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Numerical simulation of a super cyclonic storm, Orissa 1999: impact of initial conditions

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Numerical simulations are performed using the Penn State University/ National Center for Atmospheric Research Mesoscale Model (MM5) to study the impact of initial conditions on the super cyclone which hit the coast of Orissa in 1999. Because analysis of the cyclone's circulation was inadequate in the initial fields owing to the coarse resolution of the operational analysis systems and sparse oceanic data coverage, synthetic vortex data were generated using empirical relations and used in the analysis. Four-dimensional data assimilation is performed in order to assimilate the synthetic vortex in the initial stage to the model.

Considerable improvement in the track is obtained by using the synthetic vortex. With better specification of the initial vortex structure, the model successfully simulated the typical tropical cyclone characteristics, such as asymmetries in the wind field: the strongest winds occurred in the east and close to the cyclone's centre, strong wind gradients were found between the centre and the maximum wind region, and there was a slow decrease in wind speed up to the middle troposphere. Despite failing to produce the intense pressure drop observed for this cyclone, the model shows much better cyclone development with enhanced initial condition than the analysis.

1. Introduction

Poor resolution of the operational analysis systems and paucity of data over the tropical oceans often result in severe deficiencies in the analysis of tropical cyclone circulations. The analysis is frequently inadequate to define the location and structural features that are necessary for the skilful prediction of a tropical cyclone. Even with the use of non-conventional data, such as satellite wind and temperature and sophisticated assimilation schemes, numerical analyses can produce large errors compared with the observed location and intensity inferred from satellite imagery. To obtain a reasonably accurate prediction of the cyclone's track, the initial position and the flow structure in the outer region should be appropriate (see Reed et al. 1988; Chan & Williams 1987). Because of the deficiencies in the analysis a large error may occur in the prediction of a cyclone's motion and intensity.

The lack of tropical cyclone circulations in the analysis necessitates data enhancement using a synthetic vortex. This is especially required over the Indian region as the data are generally inadequate to provide a detailed structure of tropical cyclone circulation. There are two ways of inserting the synthetic vortex into the large-scale analysis. One is to insert the vortex directly into the analysis (implantation method) and the other is to augment the initial guess (large-scale analysis) by using synthetic vortex data as additional observations in an objective analysis scheme (analysis method). Recently, many operational centres and research workers have used a synthetic vortex to improve the initial conditions for tropical cyclone simulation; for example, Iwasaki et al. (1987), Davidson et al. (1993), Kurihara et al. (1993) and Heming et al. (1995)

A few attempts have been made to predict the tropical cyclones occurring over the Indian region. Abraham et al. (1995) used the implantation method and compared the results from the two types of vortices, namely (i) rankine vortex and (ii) Holland vortex using a coarse (T-63) global spectral model. Prasad et al. (1997) used the analysis method to improve the initial condition in their limited area model with 1° resolution.

The purpose of the present paper is to study the impact of initial conditions on the Orissa super cyclone using a high resolution mesoscale model. This case was selected because it was one of the most severe cyclones to hit the east coast of India in recent years. It appeared as a depression on 25 October over the north Andaman Sea and became a super cyclonic storm on 29 October when it made landfall. In the 24-h period between 28 and 29 October 1999 the pressure drop was 50 hPa with sustainable surface winds reaching 70 ms^{-1}. The infra-red (IR) satellite imagery at 0530 UTC, 29 October 1999 (Figure 1) clearly shows the eye surrounded by deep clouds and a rain band extending northwards. It caused considerable loss of life and

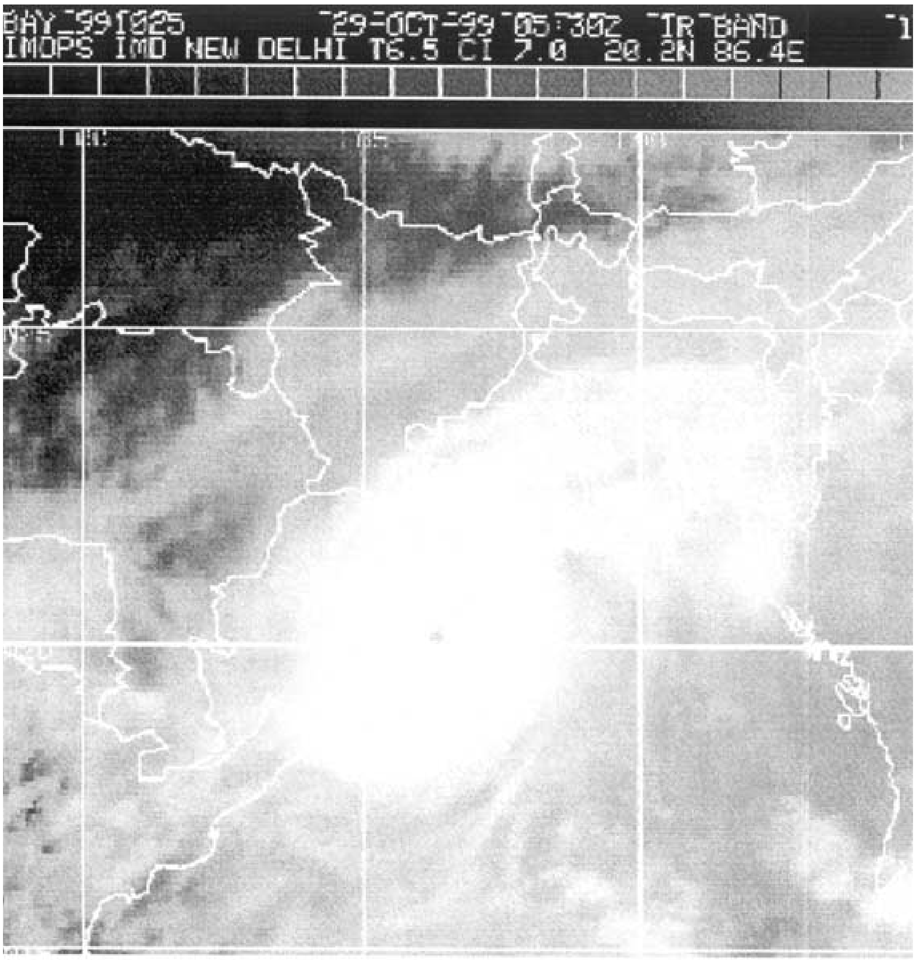

Figure 1. *Satellite cloud imagery (IR) for 0530 UTC, 29 October 1999.*

damage to property. In the following section we will describe briefly the mesoscale model and the methodology used for enhancing the initial conditions by objectively analysing a synthetic vortex. Section 3 presents the simulation results and discussion from one set of experiments. Our conclusions are presented in the final section.

