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Prediction of sea state under tropical cyclones in the UK Met Office operational global wave model

M.W. HOLT* and J.C.R. HUNT

United Kingdom Meteorological Office, Bracknell RG 12 2SZ ENGLAND

सार — ब्रिटेन का मौसम विज्ञान कार्यालय नियमित रूप से भूमंडलीय प्रचालन गणितीय मौसम पूर्वानुमान मॉडल का प्रयोग करता है। समुद्र की स्थिति के पूर्वानुमान के लिए इस मॉडल से धरातलीय वायु का प्रयोग स्पेक्ट्रमी तरंग मॉडल के माध्यम से किया जाता है। तरंग मॉडल की बनावट का संक्षिप्त विवरण इसमें दिया गया है, और प्रचालन तरंग मॉडल द्वारा वास्तविक समय में तैयार किए गए आँकड़ों के अभिलेखागार से प्राप्त आँकड़ों का प्रयोग करते हुए बंगाल की खाड़ी में आए उष्णकटिबंधीय चक्रवातों के दो मामलों का इसमें अध्ययन भी किया जाता है। ये मामले 14 से 15 जून 1996 के दौरान आए एक उष्णकटिबंधीय चक्रवात 3B और 4 से 6 नवम्बर 1996 के दौरान आए एक अन्य उष्णकटिबंधीय चक्रवात 07B से संबंधित है।

1.25° देशांतर और 0.833° अक्षांस के विभेदन पर गणितीय मौसम पूर्वानुमान मॉडल उष्णकटिबंधीय चक्रवात की गति को निरूपित नहीं करता और धरातल की वायु गति को कम आँका जाता है। अतः उष्णकटिबंधीय चक्रवात द्वारा उत्पन्न की गई समुद्र की अधिकतम स्थिति को इसमें निर्देशित नही किया गया है। तथापि तरंग मॉडल 3m की ऊँचाई से ज्यादा की दीर्घावधि महातरंग उत्पन्न करने में समर्थ रहा, जो इस स्थिति के होने के स्थान से दूर रहा।

अंततः प्रचालन तरंग मॉडल में उपयोग के लिए प्रचालन गणितीय मॉडल की धरातलीय वायु को कृत्रिम रूप से तैयार की गई उष्णकटिबंधीय चक्रवात की धरातलीय वायु के साथ एकरूप करने का जो कार्य चल रहा है, उसका वर्णन इसमें किया गया है।

ABSTRACT. The United Kingdom Meteorological Office (UKMO) routinely runs a global operational numerical weather prediction model. Surface winds from this model are used by a spectral wave model to forecast sea state. A brief description is given of the formulation of the wave model, and two cases of Tropical Cyclones in the Bay of Bengal are examined using the archived data generated in real time by the operational wave model. These are Tropical Cyclone 3B, 14-15 June 1996 and Tropical Cyclone 07B, 4-6 November 1996.

At a resolution of 1.25° in longitude by 0.833° in latitude the numerical weather prediction model does not represent the dynamics of a tropical cyclone and the surface wind speeds are underestimated. Consequently, the extreme sea state generated by a Tropical Cyclone is not modelled. However, the wave model was able to generate a long period swell of over 3m height, which propagated away from the area of generation.

Finally, work in progress to blend the operational numerical model surface winds with synthetically generated tropical cyclone surface winds, for use in the operational wave model, is outlined.

Key words — Wave modelling, Tropical cyclones, Operational wave models.

**Corresponding author* :Dr Holt email: mwholt@meto.gov.uk

1. Introduction

Tropical cyclones are the most serious form of natural disasters, both in terms of loss of life and frequency of occurrence. Most of this loss of life occurs in coastal area, because the cyclones' high winds raise the water level and generate huge waves. These effects also disrupt many econòmic activities in these areas, such as shipping, fishing, offsore oil production etc.

