Simulation of tropical cyclones using regional weather prediction models

Prabir K. Patra*, M. S. Santhanam, K. V. J. Potty, M. Tewari and P. L. S. Rao
IBM India Research Laboratory, Block-I, Indian Institute of Technology-Delhi, Hauz Khas, New Delhi 110 016, India

Two non-hydrostatic mesoscale models, namely the Regional Atmospheric Modelling System (RAMS) and the PSU/NCAR Fifth-Generation Mesoscale Model (MM5) have been used to simulate various meteorological features associated with the tropical cyclones formed over the Bay of Bengal. Some of the simulation results, such as the horizontal distributions of winds, temperature, associated rainfall, cyclone tracks, moisture convection and height of the planetary boundary layer have been presented. These results are compared with the observations to assess the capability of these models in simulating various meteorological phenomena over the Indian subcontinent and it is established that the RMS errors for predicted zonal winds *U*, the meridional winds *V*, and the temperature *T* are within the acceptable limits. Both the models are also able to produce the warm core structure of the tropical cyclones. We also highlight a few potential areas of research to improve the model simulations of various weather events, specific to this region.

NUMERICAL weather prediction models are being used to simulate the tropical cyclones for the last three decades[1,2]. Mesoscale models are favoured over the global models because they can resolve small-scale phenomena like tropical cyclones, with horizontal scale of about 100–200 km, and their resolution can be increased without much computational expenditure. A recent study shows a comparative performance of a few regional models, namely the Regional Atmospheric Modelling System (RAMS) developed at Colorado State University, the Fifth-generation Mesoscale Model (MM5) developed jointly by NCAR and Pennsylvania State University, Navy Operational Regional Atmospheric Prediction System (NORAPS), and Relocatable Window Model (RWM)[3]. This study ranks RAMS marginally ahead of MM5 in overall simulation capability in the selected geographical domains. Thus it is known that all the weather prediction models have their merits and demerits in predicting various weather phenomena. It is also established that the results can be significantly improved by making use of appropriate initial and boundary conditions in the model, by selecting suitable parameterization schemes, by choosing an ensemble of initial conditions for various weather system[4,5]. Recently, a multimodel superensemble technique has been introduced that shows major improvements in the prediction accuracy[6]. This approach obtains statistical corrections to offset the biases of the individual models that form the ensemble. Therefore, it is extremely important to evaluate the performance of the models in simulating various meteorological events.

The tropical weather systems are very complex and form under multitude of atmospheric instabilities such as barotropic, baroclinic and CISK (conditional instability of second kind), and these instabilities change rapidly from their formation to the stage of maturity. One such severe weather phenomenon is the tropical cyclone, essentially a low pressure system originating over the tropical oceans and is characterized by strong surface winds (speed exceeding 17 m s^{-1}), organized convection and warm core in the troposphere. In the north Indian basin, the Bay of Bengal is more prone to the cyclonic storms compared to the Arabian Sea. This is primarily due to higher SSTs (threshold being 26°C), larger moisture content and cloud cover leading to unstable atmospheric motion, as the tropical cyclones derive energy (sensible and latent heat) mainly from the ocean and convective clouds[7]. These cyclonic systems sometimes claim thousands of human lives and cause devastating damages to both property and crops. Considering the socio-economic implications of tropical cyclones, it is crucial to understand their genesis, development and associated characteristic features, and improve the accuracy of such forecasts. The purpose of the present study is to compare the performance of RAMS and MM5 in the context of cyclone track prediction and associated meteorological parameters for three cyclonic storms formed in the Bay of Bengal.

Model description

There are quite a few similarities as far as working of RAMS and MM5 is concerned. Both the models solve the nonhydrostatic equations of motion using time-split techniques for compressible fluid. Both offer several options for coordinate system, grid structure including multi-level nesting, advection, turbulent mixing parameterization, lateral and vertical boundary conditions, surface layer parameterizations for different kinds of soil and vegetation, convection parameterization, and short/long wave

*For correspondence. (e-mail: pprabir@in.ibm.com)

radiation calculation including cloud interaction. Much of the efforts have also gone in producing appropriate initial conditions and nudging boundary conditions towards the analysis and observational data[7]. Various engineering aspects and the options available in these models can be found in the technical reports of Aster Division[8,9] for RAMS and NCAR[10] for MM5, and some of those used in this work are listed in Table 1. There are a few more advanced features such as moving nested grids, four-dimensional data assimilation (FDDA) for analysis and observational nudging, etc. which have not been implemented in this work.