2. Methodology

2.1 The mesoscale model

The mesoscale model used for simulation of the 'super cyclonic storm', which hit the Orissa coast, is the non-hydrostatic version of Penn State University/ National Center for Atmospheric Research (PSU/NCAR) mesoscale model version 5 (MM5V3-3) described in detail by Dudhia (1993). The model physics selected for this study include a cumulus parameterisation based on quasi-equilibrium hypothesis with a simple single cloud scheme (Grell 1993), an explicit moisture scheme which predicts cloud and rainwater physics with microphysical processes including simple ice-phase processes (Dudhia 1989), an efficient planetary boundary layer parameterisation scheme based on Troen-Mahrt representation of counter gradient transports and eddy diffusivity profiles in the well mixed boundary layer (Hong & Pan 1996), and a multi-layer soil diffusion model. Klemp & Durran's (1983) upper radiative boundary condition was applied in order to prevent gravity waves from being reflected off the upper boundary of the model. The long- and short-wave radiation schemes were those described by Dudhia (1989). The radiation effects due to clouds were considered and these effects were updated every 30 minutes. For this simulation, a stationary Grid 2 (30 km) was nested within the domain of Grid 1 (90 km) using a two-way interface. For Grid 1, the domain in x-direction extends from 71° E to 102° E with 40 mesh points, and in y-direction from 5° N to 30° N with 34 mesh points. Grid 2 extends from 81° E to 95° E with 51 mesh points in x-direction, and from 12° N to 24° N with 48 mesh points in y-direction. Figure 2 shows the location of these model domains against the terrain. In the vertical, 23 unevenly spaced sigma levels were used: .995, .985, .97, .945, .91, .87, .825, .775, .725, .675, .625, .575, .525, .475, .425, .375, .325, .275, .225, .175, .125, .075, .025. More vertical levels were placed within the lower troposphere (with decreasing resolution above) to better resolve the planetary boundary layer and the moist processes.

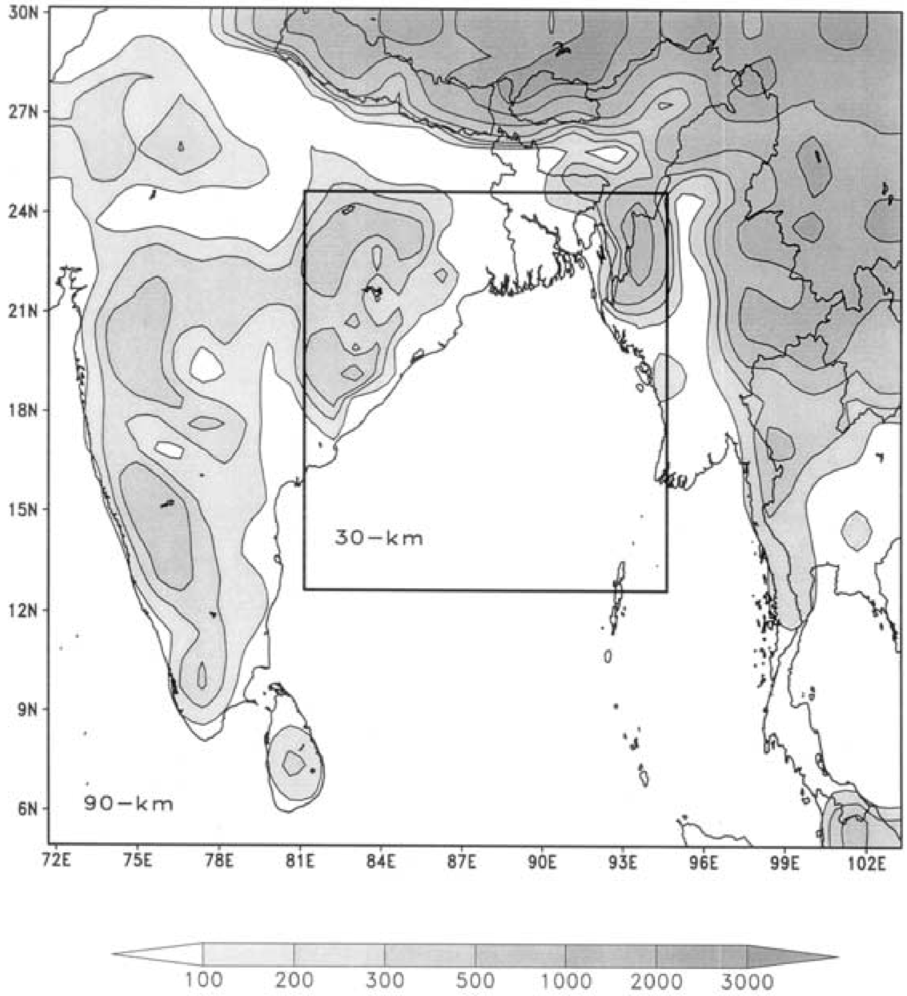

Figure 2. *Locations of the two nested domains. Orography (m) for the coarser mesh is shaded.*

