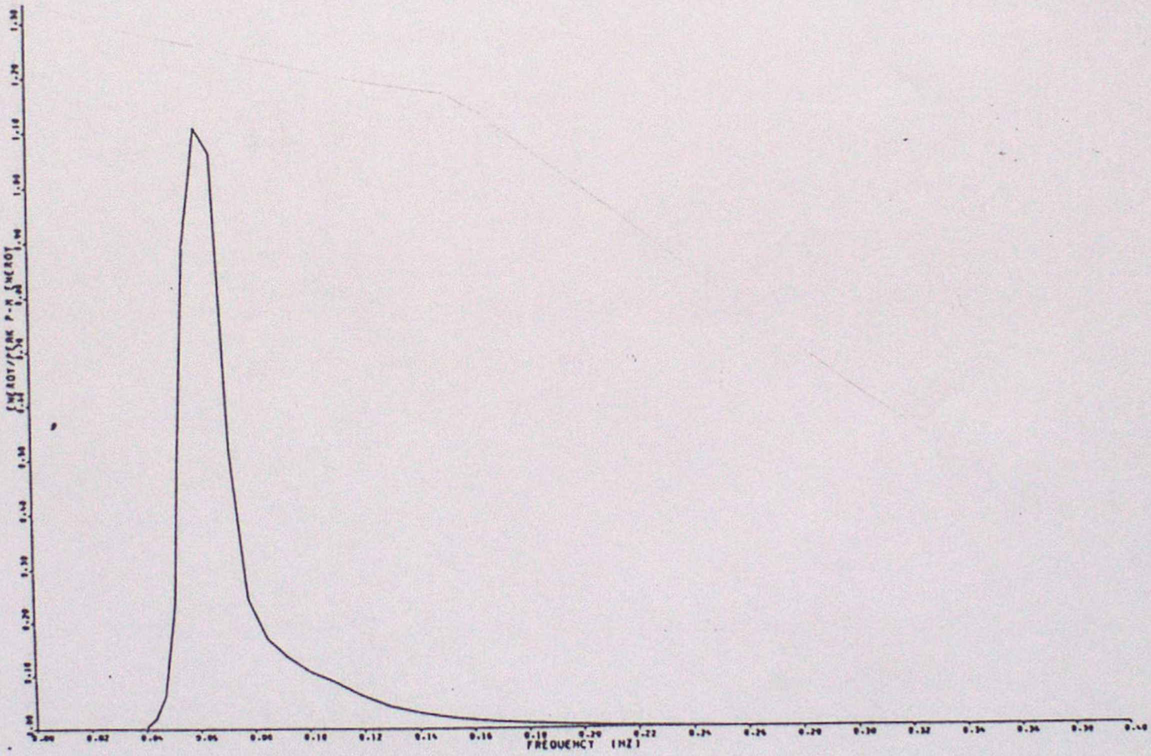
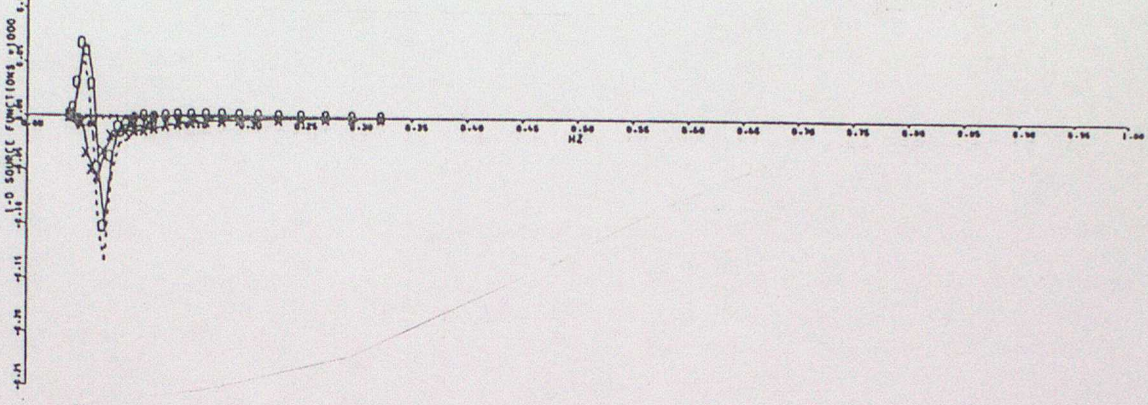


Figure 4 Falling winds: fully developed windsea 20m/s falling to zero.
a) Normalised 1D spectrum E(f) from 2G model with 13 frequencies and 1 hour timestep. (Normalised by Epm=95m²/Hz, for u=20m/s)

b) Normalised 1D spectrum E(f) from 3G model.

