Forecasts of AMEX tropical cyclones with a step-mountain model

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The numerical forecasts of tropical cyclones, which occurred during the AMEX (Australian Monsoon Experiment), have been studied. The UB/NMC (University of Belgrade/National Meteorological Center, Washington) limited area model, with vertical coordinate which permits a step-like representation of mountains and quasi-horizontal coordinate surfaces (so-called eta coordinate), was used. The physical package includes Mellor-Yamada level 2.5 turbulent exchange with level 2 used in the lowermost layer, large-scale precipitation and evaporation, Betts-Miller convective parametrization, surface processes after Miyakoda and Sirutis, and the NMC version of the GLA (Goddard Laboratory for Atmospheres) radiation scheme. The model was run with 0.5×0.5° horizontal resolution and 16 layers in the vertical.

The realistic 48-hour forecasts of AMEX tropical cyclones (Connie, Irma, Damien and Jason) based on ECMWF (European Centre for Medium Range Weather Forecasts) operational analyses, that is real-time data (without additional AMEX data available in delayed mode) for initial and forecasts for boundary data, demonstrate the model's ability to predict tropical cyclones.

Introduction

A review of the characteristics of numerical models which have been used for simulation of tropical cyclones is given in Elsberry (1979) and Anthes (1982). Several major problem areas stand out in the transition from the simulation of idealised storms to real storms, as reviewed by Anthes (1982, p.110).

Dell'Oso and Bengtsson (1985) have discussed results of integration of real cases of tropical cyclones with two models; the ECMWF operational global grid-point model and a limited area version of this same model. The boundary conditions for the limited area model were provided by the global model. The cyclone track provided by the limited area model was better than that given by the global model.

Heckley et al. (1987) described a tropical cyclone sensitivity experiment to the parametrisation of cumulus convection in an ECMWF global spectral model. The results, with lagged adjustment scheme for deep and shallow convection (Betts 1986; Betts and Miller 1986), were better than those obtained with Kuo's parametrisation of deep convection (Kuo 1974) and a diffusive scheme for shallow convection (Tiedtke 1986).

Leslie et al. (1987) discussed effects of cumulus convection, surface fluxes, topography, sea-surface temperature and horizontal resolution in the BMRC (Bureau of Meteorology Research Centre, Melbourne) limited area model on the prediction of the Australian east coast cyclones. They found that each of those subgrid-scale physical processes as well as an adequate horizontal resolution were necessary for cyclone development.

Tuleya (1988) showed good results in predicting both development and non-development of tropical disturbances during the FGGF (First GARP Global Experiment) year 1979. He utilised a regional model with a resolution of 28 km. For each case he carried out two experiments; one with boundary data from ECMWF FGGF IIb analyses, and the other with boundary data from an R30 version of a global spectral model. In each case the developments were reasonably predicted.

Krishnamurti et al. (1989) examined the formation and motion of a number of storms for the years 1979 and 1983 utilising a global spectral model and the ECMWF FGGF IIb analyses, as well as the operational ECMWF and NMC
analyses. They noted the importance of the vertical and horizontal resolution, initial conditions and parametrisation of physical processes for the formation and motion of storms.

Davidson (personal communication) successfully simulated AMEX (Australian Monsoon Experiment) tropical cyclone Irma using the FSU (Florida State University) regional prediction model and the operational ECMWF analyses without and with additional AMEX data. He reported the capability of the model to realistically simulate the genesis of the cyclone, and sensitivities of the simulation to the initial and boundary conditions.

During AMEX, 10 January through 15 February 1987, four tropical cyclones, Connie, Irma, Damien and Jason, developed in the north and northwest Australian region (Manchur 1987; Heckley and Puri 1988). Cyclone Irma developed simultaneously with Connie (forecast period in this study: 18–20 January 1987). However, their growth was due to very different conditions. Connie formed northeast of Derby and moved southwest. Irma evolved from an area of deep convection in the northern Gulf of Carpentaria. Damien formed from a monsoonal low that developed off the Kimberley coast, to the north of Cape Leveque (forecast period: 2–4 February 1987). Jason developed from a tropical low within a cloud mass over northern Cape York Peninsula and the Gulf of Carpentaria (forecast period: 11–13 February 1987).