So it is inevitable that meteorologists and National Meteorological Services (NMS) of the world continue to focus considerable efforts on improving their understanding of these phenomena, forecasting their movements and the strength of their peak winds, which often exceed 50 ms^{-1}. On the basis of recent research in Hong Kong and the United Kingdom Meteorological Office (UKMO) the standard global numerical weather prediction model has been specially adapted to take account of the detailed wind structure observed around tropical cyclones. This has led to a 30% reduction in the positional error of the trajectories, when predicted 24 to 72 hours ahead (Heming *et al*. 1995, Chan and Kwok 1997). These improved predictions, which already are reducing human and economic losses, are only being distributed operationally in certain ocean basins at present (mid 1997), namely the Atlantic, Pacific and Southern Indian Ocean. It is hoped that through WMO arrangements these will be available in all basins of the world in the next few years.

The purpose of this paper is to focus on one particular aspect of tropical cyclone forecasts : the height, period and direction of waves generated by tropical cyclone winds. At present the UKMO global numerical wave model has not been specially adapted to account for the smaller scale winds and particular features of waves generated by a tropical cyclone. A development project to remedy this is under way, and is outlined here. Clearly, this is necessary, because it is sometimes found that much higher waves are generated in decaying tropical cyclones than the models currently predict. In the Atlantic in October 1995, a maximum extreme wave height of 30m was experienced by the liner 'Queen Elizabeth II' south of Newfoundland in an extra-tropical cyclone (although this only requires a significant wave height of around 18m).

The next section of the paper describes the numerical wave model used operationally by UKMO. Then two case studies are presented, taken from the operational archive maintained at UKMO, to show the impact of a tropical cyclone on sea state prediction, even at present day resolution of global NWP models. Finally, work already in hand to improve prediction of sea state under tropical cyclones in the global wave model is outlined.

2. Numerical wave modelling

The sea state at any point may be thought of a sum of many individual waves, each of a particular direction and frequency. This can be represented as the wave energy spectrum, where the wave energy in each frequency and each horizontal direction is known. This statistical measure of the sea state, rather than the actual sea surface elevation, is predicted by a numerical wave model. If the wave energy spectrum is known, then descriptions of the sea state, such as the significant wave height or the mean wave period may be calculated. A numerical spectral wave model calculates the evolution of the wave energy spectrum according to physical laws governing the change of wave energy. These are based largely on the Miles (1957) model of wind-wave generation, and Hasselmann's (1962) theory of non-linear interactions between waves. Wave models using a parametrisation of the nonlinear interactions are known as 'second generation'. A general review of numerical wave modelling is given by Komen *et al*. (1994).

All numerical wave models, however complex the formulation of the individual source terms, depend crucially upon the quality of the surface wind data used to generate wave energy. The UKMO operational global wave model uses hourly values from the UKMO global numerical weather prediction (NWP) mode, taken from the lowest model level.

2.1. *The Met Office wave model*

The UK Met Office operational wave model is a second-generation model based on the wave model first developed and described by Golding (1983), but there has been a continuous program of development since then.

The model divides the wave energy spectrum at each grid point into 13 frequency components and 16 direction components, giving a resolution of 22.5° for the direction of wave propagation. The lowest model frequency is 0.04Hz, corresponding to waves of 25 seconds period and 975m wavelength, and the highest frequency resolved by the model is 0.323Hz, corresponding to waves of 3 seconds period and about 15 m wavelength. The effect of waves at higher frequencies is included in the calculation of source terms.

Wave energy evolves according to the energy balance equation. Input of wave energy from the winds is calculated from two terms: a linear term allows growth from rest in a calm sea, and pre-existing waves grow exponentially using the formulation due to Snyder *et al.* (1981). For wind speeds below 7 $\mathrm{ms^{-1}}$ the wave growth is calculated using a parametric expression (Holt 1994) as the explicit calculation is limited by model frequency resolution. For all wind speeds the model can reach a limiting wave height close to the Pierson-Moskowitz value (Pierson and Moskowitz 1964). Windsea heights are not allowed to exceed this limit.

Advection of wave energy is calculated using the split-explicit scheme due to Gadd (1978), as described by Golding (1983). The time step used by the scheme is calculated separately for each wave frequency. This allows use of a longer time step where possible, yet retains numerical stability. Because the global wave model runs on a regular latitude-longitude grid, a term to account for 'Great Circle' propagation of swell is also included.