2.2 Construction of a synthetic vortex

In the present study a synthetic vortex was constructed in order to augment the initial conditions to the model. Construction of the synthetic vortex follows Mathur (1991) and requires the central pressure p_c, pressure of the outermost closed isobar p_b and its size R (i.e. the distance of the outermost closed isobar from the centre of the cyclone). The surface pressure distribution at radius r is given by

$$p(r) = p_{\max} - \frac{\Delta P e^{-x^2}}{(1+ax^2)^{1/2}} \qquad r < R$$

$$= p_b \qquad r > R$$

Here, x = r/R, a = 100 is a constant. The other two constants p_{max} and ΔP are derived from the condition p(0) = p_c and p(R) = p_b. The p_c for this cyclone was derived from the satellite T- number following Mishra & Gupta (1976) who have given the relation between the T- number and pressure defect over the Indian region. Pressure defect is defined as the difference between central pressure and the environmental pressure (i.e. the pressure of the outermost closed isobar). The size of the cyclone was obtained from the surface pressure chart published in the Indian Daily Weather Report and is 500 km for this case. The p_b is taken to be the average value of mean sea level pressure at 500 km from the centre in the analysis field. The T-number was reported as 4.5 at 0400 UTC, 28 October 1999. This gave the estimated pressure defect of 30 hPa.

The upper level winds were derived from a set of horizontal and vertical structure functions. The structure of the wind obtained consists of cyclonic winds everywhere in the lower levels, with a slight decrease in their strength up to mid-troposphere, decreasing rapidly above the mid-troposphere, and anticyclonic winds appearing in the upper troposphere. Gradient wind relation using the geopotential at outermost closed isobar as the boundary condition obtained the geopotentials inside the vortex. The temperature was derived from the geopotential field using hydrostatic relation. The relative humidity was specified as nearly saturated at the centre of the cyclone and somewhat lower at the periphery. The relative humidity at the intermediate grid points is interpolated linearly from the values at the centre and the periphery. The dew point depression was derived from pressure, temperature and relative humidity.

2.3 Initial conditions and experimental design

Terrain/land use data, averaged at 30 minutes and 10 minutes, were analysed for Grids 1 and 2 respectively. Initial conditions were generated for Grid 1 domain by interpolating the NCEP/NCAR global reanalyses data (2.5° latitude–longitude resolution) to the model grid. Additional analyses generated in the same manner every 6 h were linearly interpolated in time in order to provide the lateral boundary conditions for Grid 1. The data generated at equidistant points at different radii in the synthetic vortex for 0000 UTC, 28 October 1999 were analysed in the model's coarser grid as point observations to improve the initial condition. Mere incorporation of a tropical cyclone's structure does not ensure improvements in forecasting it. Mass-wind imbalances and rejection of the vortex by the prediction model may degrade the quality of the forecast. To