The dissipation term is marked with 'X', the nonlinear term is marked with 'O' and the resultant is the dashed line. The wind input is zero in this case.

c)



d)

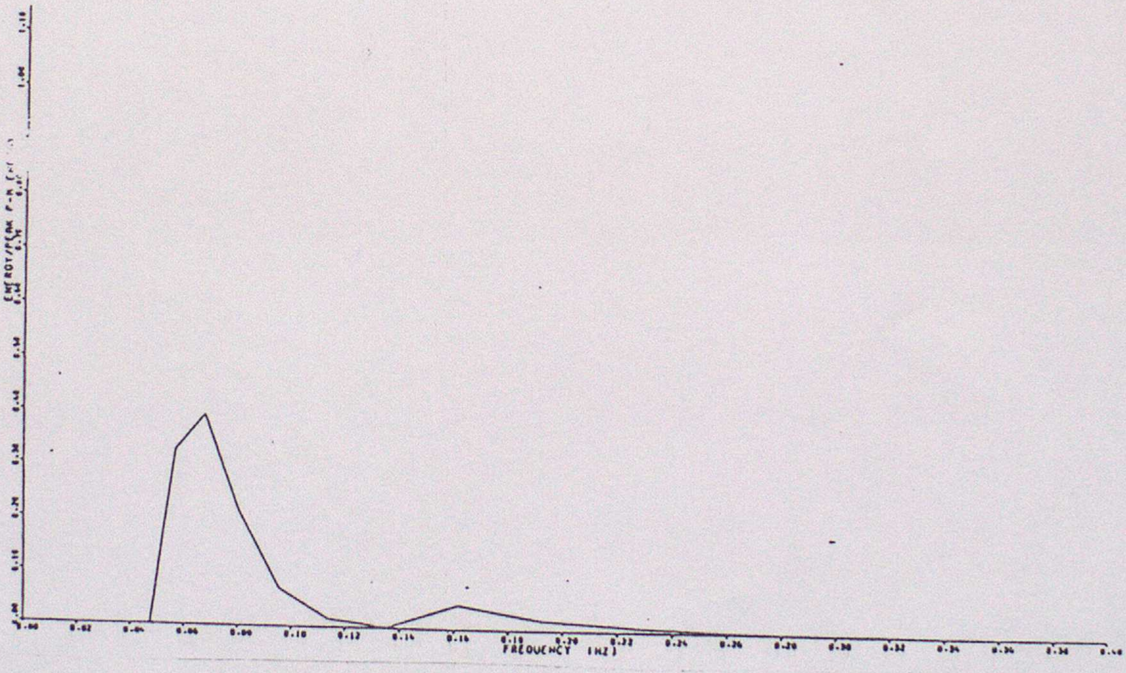
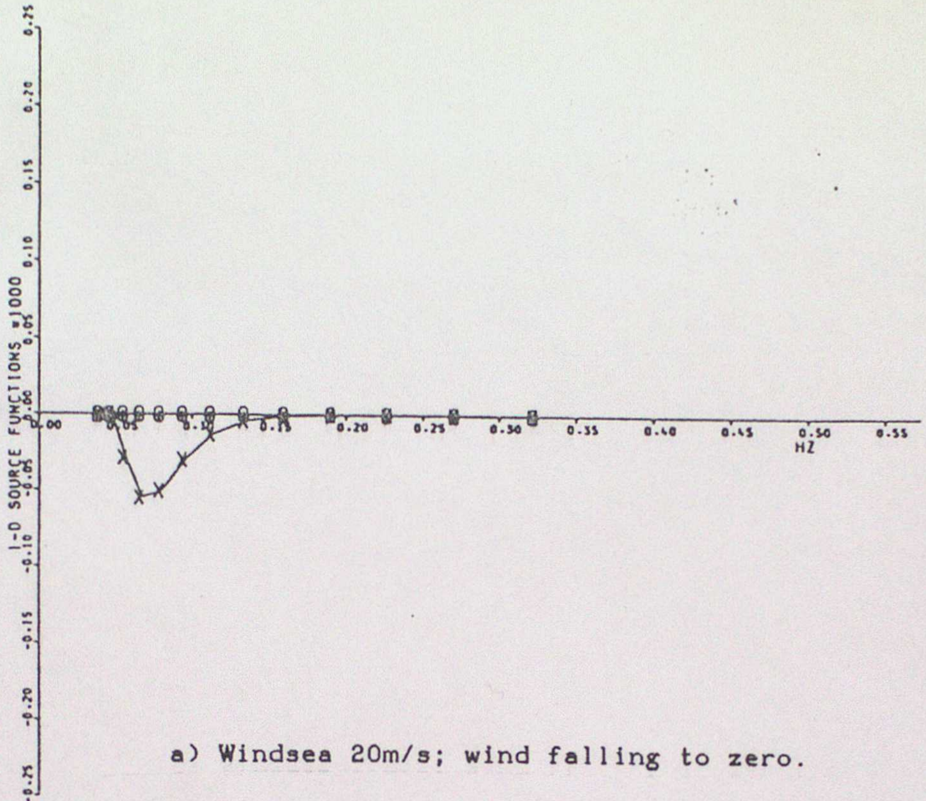


