The impact of fierce weather on lazy modelling

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Abstract

The wind forcing used to drive wave models at CCMS-POL is obtained from the UK Meteorological Office. The winds are generated by their 50km resolution meteorological model, with temporal resolution of one hour. They are then interpolated to a 36km grid of the Northern European Continental Shelf on which the spectral wave model WAM is run. Other modellers elsewhere use a variety of different spatial and temporal resolutions, but the dominant factors in the choice are often economics and convenience rather than a rigorous assessment of the requirements for accurate wave modelling. In this paper, this issue is investigated in several ways, by testing the sensitivity of WAM to different wind inputs as well as comparing the UKMO wind fields with those obtained by direct measurement. Six-hourly wind fields are not adequate to reproduce peak events, and if more frequent winds are available then the numerical errors of the model are an important factor.

1. Wind input timescales in WAM

Spectral wave models, of which WAM [1] is a typical example, are used in a wide variety of applications throughout the world. Winds obtained from meterological models are generally used for model forcing but the frequency of input is sometimes as infrequent as six hours.

1.1 A Storm in the North Sea

To test the sensitivity of WAM to a variety of different wind input time scales, a storm in the North Sea was modelled. This event produced the largest waves measured off the east coast of the UK in the Holderness region during a measuring campaign that covered the two winters between October 1994 and March 1996. The coastline at Holderness consists of a 40km length of 20m high boulder clay cliffs that are receding at an average rate of 1.7m per year, constituting a major source of sediment to the North Sea. The maximum significant wave height observed at a waverider buoy 15km offshore at 30m water depth (located at 53°50′35″N, 0°9′59″E and called station N3 hereafter) was 6m.

The wave model was run from the 25th December 1994 to the 5th January 1995 over the Northern European Continental Shelf (covering the region 47°50′ to 63°10′N, 12°15′W to 13°15′E with a grid spacing of 1/3° latitude by 1/2° longitude, which is roughly 36km in size) using UKMO hourly winds sampled at 1, 3, 6 and 12 hourly intervals, and spectral boundary data from the UKMO 2nd generation operational wave model. The wave heights obtained over the entire grid using hourly input were compared with those for the other three runs. The results are shown in Figure 1. For low wave heights the model behaves comparably for all the different input regimes, but the model systematically underestimates high wave events with a bias which increases as the frequency of wind input decreases. This is caused by the less frequent winds failing to reproduce the peak of the storm. Only just over 300 data points from the $O(10^6)$ values generated by the model run have a wave height of over 9m so working out global statistics for the entire run would not reveal this discrepancy. The size and frequency of peak events are, however, of disproportionate importance in, for example, the design of offshore structures, marine safety and coastal erosion. Figure 1 also shows that interpolating the winds linearly between consecutive samples gives worse results than using constant values. This effect has been noted elsewhere [2].

This experiment was validated by performing five more runs all using winds sampled at six hour intervals but staggered by hourly intervals. The combined results for all six of the six-hourly runs show that the highest waves are underestimated by more than 10% in 3 cases, more than 5% in 2 cases and are overestimated by almost 5% in one case (when the six hour wind sample hits the storm peak). If the time scale of this storm is typical for the North Sea then one would expect six hourly

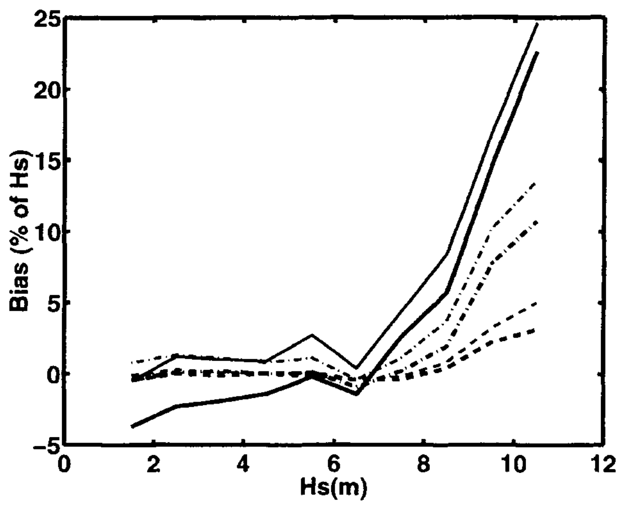

Figure 1: Model errors when wind fields are given at specified intervals. Solid lines are for 12h winds, the dot-dash lines are 6h winds and the dashed lines are for 3h winds. The thinner lines are obtained with temporal interpolation of the wind fields.

wind input to display this range of performance over a number of storms. The relative importance of this numerical error in comparison with the inherent model error and errors in the wind fields is explored in the next subsection.

1.2 Comparison with satellite data

WAM was run with hourly wind input for the two month period of 1st December 1994 to 31st January 1995. Over this period we have wave height measurements from the Topex/Poseidon satellite altimeter along roughly 125 tracks within the area covered by the model.