Description of the experiment

In this article, we have chosen to simulate three Bay of Bengal cyclones whose centres were initially located as follows: (1) at (13.0°N, 88.5°E), about 500 km north-west of Port Blair on 8 November 1995 moving in a north-westerly direction; (2) at (16.0°N, 84.5°E), about 380 km east of Machilipatnam in Andhra Pradesh on 6 November 1996 moving in a west-ward direction; and (3) at (11.0°N, 91.4°E), less than 100 km away from Port Blair in the west on 17 May 1997 moving in a north to north-easterly direction, while we started the model runs. The reasons for selecting these cases are: they formed during pre- and post-monsoon periods (which elucidate the models' ability to capture the intraseasonal features), and the cyclone tracks are in different directions (these simulations reveal the biases of the models, if any).

Both the models have been implemented on IBM-RS/6000. We have used the grided pressure level data from the NCMRWF (National Centre for Medium Range Weather Forecasting), New Delhi operational analysis[11]. Five large-scale meteorological parameters (geopotential, zonal wind, meridional wind, temperature, and relative humidity) at 12 mandatory levels, (i.e. 1000, 850, 700, 500, 400, 300, 250, 200, 150, 100, 70, 50 hPa) are used to generate the initial and boundary conditions for the 48 h model integrations. Climatological mean monthly SSTs

Table 1. Various specifications for model simulations of cyclonic storms in the Bay of Bengal using RAMS and MM5

Model specifications	RAMS	MM5
Basic equations	Nonhydrostatic time-split compressible	Nonhydrostatic time-split compressible
Vertical coordinate	Terrain-following height coordinate	Terrain-following sigma coordinate
Horizontal coordinate	Rotated polar-stereographic transformation	Standard Cartesian coordinate
Grid structure	Arakawa-C grid stagger	Arakawa-B grid stagger
Time differencing	Hybrid combination of Leapfrog and Forward	Semi-implicit time splitting
Turbulence closure	Turbulent kinetic energy (Mellor–Yamada[16] type)	Deardorff type
Radiation	Chen and Cotton[17] long/short-wave model	Dudhia's[18] long/short-wave model
Lower boundary	Tremback and Kessler[19] soil temperature and vegetation model	Multi-layer soil temperature model
Upper boundary condition	Rigid lid ($w = 0$)	Klemp and Durran[20] upper radiative condition
Lateral boundary condition	Klemp–Wilhelmson[21] radiative condition	Relaxation boundary condition
Initialization	Analysis of grid point data/obs. on isentropic surfaces	Analysis of grid point data/obs. on sigma surfaces

Table 2. Estimated RMS errors for zonal and meridional winds (U, V in m s^{-1}) and temperature (T in K) from RAMS and MM5 simulations at 24 h and 48 h forecast times at three representative vertical levels

		From RAMS simulations						From MM5 simulations					
		For 24 h FCST			For 48 h FCST			For 24 h FCST			For 48 h FCST		
Event	Vertical level (z/σ)	U	V	T	U	V	T	U	V	T	U	V	T
1995	1.5/0.85	4.49	3.02	1.09	3.15	2.58	1.25	4.86	3.91	1.67	3.33	3.45	1.79
	5.5/0.50	2.91	2.53	1.59	2.09	1.85	1.22	3.65	3.78	1.23	3.07	3.12	0.69
	9.5/0.25	2.85	2.68	0.88	2.01	2.86	0.66	4.26	3.38	1.10	3.18	4.08	0.73
1996	1.5/0.85	2.01	2.04	1.27	1.41	1.84	1.78	2.46	2.77	1.33	2.88	1.92	1.97
	5.5/0.50	1.93	2.15	0.46	1.27	1.40	0.66	2.11	2.62	0.41	2.45	1.93	0.61
	9.5/0.25	2.07	2.09	0.37	1.26	1.46	0.56	2.51	2.73	0.44	2.35	2.60	0.48
1997	1.5/0.85	3.54	2.73	1.30	2.72	2.75	1.46	6.51	7.36	1.97	4.78	8.15	1.82
	5.5/0.50	3.90	3.20	1.06	2.24	2.77	0.77	6.10	8.18	1.84	5.61	8.68	1.38
	9.5/0.25	3.93	2.91	0.81	3.81	3.21	0.74	5.74	8.69	1.52	5.74	9.32	1.59

We have used two vertical coordinate systems, altitude (z in km) for RAMS results and sigma ($\sigma = P/P_s$) for MM5 results, for corresponding pressure levels of approximately 850, 500 and 250 mb.