Dissipation of wave energy, due to whitecapping (wave breaking) and other processes, follows the formulation of Komen *et al.* (1984). In line with the latest understanding of the energy balance, the coefficient for swell dissipation is reduced by a factor of one half (Holt 1994). This allows windsea growth at the correct rate, corresponding to the Snyder input expression, but dissipates swell energy at a slower rate.

Nonlinear transfer of energy due to wave-wave interactions is parametrised by fitting growing windsea to a spectrum from the JONSWAP family (Jonswap 1973). The effect of the wave-wave interactions in delaying the response of waves to a turning wind is also parameterised.

2.2. *Operational application*

The UKMO operational global wave model covers 80.42°N to 77.017°S on a regular latitude-longitude grid, at a resolution of 1.25° longitude by 0.833° in latitude. This is the same resolution as the operational atmosphere forecast model which provides the wind data. (Fig. 1 shows the distribution of gridpoints in the Bay of Bengal and around India). The global wave model grid points are co-located with the wind data points in the NWP model.

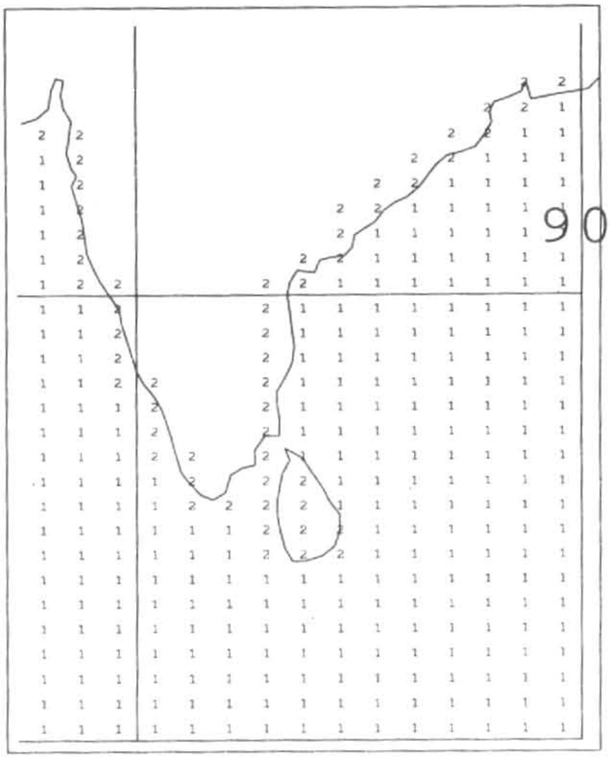


Fig. 1. UK Met Office (UKMO) operational global wave model - location of gridpoints near India and in the Bay of Bengal. Grid resolution is 1.25° in longitude by 0.833° in latitude. Points labelled '2' are coast points at which there is no growth of wave energy, but incoming wave energy is absorbed.

The model is run twice daily, following the run of the global atmosphere model, providing a forecast to 5 days ahead. Each run begins with a 'hindcast', starting from the wave conditions of 12 hours earlier and running forward with wind data from the NWP assimilation. This gives the best possible starting conditions for the forecast run.

The Met Office wave data assimilation scheme takes observations of wave height and surface windspeed, and calculates the necessary changes to the model wave spectrum so that the model wave height is nudged closer to the observed value. The scheme to calculate the wave height changes is based on the 'analysis correction' scheme used to assimilate observations into the NWP model, and the procedure to transform wave height and wind speed to spectral energy values was developed by Thomas (1988). The observed wind speed value is used to decide whether