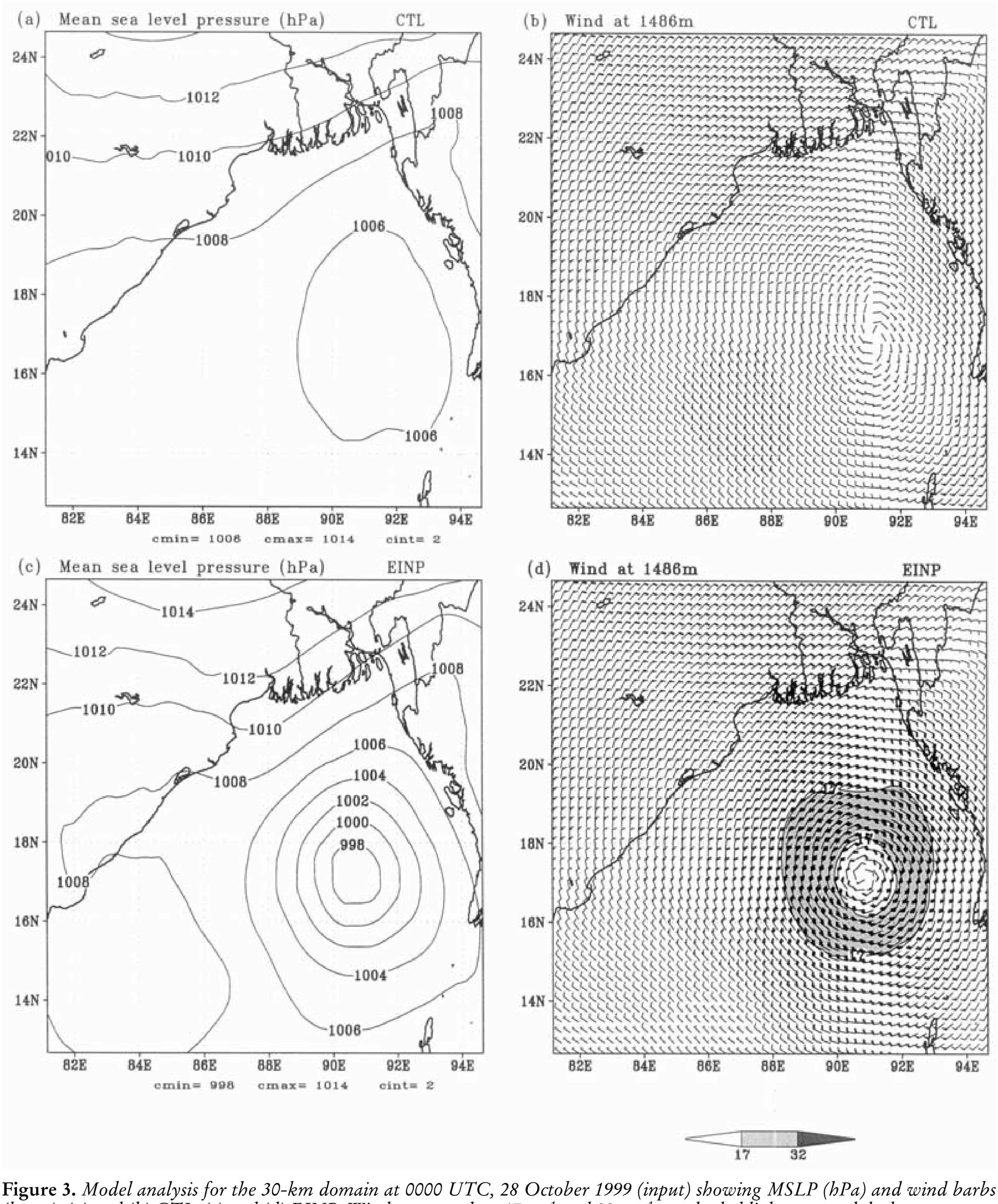

Figure 3. *Model analysis for the 30-km domain at 0000 UTC, 28 October 1999 (input) showing MSLP (hPa) and wind barbs (knots). (a) and (b) CTL; (c) and (d) EINP. Winds greater than 17ms^{-1} and 32 ms^{-1} are shaded light grey and dark grey respectively.*

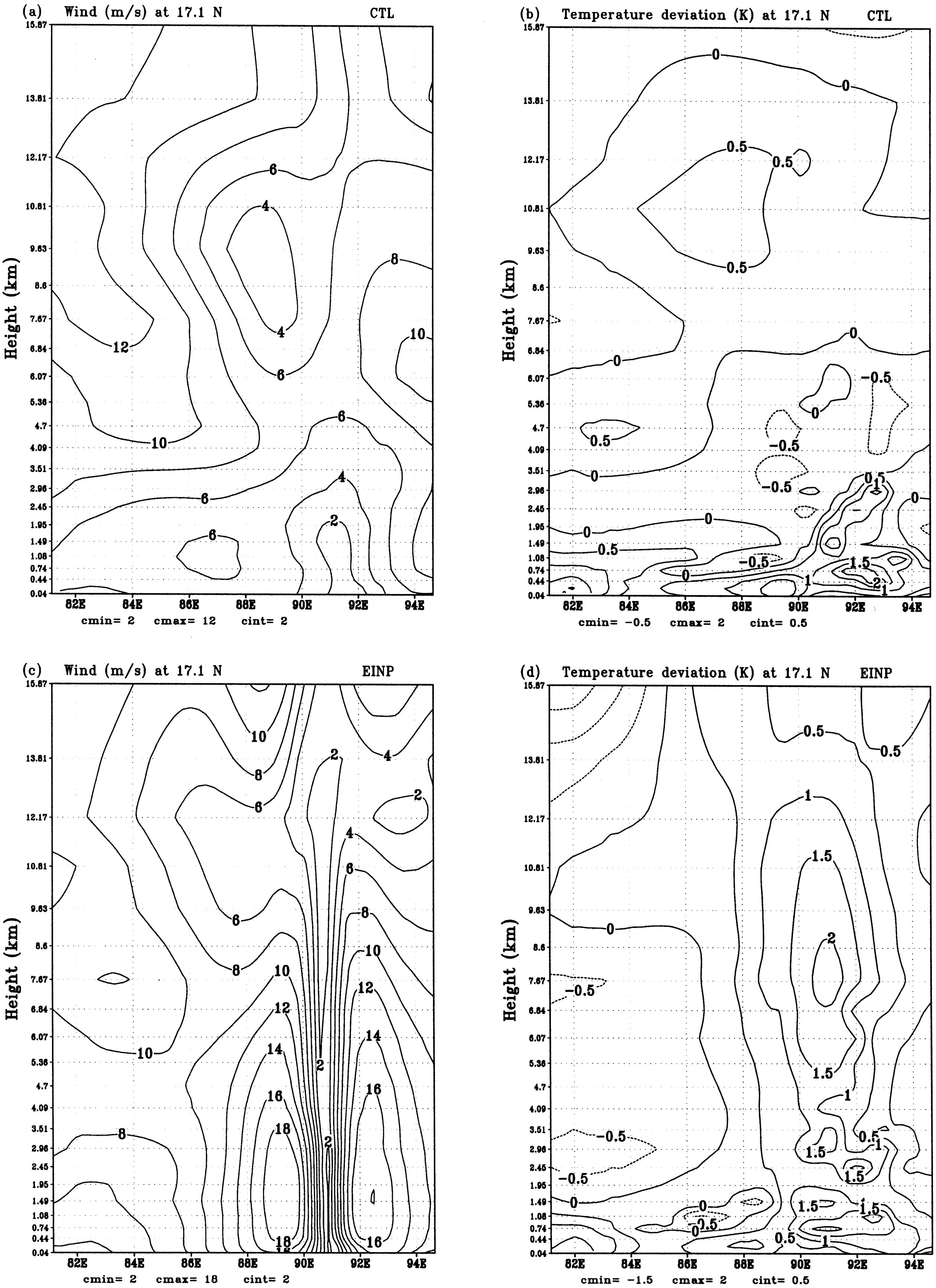

Figure 4. *As for Figure 3, except for west–east cross-sections through the centre of the cyclone for wind speed (ms^{-1}) and temperature anomaly (K).*

avoid this, four-dimensional data assimilation (FDDA) was applied to Grid 1 for the purpose of dynamic initialisation. The Newtonian relaxation or nudging technique was applied for FDDA. In the MM5 model Newtonian relaxation terms are added to the prognostic equations for wind, temperature and water vapour.

These terms force the evolution of the model variables towards a given or target analysis. The target analysis used here was the data enhanced by the synthetic vortex for the input data of 0000 UTC, 28 October 1999. FDDA was applied to Grid 1 during the first 12 hours of the integration starting with the large-scale analysis of 1200 UTC, 27 October. Then, starting at 0000 UTC, 28 October 1999, a 24-h simulation was carried out with both domains in nested mode. The initial conditions for Grid 2 were obtained by interpolating the FDDA output from the Grid 1 mesh and vertically adjusting to higher resolution topography data.