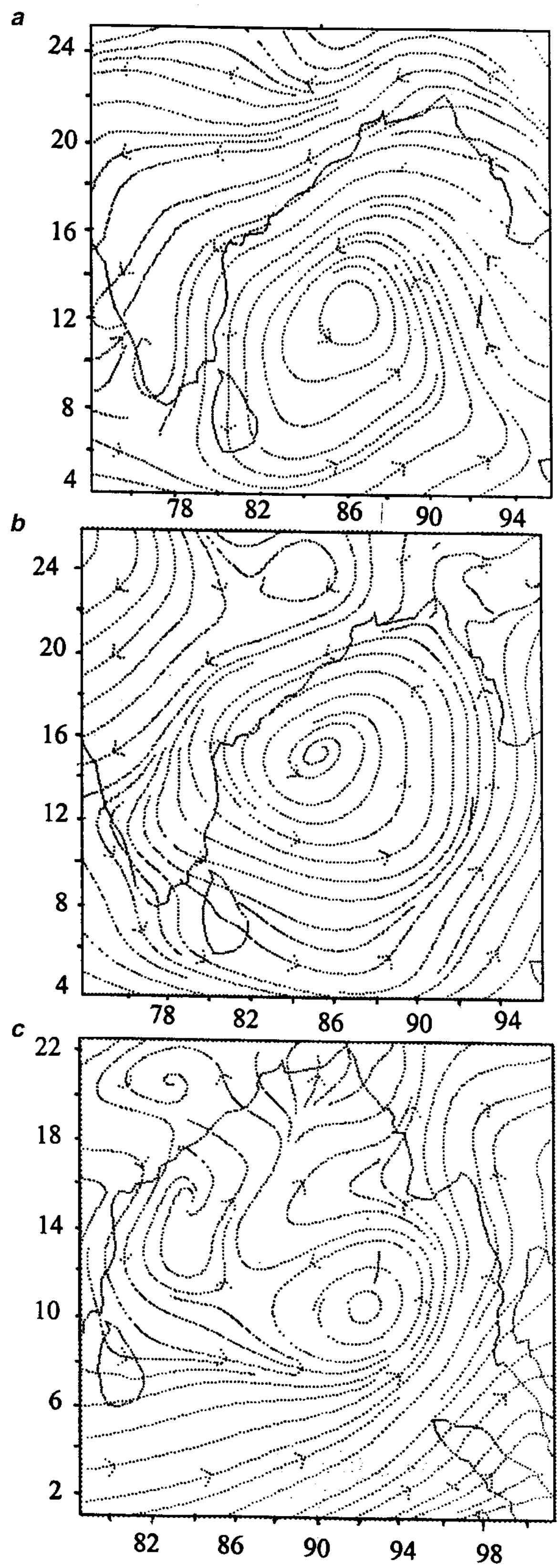


Figure 1. Initial conditions for model runs for the cyclones during: ***a***, 7–10 November 1995; ***b***, 5–7 November 1996; and ***c***, 15–20 May 1997 generated from the NCMRWF daily analyses. The models were started at 00 UTC on 8 November 1995, 6 November 1996 and 17 May 1997, respectively.