The UB/NMC (University of Belgrade/National Meteorological Center, Washington) eta model was used to predict the AMEX tropical cyclones listed above. The eta model is being run experimentally at the University of Belgrade and NMC. Janjić and Lazić (1988) and Mesinger (personal communication) have reported on the results of the extratropical integrations. This is the first report on model integrations in the tropics.

We shall first outline the UB/NMC eta model. Then, we will discuss the 48-hour forecasts of the AMEX tropical cyclones.

Model outline

The general characteristics of the UB/NMC eta model are the following:

- a limited area and grid-point model defined on the semi-staggered Arakawa E grid;
- a special technique is used to prevent grid separation (Mesinger 1973; Janjić 1979);
- the vertical coordinate is the step-mountain, \( \eta \) coordinate, a generalisation of the \( \sigma \) coordinate with the step-like representation of mountains (Mesinger 1984; Mesinger et al. 1988);
- a built-in nonlinear energy cascade control in horizontal advection (Janjić 1984);
- split-explicit time differencing (Mesinger 1973; Janjić 1979);
- the Mellor-Yamada Level 2.5 scheme for the planetary boundary layer and the Mellor-Yamada Level 2 scheme for the 'surface' layer, with a shallow dynamical turbulence layer at the bottom (Mellor and Yamada 1974, 1982);
- a fourth order lateral diffusion scheme with the diffusion coefficient depending on deformation and the turbulent kinetic energy;
- ground surface processes affecting changes of temperature and wetness, including surface hydrology, are designed (Janjić 1990) following Miyakoda and Sirutis (1977, 1984);
- large-scale precipitation and modified Betts and Miller shallow and deep convection schemes (Betts 1986; Betts and Miller 1986);
- the NMC version of the GLA (Goddard Laboratory for Atmospheres) radiation scheme with interactive random overlap clouds (Harshvardhan et al. 1989).

The horizontal domain was defined to be between 0° and 30°S, and 105°E to 155°E. For this region, the US Navy high resolution (10’ × 10’) orography, provided by NCAR, was used to compute 'silhouette' mountains. Silhouette mountains are defined as having their elevation equal to the average height of the silhouette which the terrain presents to horizontal flow. To produce the model's step-orography, averages are then calculated over groups of four neighbouring points and are subsequently rounded off to the nearest reference interface elevation. The horizontal domain and the resulting orography are shown in Fig. 1.

Fig. 1 Horizontal domain, places mentioned in the text, and step-mountains used in the model.
ECMWF global initialised analyses on a 0.5°×0.5° rotated longitude/latitude E grid. Sea-surface temperature was also obtained from the ECMWF global sea-surface temperature field by bilinear interpolation. Albedo and ground wetness were taken from the ECMWF climate data.

Interpolation of geopotential height and specific humidity from pressure levels to eta surfaces is done by fitting the three nearest values quadratically in ln(p). However, wind components in the middle of the eta layers are obtained by linear interpolation in ln(p). Initial temperatures in the middle of the eta layers were calculated from the given geopotential height and relative humidity using the hydrostatic equation.

Time-dependent boundary values of all of the prognostic variables were updated by linear time interpolation of ECMWF forecasts taken at six-hour intervals. Prognostic variables are updated at the single outermost row of grid points. The integration domain of the model begins at the third row of grid-points at which time-stepping of the prognostic variables is performed. This done, variables at the second row from the boundary are calculated by four-point averaging the updated and the time-stepped variables. The four-point averaging along this 'buffer' line of grid-points is a boundary noise-control feature of the model as it couples the solutions on two C subgrids of which an E grid is composed (Mesinger 1973, 1977).

**Tropical cyclone descriptions**

Only synoptic aspects important for the forecast experiments described here are summarised below.

*Connie* formed from a low at about 17.1°S, 121.9°E, at 1200 UTC 17 January 1987 (Manchur 1987). It moved southwest and continued to intensify. Central surface pressure at 0000 UTC 18 January (initial data in this study, Fig. 2) was 988 hPa, at 0000 UTC 19 January it was 962 hPa and at 0000 UTC 20 January it was 974 hPa. *Connie* dissipated at about 36.9°S, 127.1°E at 0600 UTC 23 January. However, it weakened below tropical cyclone intensity at about 23.5°S, 118.2°E at 1200 UTC 20 January, soon after crossing the coast.