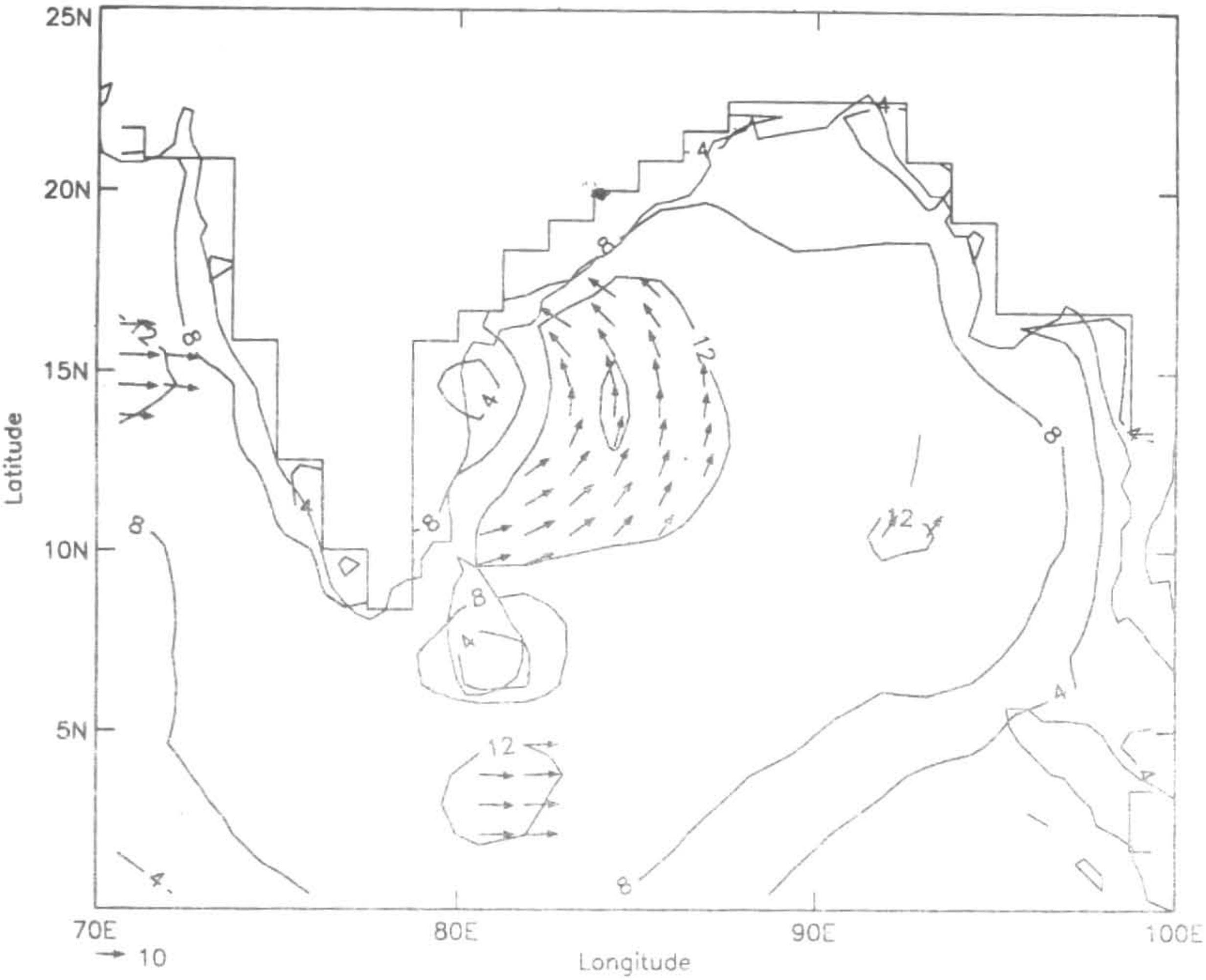


Fig. 2. Surface wind speeds (ms^{-1}) and direction from the operational global NWP model, at 18 UTC on 14 June 1996. Contour interval is 4 ms^{-1}. Direction arrows are plotted for wind speeds greater than 12 ms^{-1}

to increment the model wind sea energy or swell energy.