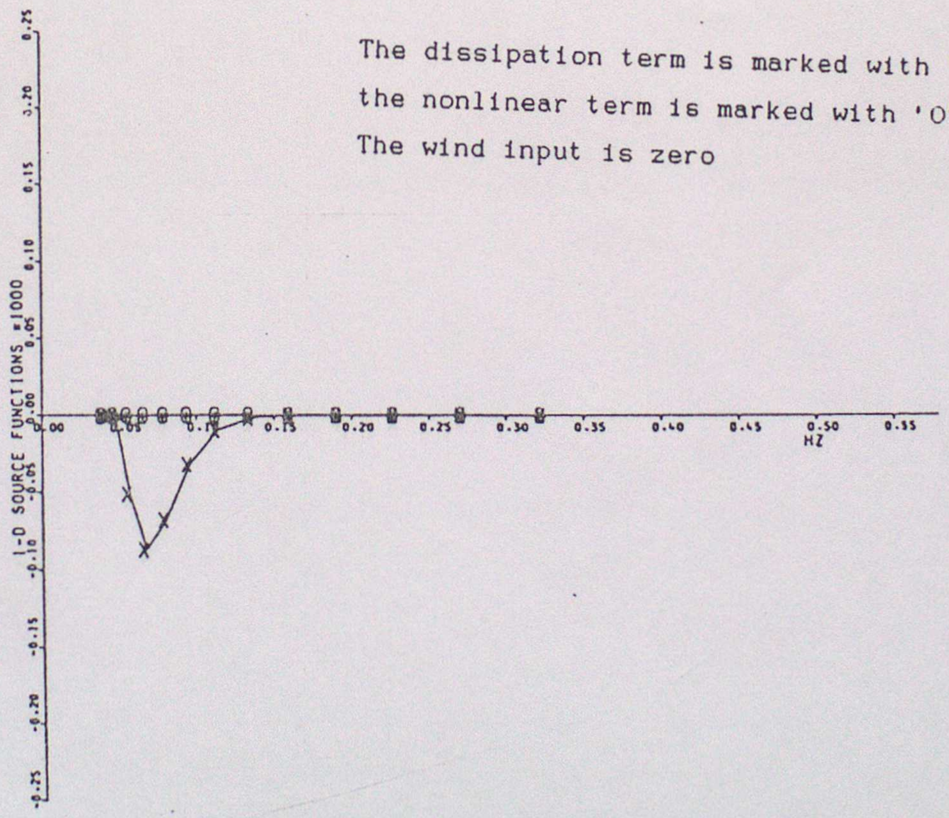
Figure 4 Falling winds : Fully developed windsea at 20m/s, windspeed falling to zero.

c) Source terms as a function of frequency in the 3G model, after 60 hours. Units m^2/sec.

d) Normalised 1D Spectrum at 60 hours in the 2G model; wind falling from 20m/s to 10m/s.



a) Windsea 20m/s; wind falling to zero.



The dissipation term is marked with 'X',
the nonlinear term is marked with 'O'.
The wind input is zero

b) Windsea 20m/s; wind falling to 10m/s.

Figure 5 Falling winds: Source terms in the 2G model as a function of frequency, after 60 hours. (Units m^2/sec)

<u>Short Range Forecasting Division Technical Reports</u>

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