One set of experiments was performed to determine the impact of initial conditions on the forecast of the super cyclonic storm. Henceforth, the experiment with large-scale analysis as its input will be referred to as CTL, while that with enhanced initial conditions will be referred to as EINP.

Figure 3 shows the initial mean sea level pressure (MSLP) and wind at 1486 m (model reference height at sigma level 17) for Grid 2 domain after 12 h FDDA at 0000 UTC, 28 October 1999. In CTL the cyclone located off the east coast of India is, not surprisingly, quite inadequate with a very weakly defined MSLP (Figure 3(a)) and low-level cyclonic wind (Figure 3(b)). EINP shows a more detailed structure in MSLP (Figure 3(c)) with a minimum pressure of 998 hPa with strong gradients. Cyclonic winds around the centre of the system are also more realistic with maximum speeds of 18 ms^{-1} (Figure 3(d)). The west to east cross-section of the wind and temperature deviation from the mean taken through the centre of the cyclone is shown in Figure 4 for CTL and EINP experiments. For EINP (Figure 4(c)) a realistic vertical structure of the wind field is evident, with the maximum wind located close to the centre in the lower troposphere, strong wind gradients between the centre and the maximum wind region, and a slow decrease of wind up to the middle and upper troposphere. These typical characteristics of a mature tropical cyclone are not found in CTL (Figure 4(a)). In addition, the EINP (Figure 4(d)) shows a warm temperature anomaly in the middle and upper troposphere. Thus the initial conditions with the vortex are consistent with the observed structure of tropical cyclones (Frank 1977).

3. Forecast results and discussion

It is well known that the position of a cyclone determined from satellite data will be closer to that obtained by observation. The centre of the cyclone in the initial condition, as well as in the verification obtained from the large-scale analysis, will differ from that derived from the satellite data. For example, in the initial condition for 0000 UTC, 28 October 1999, the centre of the cyclone in the large-scale analysis differs by 88 km from the estimate of the satellite data. As in the present study, the synthetic vortex has been created at the position of a weakly defined cyclone in the large-scale analysis, and the forecast positions in the simulations are compared against the position obtained in the large-scale analysis.

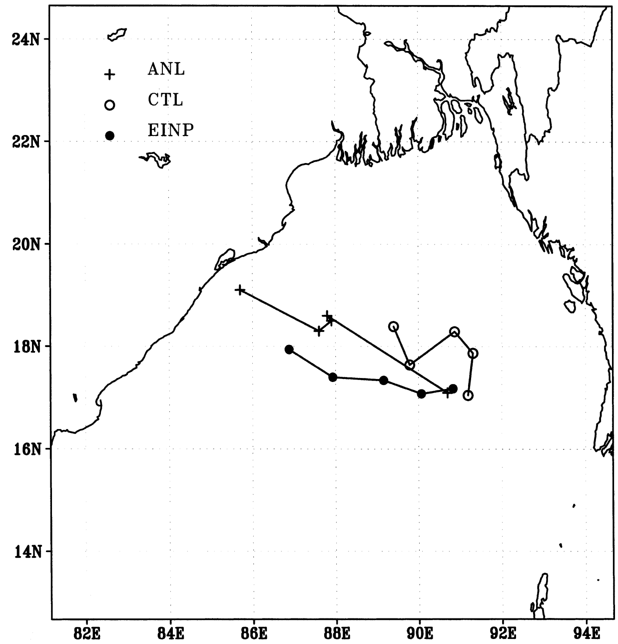

Figure 5. *Tracks of the cyclone from the analysis and model simulations. Data are plotted at 6-hour intervals.*

The evolution of tracks from the simulations is shown in Figure 5. The forecast positions of the cyclone are diagnosed from the low-level wind circulation at 6-hourly intervals. The track derived from the large-scale analysis (ANL in Figure 5) shows north-westerly movement during the entire integration period. The track in CTL is very erratic. It shows a change of direction at every 6 hours, and its speed is also too slow. The erratic motion seems to be the product of a resolution difference between the model grid and the global analysis. Bender et al. (1993) had reported this type of erratic motion during initial period of forecast. The EINP produced a much better track with a west-north-west movement, but the predicted position is much further south than the observed position after 24 hours. The smoothness of the EINP track suggests that the vortex has been assimilated well into the initial condition by the FDDA. Predicted track errors shown in Table 1 clearly indicate that EINP has reduced the track errors significantly compared with the CTL run. The better track forecast for EINP may be due to the simulated cyclone being stronger in this run than the CTL. Anthes (1982) has suggested that the motion of a tropical cyclone depends upon its size and intensity.

The time evolution of minimum MSLP in the two experiments is shown in Figure 6. The CTL shows only small cyclonic development, with a drop of 5 hPa, while EINP produced a rapid intensification of the cyclone with a pressure drop of 17 hPa during the integration period. However, neither integration repro-

Table 1. *Forecast track errors (in km) at 6-hour intervals.*

Forecast hour	CTL	EINP
0	54	16
6	394	300
12	327	188
18	251	105
24	414	182

duced the observed rapid deepening of 50 hPa between 0000 UTC, 28 October and 0000 UTC, 29 October 1999. This is probably due to the model resolution, which is not able to resolve the very detailed structure of the eye and the eye-wall region, and could also be due to the diffusive processes applied to preserve the stability. The slow movement predicted in both the runs may be due to this underprediction of intensity. The relationship between tropical cyclone motion and its strength has been shown by Chan & Williams (1987).