Comparison of model and satellite wave heights produced the following form for the variation of model wave height error as a function of measured wave height:

$$\text{Mean}(\text{Hs}_{sat} - \text{Hs}_{mod}) = 0.26\text{Hs}_{sat} - 0.4, \quad (1)$$

$$\text{St.Dev.}(\text{Hs}_{sat} - \text{Hs}_{mod}) = 0.12\text{Hs}_{sat} + 0.4, \quad (2)$$

in which it is implicitly assumed that the satellite error is small compared with the model error. The satellite data have been estimated to have about 10% random error and the known bias has been removed and quality control procedures applied [3].

These equations indicate that for 7.5m significant wave height the model bias and standard deviation are 1.6m and 1.3m and for 10.5m wave height they are 2.3m and 1.7m respectively. Comparing these values with those from Figure 1, an additional bias of around 10% or 1m caused by six-hourly wind fields would certainly be an important addition to the total error, but the smaller bias of under 5% arising from three-hourly wind input is probably acceptable. It is therefore fair to conclude that for North Sea applications, wind input should not be less frequent than three hourly, and should not be interpolated in time.

2. True versus modelled temporal variation.

In the previous section it was demonstrated that there was only a small difference in model output between runs with wind forcing applied at one or three hour intervals. This may be due to the reaction time scale of the wave model or the temporal smoothness of the wind forcing, and does not in itself indicate that the model is properly reproducing the actual variability.

2.1 Waves

The ability of the model to reproduce rapid changes in the wave field was investigated by analysing the power spectrum of the time series of model and buoy wave heights at the location of a waverider at N3. The power series is calculated via a continuous wavelet transform using the Morlet wavelet, and details of this procedure are contained in [4]. The effect is similar to a windowed Fourier transform, and enables characteristic frequencies of variation to be identified in aperiodic data sets.

Figure 3 shows the power spectra of the time series of wave height as measured by the waverider buoy and modelled by WAM for the same two month section studied in the last section. WAM is far too smooth at high frequencies (above $0.2h^{-1}$). The higher variability of the buoy cannot be simply due to a noise floor on the measurements, for this would generate a flat spectrum (the logarithmic scaling exaggerates the apparent flatness towards high frequencies).

The degree of smoothing in the model results is sufficiently large to cause concern as to its cause. In the next subsection the wind input is considered.

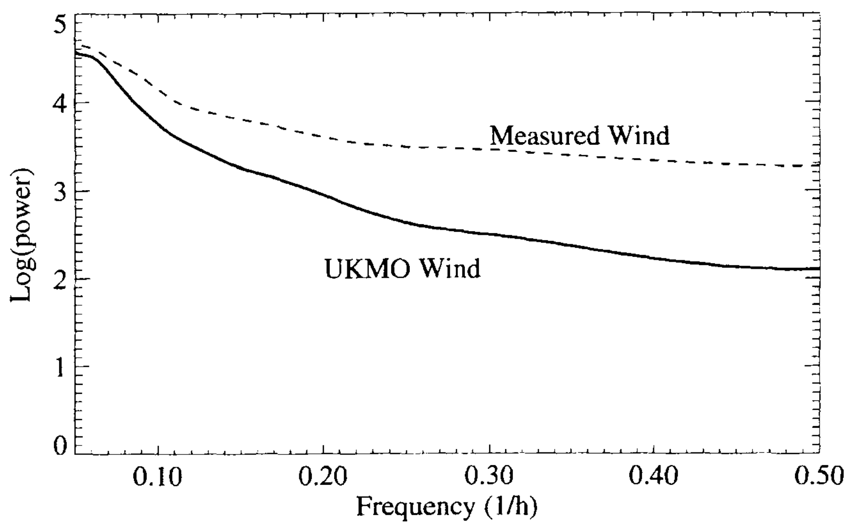

Figure 2: Wavelet power spectra of wind time series.

2.2 Winds

The winds are provided by the UKMO model at hourly intervals, but that does not mean that the wind fields reflect the true variability of the wind over the hourly time scale. For comparison with model winds at N3 we have hourly 10 metre wind speeds measured at a coastal station (Donna Nook, located at 53°29′N, 0°9′E, 40km south of N3). Since the location of N3 and Donna Nook are not coincident, differences in the value of the wind speed are to be expected, although the UKMO winds are spatially rather smooth over the distance in question. It is, however, reasonable to assume that they will have a similar variability and so the power spectra should be similar.

The comparison of the wavelet power spectra is shown in Figure 2. At periods below 10 hours, there is considerably more variability in the measured winds from Donna Nook than those from the UKMO. As before, random errors on the measured winds would create a flat noise floor in the spectrum and Figure 2 indicates that this must be small compared to the 3–10h signal. This implies that the UKMO winds which we use for forcing WAM do not have sufficient variability over time scales of a few hours duration. The aliasing evident in both spectra also suggests that hourly winds do not resolve the true temporal variability.

2.3 Effect of wind variability on WAM

It is not immediately clear how much effect the smoothness of the wind field will have on the wave model performance since waves take time to grow and decay and this integrating effect means that the wave height should have less rapid variability than the wind fields.

To test the sensitivity of the model to different amounts of high frequency variability of wind forcing, two model runs were performed using a single point version of WAM (*i.e.* without propagation). For one experiment, the UKMO wind from the point N3 was used, and in the other experiment the measured winds from Donna Nook were used to drive the model.