Observations of wave height and surface wind speed from the radar altimeter carried on the satellite ERS-2 are assimilated into the global wave model (ERS-1 data were used between June 1993 and April 1996). Before use the observations are grouped into a 20- second average, giving a value every 140 km - approximately the model grid spacing. Each observation influences a region of radius 250 km. A strict quality control is carried out, both against climatological values and a 'buddy check' against neighbouring observations. This is necessary because unrealistic waveheight values are measured as the satellite crosses the coast or over islands.

However, in both cases presented here, there were no ERS-2 altimeter observations in the Bay of Bengal during the period of the Tropical Cyclone.

3. Case studies

(a) *Tropical Cyclone 3B 14-15 June 1996*

The evolution of sea-state in the UKMO operational global wave model during this Tropical Cyclone is shown using 6-hourly data taken from the archive of global wave model analysis (t + 00) fields.

The strongest surface winds in the NWP model occurred between 12UTC, 14 June 1996 and 00UTC 15 June 1996, with the strong cyclonic southerly flow (Fig. 2). Maximum winds speeds of 16 m/s were

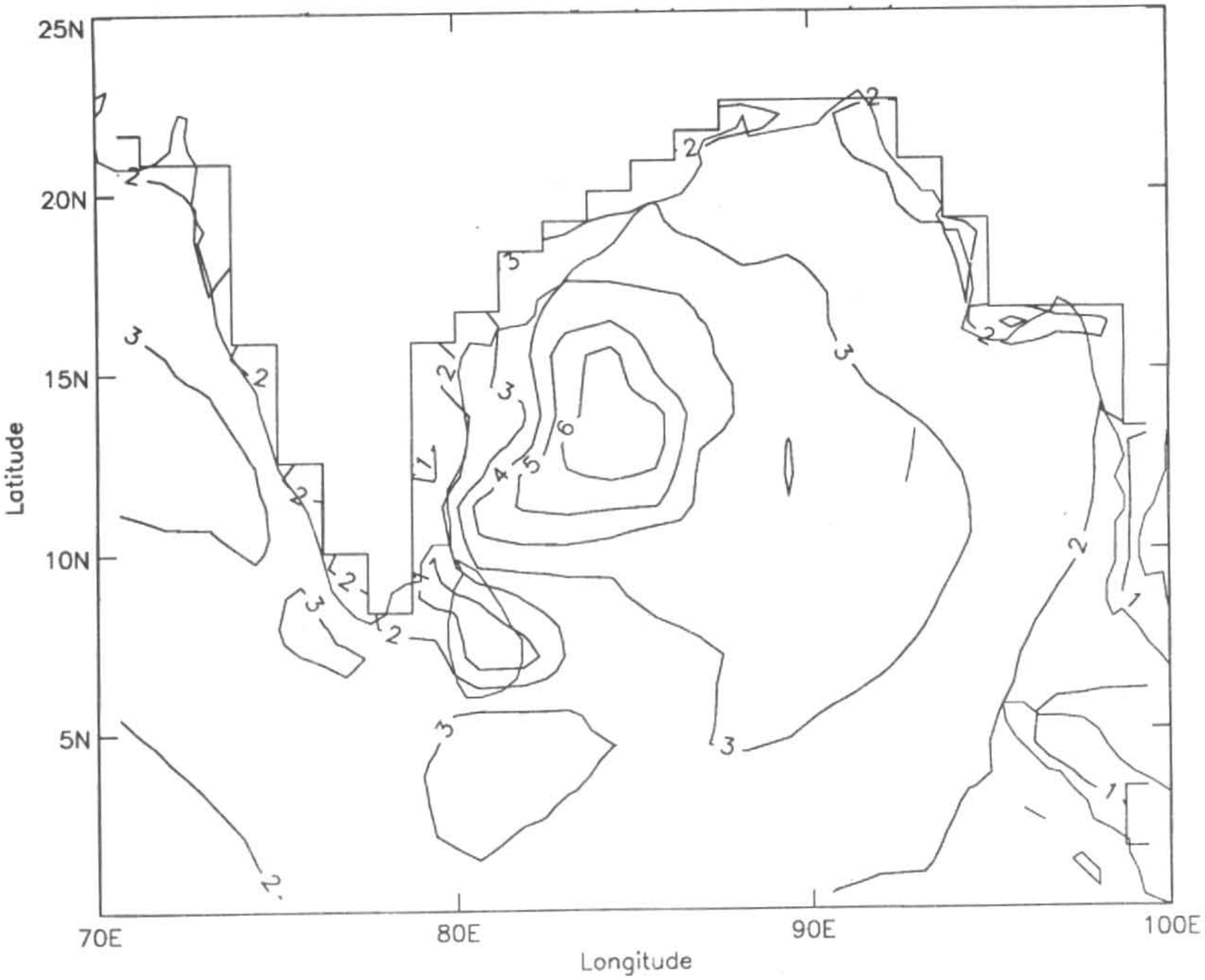


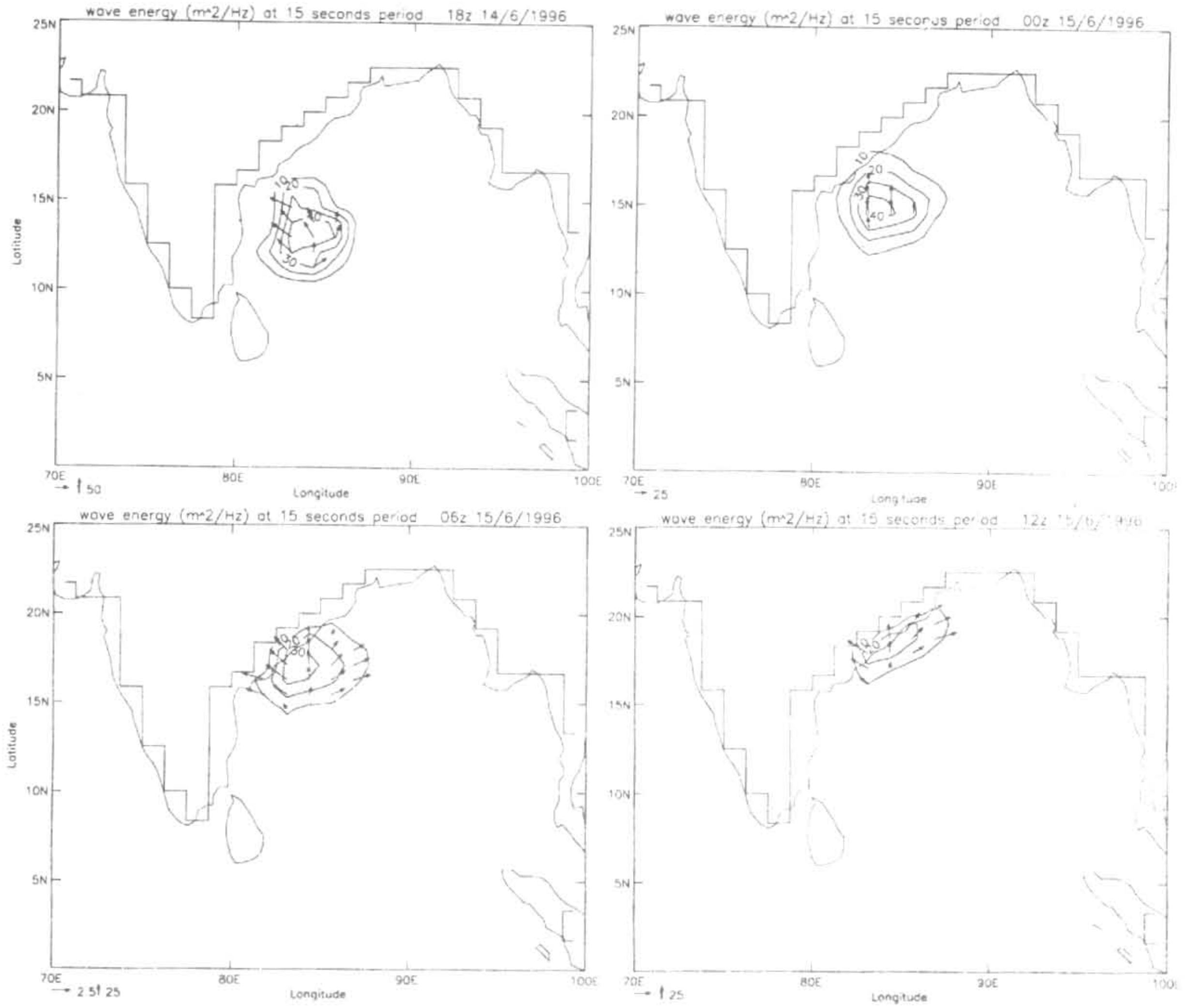
Fig. 3. Significant wave height at 18 UTC on 14 June 1996. Contour interval is 1m