The horizontal structure of a cyclone in the lower troposphere is characterised by a relatively calm wind surrounded by very strong winds close to the centre, known as the radius of maximum wind, and many closed isobars with steep pressure gradients in the region of maximum winds. Figure 7 presents 24-h forecast horizontal structure in terms of mean sea level pressure, accumulated rainfall and wind at 1486 m for Grid 2. Winds of more than 70 ms^{-1} associated with this cyclone were reported over the Orissa coast on 29 October 1999. The winds in CTL could not produce the characteristic features, as is evident from Figure 7(b). The isolated maxima of 20 ms^{-1} are located far from the cyclone's centre and characterise the cyclonic storm strength only. In EINP (Figure 7(d)), winds stronger than 17 ms^{-1} extend 2(3° from the centre, with maximum winds of 40 ms^{-1} surrounding the relatively calm eye, showing the more realistic horizontal structure of a very severe cyclonic storm. Although EINP produced much better wind strength than CTL, it failed to produce the very strong winds that were observed. This under-prediction of wind may partially be attributed to the resolution of the model. The asymmetric wind distribution around the cyclone's centre, with maxima to the right, agrees well with the findings of Shea & Gray (1973). EINP produced a much better structure for MSLP (Figure 7(c)), with many closed isobars and steep pressure gradients in the region of maximum wind close to the cyclone's centre, than the CTL run (Figure 7(a)), which is unable to show the characteristic MSLP of a tropical cyclone. The overall pattern of predicted rainfall was the same in both experiments, with more spreading to the right (Figure 7(a) and (c)), but the predicted rainfall intensity is greater in EINP, which is consistent with the simulated intense cyclone. The spreading of rainfall to the right was reported by Raghavan (1990) for tropical cyclones over the Indian region. The absence of simulated rainfall over the Orissa coast may be due to the fact that predicted positions in both the experiments are some distance off the coast. Mandal (1991) reported that most rainfall activity in any cyclone occurs within a 200-km radius of the cyclone's centre. The simulated rainfall in both the experiments produced the rain band extending to the north from the central region. The satellite imagery (Figure 1) also showed a rain band extending towards the north from the central, dense cloud region.

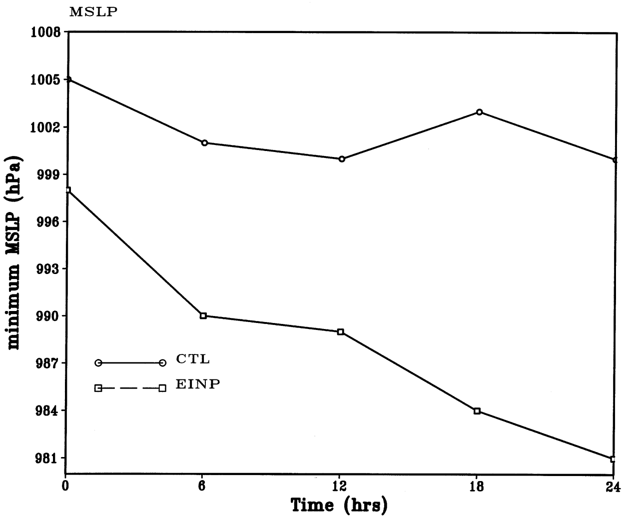

Figure 6. *Time evolution of central mean sea level pressure (hPa) for CTL and EINP.*

The vertical structure of the simulated cyclone is depicted in Figure 8. The left panel shows the west to east cross-section of the wind speed through the predicted centre, while the right panel is the temperature deviation. The wind in CTL (Figure 8(a)) shows higher speeds in the middle troposphere than the lower, which is unrealistic for a tropical cyclone. The wind in EINP (Figure 8(c)) shows a strong wind speed gradient between the centre and the region of wind maxima, decreasing outside the maximum wind region, and a slow decrease of wind speed with height. These features produced in EINP are typical of tropical cyclone structure. Hawkins & Imbembo (1976) demonstrated the existence of very sharp wind gradients near the region of maximum wind. Similarly, the temperature deviation through the centre shows much more warming in EINP (Figure 8(d)), with maximum deviation of 5 K, than the CTL (Figure 8(b)) in the middle and upper troposphere. Thus, the enhanced initial condition shows considerable impact on the vertical structure of the cyclone after the 24-hour forecast.

4. Conclusions

This numerical study aims to demonstrate the impact of enhancing the initial conditions on the forecast of a super cyclone using a high resolution nonhydrostatic mesoscale model (MM5). The enhanced analysis with a