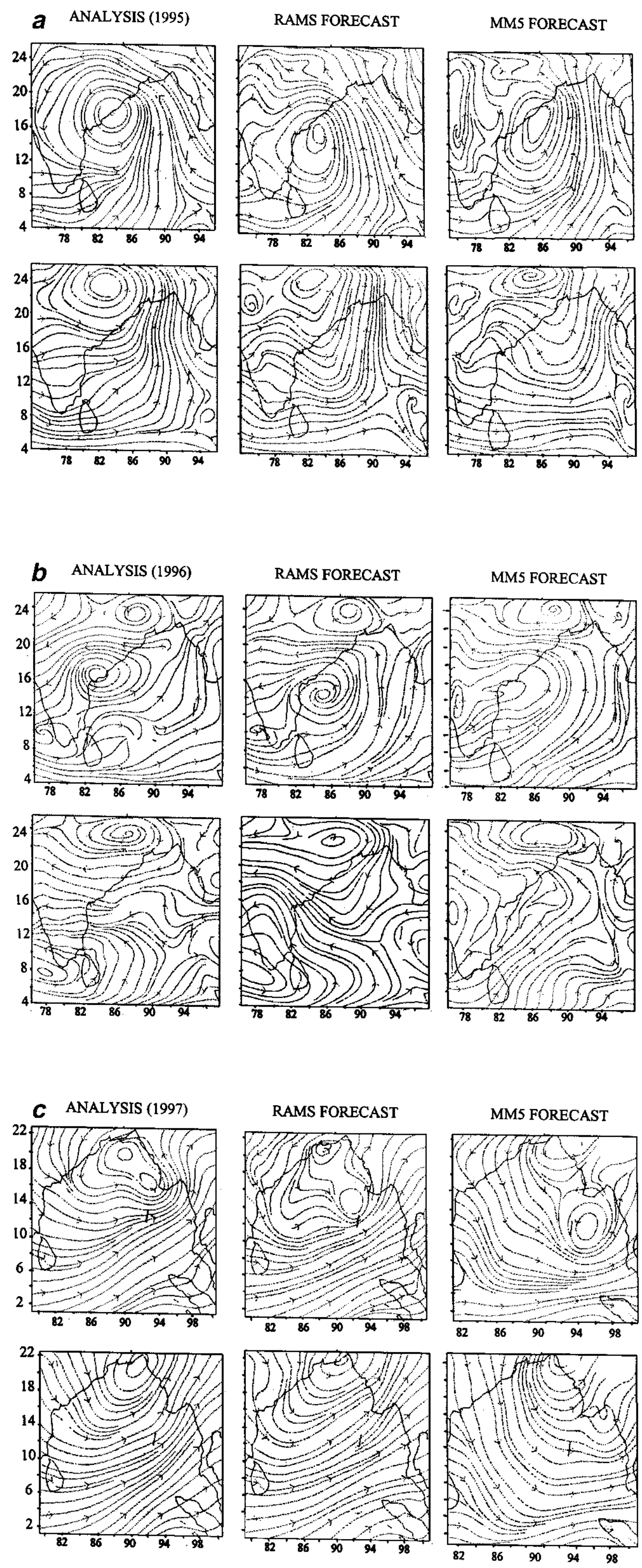


Figure 2. ***a***, Horizontal streamlines of analysed data (left panel), model forecasts by RAMS (middle panel) and model forecasts by MM5 (right panel) at 24 h forecast time (upper panels) and 48 h forecast time (lower panels), for the cyclonic storms which occurred in November 1995; ***b***, Same as ***a*** but for November 1996; ***c***, Same as ***a*** but for May 1997.

and US Navy 10′ × 10′ orography data have been used We have selected a 62 × 62 horizontal domain at the resolution of 40 km (polar steoreographic for RAMS and standard Cartesian for MM5) with the centres at (15°N, 80°E), (15°N, 80°E), and (12°N, 85°E) for the 1995, 1996, and 1997 cyclones, respectively. RAMS has 25 vertical levels spreading from ground to a height of about 16.7 km. The vertical resolution of RAMS starts at 100 m near the ground and attains about 1 km at the final altitude levels. MM5 has 25 vertical σ-pressure levels, starting from 1.0 at the ground to 0 at the model top. Figure 1 shows the horizontal streamlines at the start of model integration, i.e. on 8 November 1995, 6 November 1996, and 17 May 1997 at 00 UTC. All the model simulations started when the state of the storms is classified as cyclonic (T. number ≥ 2.5 on Dvorak's scale[12]) and just before (3–6 h) they turned to severe cyclonic storms (T. number ≥ 3.5 on Dvorak's scale).

Results and discussion

General dynamical features

In general, both the RAMS and MM5 simulations depict a fairly good match with the analysis (see Table 2 for detailed error analysis). Figure 2 *a* shows the horizontal streamlines of NCMRWF analyses, RAMS and MM5 simulations at around 1.5 km height (equivalent to 850 mb pressure level) for 24 h forecast time (i.e. 9 November 00 UTC), and 48 h forecast time (i.e. 10 November 00 UTC) for the cyclone in 1995. The IMD observation