reached, just over 32 knots. This allowed a significant wave height of close to 7m to be generated (Fig. 3). Note that these conditions are not exceptional for the wave model, they are often exceeded in mid-latitude storms in winter.

Considering the individual spectral energy levels in the wave model, significant amounts of wave energy of period 15 seconds, and also of 18 seconds, were generated between 12-18 UTC on 14 June 1996 (Figs. 4a & 5a). The longest period energy generated by the wave model during the storm was this 18 second energy. To generate an 18 second swell in the wave model requires a wind speed of at least 19.2 ms^{-1} for sufficient fetch and duration. To allow swell to reach 21 seconds period in the model would require wind speeds to reach 22.9 ms^{-1}. (The model frequency component centred at 15 seconds period has a bandwidth of 0.0118 Hz, the component at 18 seconds period has bandwidth of 0.0099 Hz).

The subsequent evolution of this long period swell, shown in Figs. 4 & 5, is interesting. The energy is generally travelling from the south, but there is a component from both SSE and SSW, corresponding to the direction of the wind when the energy was generated. This swell energy propagates northward away from the area of the Tropical Cyclone, and interestingly arrives on the northwest coast of the Bay of Bengal as over 4m of swell at around 06UTC, 15 June 1996 (Fig. 6).

However, as no wave observations from moored buoys are available in this area from the WMO Global Telecommunications System, it is not possible to verify these values.



Figs. 4(a-d). Energy density and direction of propagation for wave energy in the model component centred on 15 seconds period. Contour interval 10 m^2 Hz^{-1} at (a) 18 UTC, 14 June 1996, (b) 00 UTC, 15 June 1996, (c) 06 UTC, 15 June 1996 and (d) 12 UTC, 15 June 1996

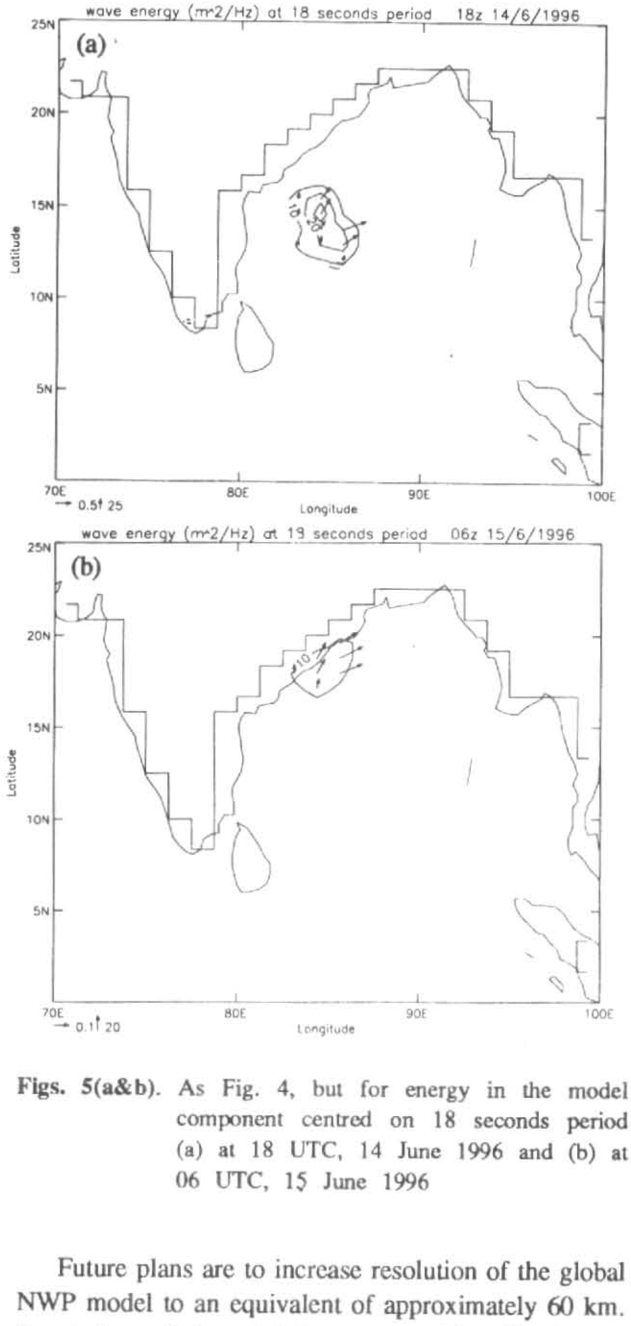
(b) *Tropical Cyclone 07B 4-6 November 1996*