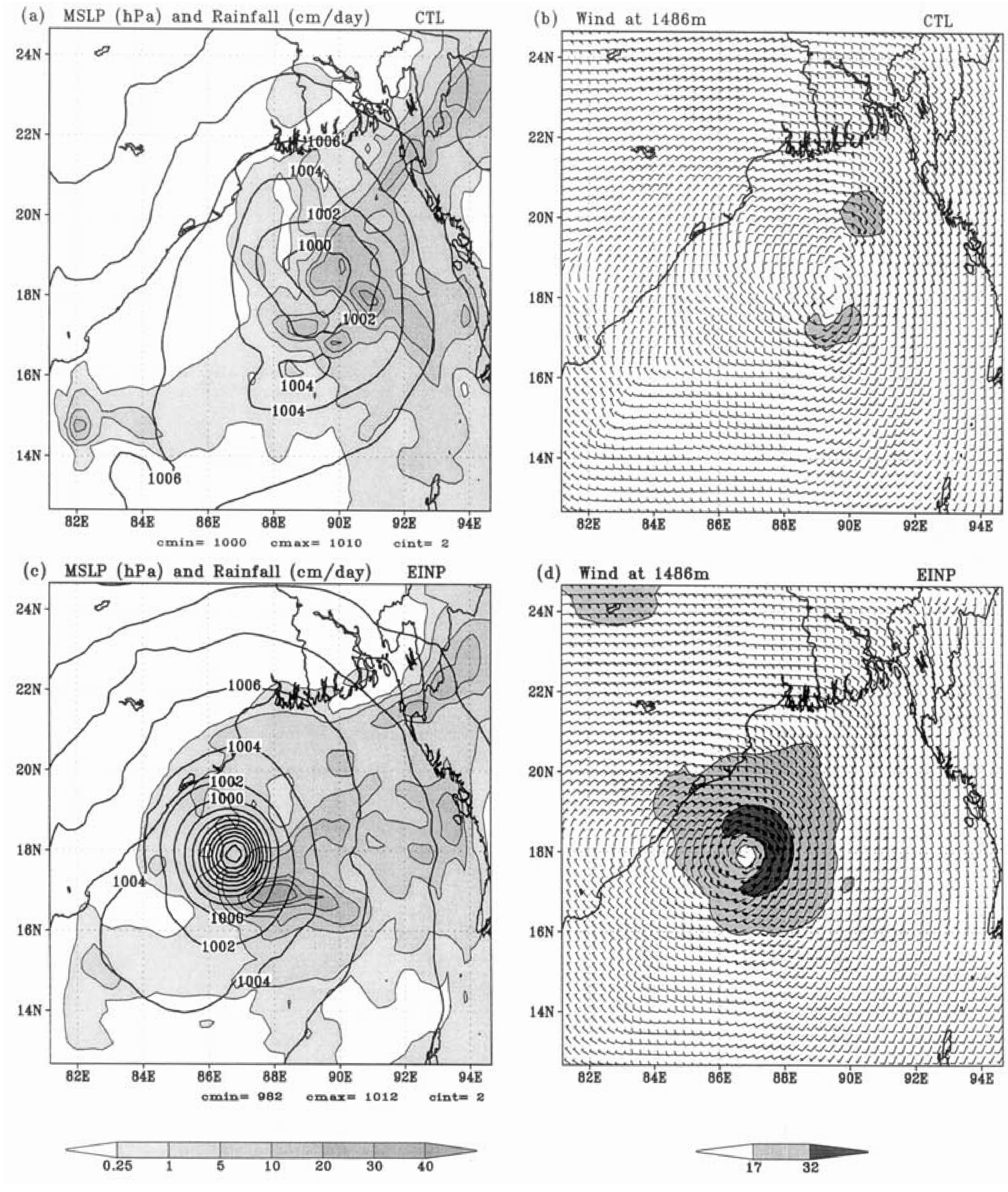

Figure 7. *Model analysis for the 30-km domain at 0000 UTC, 29 October 1999 (24-hour forecast) showing MSLP contours in hPa, rainfall shaded in cm/day and wind barbs in knots. (a) and (b): CTL; (c) and (d): EINP. Winds greater than 17 ms^{-1} and 32 ms^{-1} are shaded light grey and dark grey respectively.*

synthetic vortex results in a tropical cyclone structure that is more consistent with composite studies of tropical cyclones. Forecast track errors are significantly reduced in the simulation using the synthetic vortex than in the integration without the vortex. Enhancement of data has resulted in a more intense simulated cyclone. The horizontal structure in terms of the lower tropospheric winds and mean sea level pressure distribution is better produced with enhanced initial condition. The rainfall is more intense in EINP, with the distribution pattern almost the same in both experiments. The vertical structure with strong winds close to the surface, less vertical shear and a warm temperature anomaly in the middle and upper troposphere depicts the typical characteristics of a tropical cyclone in the experiment with synthetic vortex.