*Irma* developed from an area of deep convection in the northern Gulf of Carpentaria at 1200 UTC 19 January 1987 (Manchur 1987). Central surface pressure in its pre-cyclone stage was 998

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**Fig. 2** Initial conditions — *Connie and Irma*. Analyses of geopotential height (200 hPa — contour interval 40 gpm, 500 hPa and 850 hPa — 20 gpm), streamlines, isotachs (shown by shading, contour interval 10 m/s) and sea level pressure (contour interval 2.5 hPa) at 0000 UTC 18 January 1987.
Fig. 3 Initial conditions — Damien. As in Fig. 2, but at 0000 UTC 2 February 1987.

Fig. 4 Initial conditions — Jason. As in Fig. 2, but at 0000 UTC 11 February 1987.
hPa at 0300 UTC 19 January. Irma moved in a west-southwesterly direction across the Gulf of Carpentaria, with central surface pressure of 985 hPa at 0000 UTC 20 January. The system lost its identity at 0000 UTC 21 January in the central Northern Territory. Irma became a very active rain depression with a 24-hour total rainfall of 409 mm at Larrimah.

Damien formed from a monsoonal low at 1800 UTC 1 February 1987. It moved generally southwest (parallel to the coast). Central surface pressure at 0000 UTC 2 February (initial data, Fig. 3) was 988 hPa (15.5°S, 123.5°E), at 0000 UTC 3 February it was 980 hPa (maximum intensity) and at 0000 UTC 4 February it was 983 hPa (Manchur 1987). Damien weakened below tropical cyclone intensity at about 18.1°S, 117.6°E at 0000 UTC 5 February and dissipated at about 20.0°S, 111.0°E at 0000 UTC 9 February.

Jason developed from a tropical low within a cloud mass over the northeast of the Gulf of Carpentaria at 0600 UTC 7 February 1987. Firstly it moved west-southwest across the Gulf of Carpentaria and, after coastal crossing, it turned and moved southward over water by 0000 UTC 11 February (initial data, Fig. 4) with a central surface pressure of 994 hPa. Central surface pressure at 0000 UTC 12 February was 980 hPa and, at 0000 UTC 13 February, it reached a maximum intensity of 970 hPa (15.1°S, 139.6°E) (Manchur 1987).

**Model performance**

The model forecasts are verified at 48 hours against ECMWF initialised analyses. Tracks of predicted tropical cyclones are verified against both the observed and the analysed tracks.

The 48-hour forecast with corresponding verification of Connie and Irma is shown in Figs 5 and 6. High pressure over central and northern Australia at 200 hPa and development of cyclones at upper levels (500 and 850 hPa) are successfully predicted. Verifying analyses and the forecasts of the wind field are in reasonable agreement. The central pressures of 977 hPa and 995 hPa in Connie and Irma, respectively, are predicted, while observed values are 974 hPa and 985 hPa (Manchur 1987). The model correctly predicted the development of a circulation at the surface in Irma.

Tracks of predicted, observed and analysed central pressure of Connie are shown in Fig. 7.

The mean absolute error (MAE) of analysed
Fig. 6 Verification (left-hand panels) and 48-hour forecast (right-hand panels) of Connie and Irma: 850 hPa, sea level pressure (as in Fig. 2) and total precipitation (shown by shading) accumulated over the last 12 hours of forecast (contour interval 15 mm).

Fig. 7 Tracks of predicted, observed and analysed central pressure of Connie.

Fig. 8 Tracks of predicted, observed and analysed central pressure of Irma.
Connie locations during the forecast period compared to observations is 214 km, while the same error in forecasts is 174 km. Thus, positions of Connie during integration are better predicted than analysed. The MAE of Connie central pressure in analyses compared to observations is 21.6 hPa, while the same error in forecasts is 11.8 hPa.

Initial errors of Connie analysis are the position error, 236 km, and the central pressure error, 7.0 hPa. Final (48-hour forecast) position and central pressure errors are: analysis, 153 km and 22.0 hPa, and forecast, 117 km and 3.0 hPa.

Because of the large values of these analysis errors, an experiment was performed in which a nudging procedure was used to avoid the initial position and central pressure errors of the Connie vortex during the first three hours of integration. In this forecast the MAEs are 95 km and 7.8 hPa.