In this case, although the NWP model was able to predict the surface position of the Tropical Cyclone, the intensity of circulation was not captured. Maximum surface windspeeds during the period did not exceed 12 m/s and so, in contrast to the first case, no extreme waves could develop.

4. Discussion

In the first example the global model represented the Tropical Cyclone surface wind speeds in a manner comparable to an intense mid-latitude depression. The intensity of circulation of a Tropical Cyclone, however, was not resolved. In this example the large scale flow features were captured, but as the maximum model wind speeds were only at most 20 m/s, the local extreme values of significant wave height or peak periods were not modelled. An area of significant long period swell propagating northward from the storm was identified.

In the second case, the NWP model did not generate any strong winds in the circulation, even though a surface vorticity minimum was present, allowing the cyclone position to be predicted using the scheme of Heming *et al.* (1995).



Figs. 5(a&b). As Fig. 4, but for energy in the model component centred on 18 seconds period (a) at 18 UTC, 14 June 1996 and (b) at 06 UTC, 15 June 1996

Future plans are to increase resolution of the global NWP model to an equivalent of approximately 60 km. Resolution of the global wave model will also be increased. A scheme is being developed to insert onto global model surface winds, a synthetic windfield from an analytic model of a Tropical Cyclone (Holland 1980), using the NWP predicted track along with observed actual parameters (maximum wind speed / radius of maximum winds/central pressure). Even on a 1.25° grid this could double the maximum surface wind speed used to generate waves. This will allow better representation of extreme significant wave height under the Tropical Cyclone, and also better prediction of the long period swell generated by the Tropical Cyclone and travelling to remote areas.

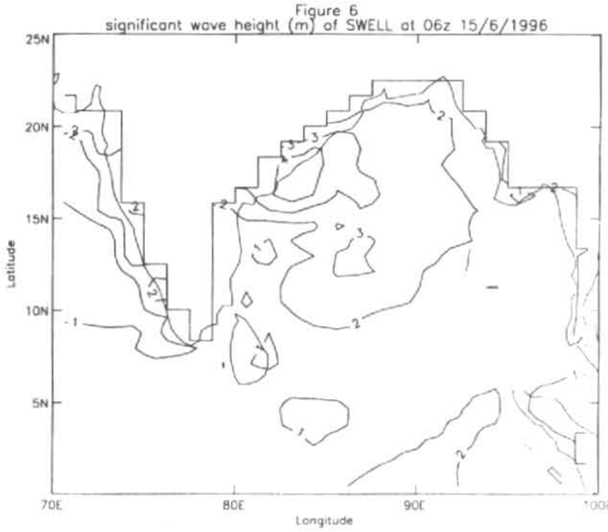


Fig. 6. Significant wave height of SWELL at 06 UTC, 15 June 1996. Contour interval 1m

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