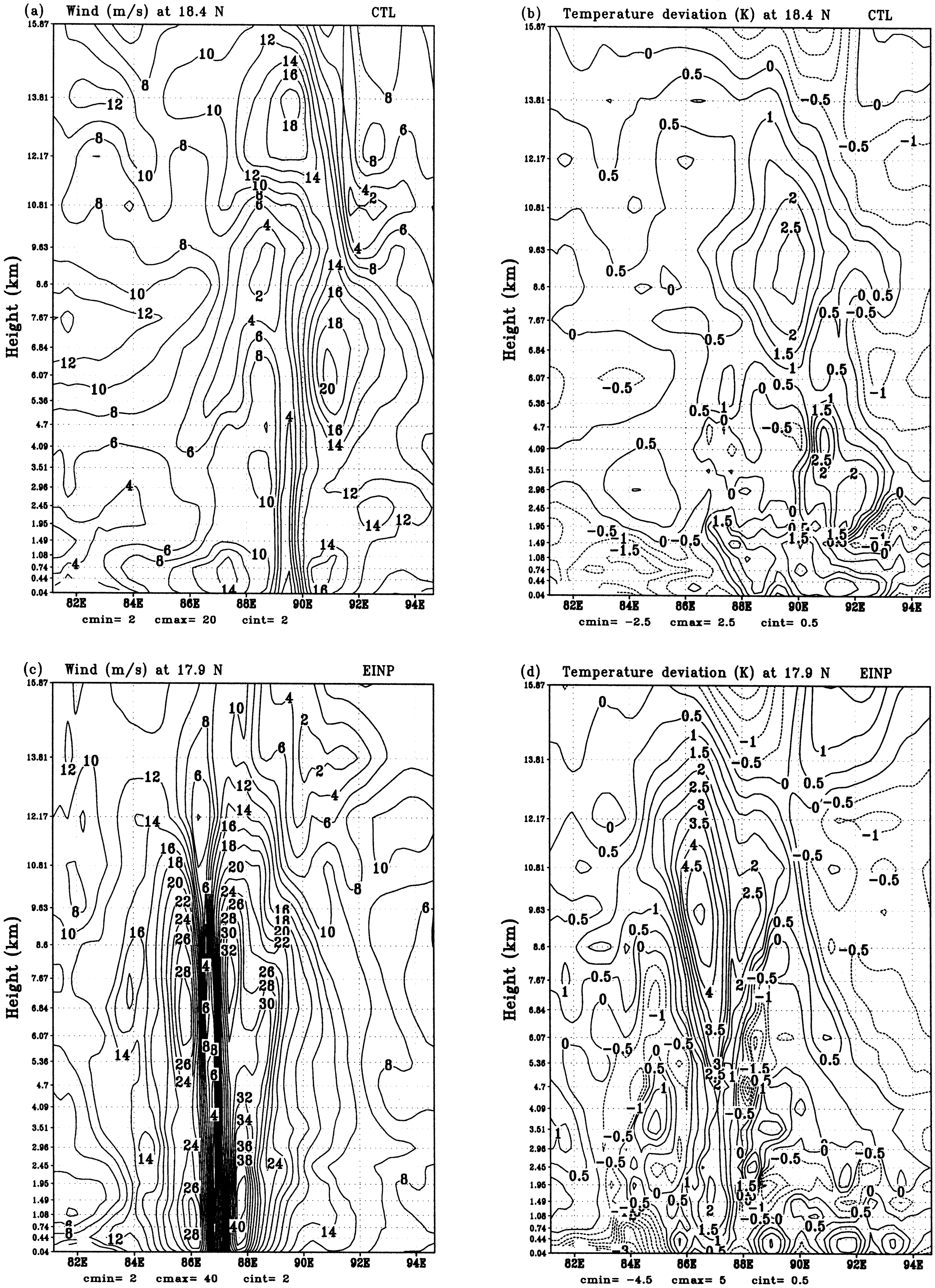

Figure 8. *As for Figure 7, except for the west–east cross-section through the centre of the cyclone for wind speed (ms^{-1}) and temperature anomaly (K).*

The enhancement of the initial condition has thus yielded better movement, better development and more realistic horizontal and vertical cyclone structures. Despite these improvements, the model could not produce the observed intensity and motion. These problems can be addressed by refining the model resolution, by improving the synthetic vortex and by adopting suitable parameterisation schemes. These topics will be addressed in future work.

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References

Abraham, K. R., Mohanty, U. C. & Dash, S. K. (1995) Simulation of cyclones using synthetic data. *Proc. Indian Acad. Sci.* (*Earth Planet. Sci.*) **104:** 635–666.

Anthes, R. A. (1982) *Tropical Cyclones: Their Evolution, Structure and Effects*. Meteorological Monograph. Am. Meteorol. Soc., 203pp.

Bender, M. A., Ross, R. J., Tuleya, R. E. & Kurihara, Y. (1993) Improvements in tropical cyclone track and intensity forecasts using the GFDL initialization system. *Mon. Wea. Rev.* **121:** 2046–2061.

Chan, J. C. L. & Williams, R. T. (1987) Analytical and numerical studies of the beta effect in tropical cyclone motion. Part I: Zero mean flow. *J. Atmos. Sci.* **44**: 1257–1265.

Davidson, N. E., Wadsley, J., Puri, K., Kurihara, K. & Ueno, M. (1993) Implementation of the JMA typhoon bogus in the BMRC tropical prediction system. *J. Meterol. Soc. Japan* **71**: 437–467.

Dudhia, J. (1989) Numerical study of convection observed during the Winter Monsoon Experiment using a mesoscale 2-dimensional model. *J. Atmos. Sci.* **46**: 3077–3107.

Dudhia, J. (1993) A nonhydrostatic version of the Penn State/NCAR mesoscale model: validation test and simulation of an Atlantic cyclone and cold front. *Mon. Wea. Rev.* **121**: 1493–1513.

Frank, W. M. (1977) The structure and energetics of the tropical cyclone. Part I: storm structure. *Mon. Wea. Rev.* **105**: 1119–1135.

Grell, G. A. (1993) Prognostic evaluation of assumptions used by cumulus parameterizations. *Mon. Wea. Rev.* **121**: 764–787.

Hawkins, H. F. & Imbembo, S. M. (1976) The structure of a small intense hurricane, Inez 1966. *Mon. Wea. Rev.* **104**: 418–442.

Heming, J. T., Chan, J. C. L. & Radford, A. M. (1995) A new scheme for the initialisation of tropical cyclones in the UK Meteorological Office Global model. *Meteorol. Appl.* **2**: 171–184.

Hong, S-Y. & Pan, H-L. (1996) Non local boundary layer vertical diffusion in a medium range forecast model. *Mon. Wea. Rev.* **124**: 2322–2339.

Iwasaki, T., Nakano, H. & Sugi, M. (1987) The performance of a typhoon track prediction model with cumulus parameterisation. *J. Meteorol. Soc. Japan* **65**: 555–570.

Klemp, J. B. & Durran, D. R. (1983) An upper boundary condition permitting internal gravity wave radiation in numerical mesoscale models. *Mon. Wea. Rev.* **111**: 430–444.

Kurihara, Y., Bender, M. A. & Ross, R. J. (1993) An initialization scheme of hurricane models by vortex specification. *Mon. Wea. Rev.* **121**: 2030–2045.

Mandal, G. S. (1991) *Tropical Cyclones and their Forecasting and Warning Systems in the North Indian Ocean*. Tropical Cyclone Programme, WMO TD No. 430, 417pp.

Mathur, M. B. (1991) The National Meteorological Center's quasi-lagrangian model for hurricane prediction. *Mon. Wea. Rev.* **119**: 1419–1447.

Mishra, D. K. & Gupta, G. R. (1976) Estimation of maximum wind speeds in tropical cyclones occurring in Indian seas. *Indian J. Meteorol. Hydrol. Geophys.* **27**: 285–290.

Prasad, K., Rama Rao, Y. V. & Sen, S. (1997) Tropical cyclone track prediction by a high resolution limited area model using synthetic observation. *Mausam* **48**: 351–366.

Raghavan, S. (1990) Structure of tropical cyclones in the Bay of Bengal. *Mausam* **41**: 325–328.

Reed, R. J., Hollingsworth, A., Heckley, W. A. & Delsol, F. (1988) An evaluation of the performance of ECMWF operational system in analysing and forecasting easterly wave disturbance over Africa and Tropical Atlantic. *Mon. Wea. Rev.* **116**: 824–865.

Shea, D. J. & Gray, W. M. (1973) The hurricane inner core region: I. Symmetric and asymmetric structure. *J. Atmos. Sci.* **30**: 1544–1564.