The MAEs of Connie analyses are reduced using reanalysed initialised analyses with the new ECMWF parametrisation schemes (e.g. mass flux, radiation, surface processes) (G. Sommeria, personal communication) and with added delayed mode AMEX data. These reduced errors are 97 km and 18.0 hPa. There is some improvement in the forecast obtained by using new analysis as the initial condition and new forecasts as boundary conditions. In such a case forecast MAEs are 122 km and 8.8 hPa.

Comparing these Connie results with those obtained using other limited area models (e.g. LAM ECMWF T106) we can see that MAEs are somewhat smaller in our forecasts. Forecast MAEs in LAM ECMWF T106 are: location, 317 km, and central pressure, 20.6 hPa.

Tracks of predicted, observed analysed central pressure of Irma are shown in Fig. 8. In this case, MAEs of the analyses are 149 km and 13.0 hPa, and of the forecasts are 91 km and 5.7 hPa.

The maps of 48-hour forecasts with corresponding verifications (only 850 hPa and sea level pressure) of tropical cyclone Damien are shown in Fig. 9. There is agreement between forecast and verification. Tracks of Damien with surface pressure are shown in Fig. 10.

In the Damien case, the MAEs of the analyses are 125 km and 14.8 hPa, while in the forecasts these are 133 km and 8.4 hPa. By ‘nudging’ of the initial vortex the forecast errors are reduced to 97 km and 5.0 hPa.

The 48-hour forecast of tropical cyclone Jason, with corresponding verification, is shown in Fig.
11. There is a satisfactory agreement between predicted cyclone positions and initialised analyses. Tracks of Jason with surface pressure are shown in Fig. 12.

There are differences in initial position and central pressure between observation and analysis (224 km and 9.0 hPa), although forecast tracks are not so different. The 48-hour forecast differences are 88 km and 16 hPa. The final differences between the analysis and observation are 189 km and 33 hPa. The MAEs of the analyses are 183 km and 21.6 hPa; and of the forecasts are 212 km and 12.4 hPa. With the procedure of nudging the initial vortex, forecast MAEs are 185 km and 8.4 hPa.

The MAEs of AMEX tropical cyclones are summarised in Table 1.

The control forecasts are based on the ECMWF operational forecasts for boundary conditions. Concerning the position and pressure of the tropical cyclone centre and maximum precipitation, there is a small impact due to the use of the initialised and the uninitialised analyses as boundary conditions, or even constant boundaries. The large domain (about 5500 km by 3500 km) used in the forecast experiments has probably reduced the effect of lateral boundaries to the tropical cyclones in our experiments.

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Fig. 10  Tracks of predicted, observed and analysed central pressure of Damien.

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Fig. 11  Verification and 48-hour forecast of Jason: 850 hPa, sea level pressure and total precipitation, as in Fig. 6.
different. The ECMWF operational global analyses are not quite satisfactory in the tropics, as is well known. However, there is no better operational product from this region available for use in our study. The model sensitivity to the specification of the correct position and intensity of the initial vortex, as mentioned in the section on model performance, remains to be further investigated. The results presented in this paper do not include details of tropical cyclone structure such as humidity, vorticity, divergence, vertical motion, etc., nor model sensitivity to the initial and boundary conditions, orography, resolution, parametrisation of physical processes, etc. As has been recently reported (Lazić 1989), this research is in progress and is the subject of further study.

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All results presented here were produced using the ECMWF data bases and computer facilities.

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References

**Conclusion**

It was demonstrated in the control forecasts that the UB/NMC eta model satisfactorily predicted most of the features of the AMEX tropical cyclones. Timing of cyclogenesis and subsequent cyclone tracks, central surface pressure, and wind (especially maximum wind) were all predicted with reasonable skill. However, one should note that positions and central surface pressure of cyclones in analyses and observations, especially the initial conditions of Connie and Jason, are dif-

Table 1. MAEs of analyses and forecasts against observations.

<table>
<thead>
<tr>
<th>Tropical cyclone</th>
<th>Version of experiment</th>
<th>Analyses Posit. C. Press (km)</th>
<th>Forecasts Posit. C. Press (km)</th>
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<td>174</td>
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<td>Nudging</td>
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<tr>
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