The wavelet transforms of these two runs are shown in Figure 3. The difference is small compared with that seen for the winds themselves, especially at the highest frequencies. This is due to the model smoothing high-frequency wind variability into lower frequency wave height variability (the difference between the spectra is much greater in the 0.1–0.2^{-1}h range). Figure 3 also shows that the variability of the one point model is considerably less than that of the buoy. It would be reasonable to hope that the buoy data should be somewhat smoother than the point model, since the dispersion relation (waves of different frequencies propagating at different speeds) will tend to smooth the time series of wave heights at a point in space, and this effect is not present in the point model.

It is likely that some of the high frequency variability of the buoy is due to wind variability on sub-hourly time scales being shifted into wave energy variability over longer time scales, by the smoothing effect of wave growth. To test this effect, an artifical wind field consisting purely of white noise sampled at 5 minute intervals was used to drive the point model. With a wind variability equivalent to the hourly variability of the measured winds at Donna Nook (see [5] for further explanation), the model generates the power spectrum shown in Figure 3. The similarity with the buoy data spectrum at high frequencies is striking, and this implies that the lack of sub-hour resolution in the forcing wind field is largely responsible for the difference between the high frequency regions of the spectra of the buoy data and the one point model forced with measured winds.

For both the one point model runs, the high frequency variability is much greater than for 2D WAM, and this situation is reversed over longer time scales. Because of the dispersion relation this is qualitatively reasonable, since brief events will be smoothed into events of longer duration in the

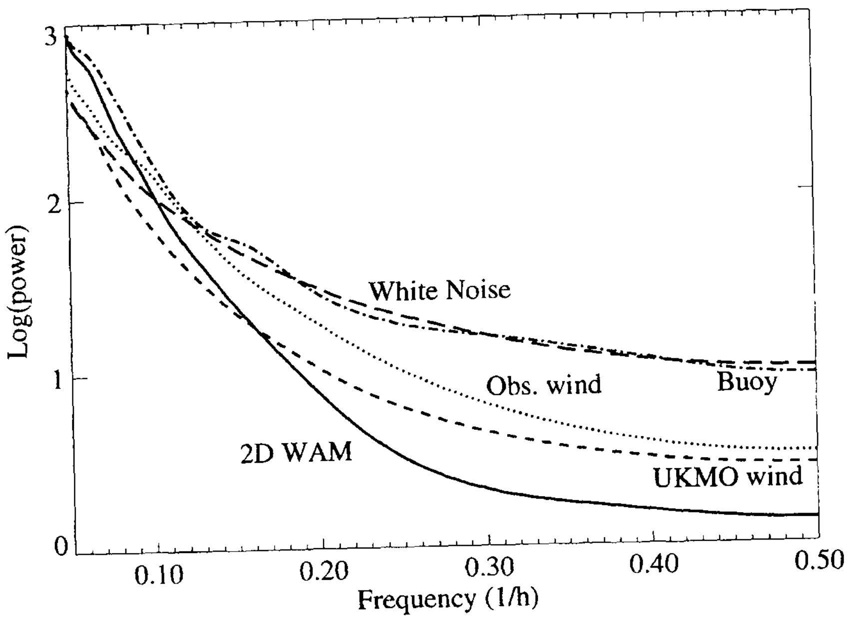

Figure 3: Wavelet power spectra of wave time series.

2D model, but the accuracy of the propagation scheme used in WAM may also be significant here.

2.4 Propagation in WAM

Waves of different frequencies travel at different speeds in the real world, but WAM propagates the energy in a finite width spectral bin at a uniform speed appropriate for the mean frequency of that bin, and relies on the numerical diffusion of the first order upwind advection scheme to provide smoothing. We can consider the significance of the propagation scheme by some simple calculations.

Following the ideas of [6] it is possible to estimate a diffusion coefficient that approximates the appropriate dispersion for the propagation of energy in a spectral bin. A typical value is in the region of $1800\mathrm{m}^2\mathrm{s}^{-1}$. This can be compared with the numerical diffusion of the first order upwind scheme used in WAM, which in the application used for the work in this paper is roughly $150000\mathrm{m}^2\mathrm{s}^{-1}$. The importance of these different diffusion coefficients is easily checked by using a simple 1D numerical model to propagate an energy signal. When appropriate values are used to simulate the performance of WAM, high frequency variability is rapidly smoothed, but the correct solution allows for propagation over much larger distances and times with only a small decay in signal strength. The diffusive properties of the upwind propagation in WAM is,therefore, a significant handicap to predicting peak events.

3. Conclusions

WAM has difficulty in modelling extreme events of short duration. Wind forcing should be obtained at hourly intervals if possible, and certainly not as infrequently as six-hourly. Although the winds obtained from the UKMO model are smoother than the true wind field over time scales of the order of hours, this discrepancy is not the only factor in the ability of WAM to reproduce rapid change. The numerical diffusion of the first order upwind scheme prevents the accurate propagation of short duration events. With a more accurate propagation scheme, obtaining wind fields at an interval of less than one hour would become important.

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