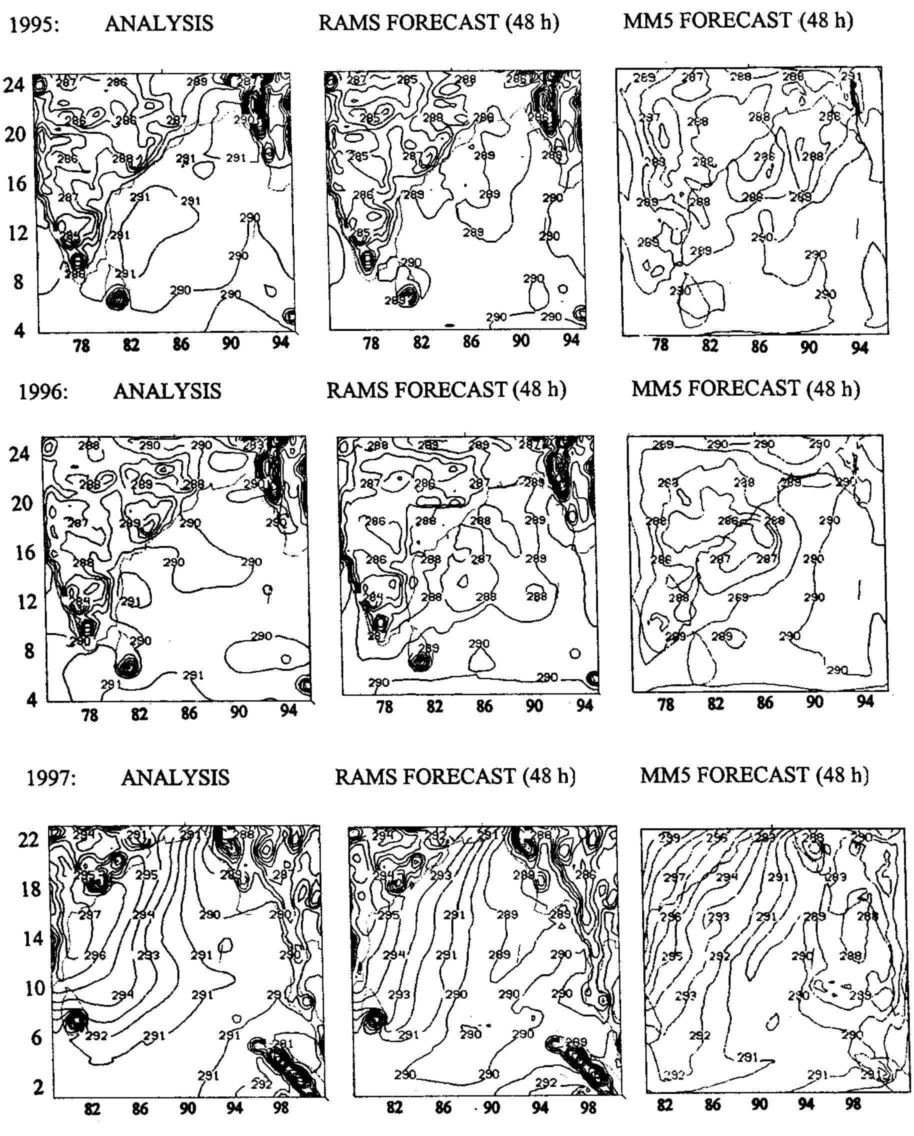


Figure 3. Horizontal cross-sections of temperature (in K) at around 850 mb as simulated by RAMS (middle) and MM5 (right) at 48 h forecast time and corresponding verification analyses (left) for all the cyclones (upper pannel, 1995 cyclone; middle panel, 1996 cyclone; and lower panel, 1997 cyclone).

system detected that the cyclone hit the Indian east coast at 0500 UTC on 9 November 1995 near Ichchapuram (19.5°N, 85.0°E), which compares well with the RAMS forecast (hit the land at 0600 UTC). MM5 predicts landfall slightly ahead of time (not shown here). The 48 h forecasts and analysis indicate that the cyclone centre has traversed the land in a northerly direction and weakened with time. The distance travelled by the cyclone eye in the first 24 h is much less than that in the last 24 h (speeds reaching up to 25 km/h and 32 km/h, respectively, from simulation) in comparison with the IMD observations (average speed of 30 km/h).

Figure 2 *b* depicts the streamlines for the analysis, simulations of RAMS and MM5 for 24 h and 48 h for the cyclone of 1996. This cyclone is the shortest lived (less than one day as severe cyclonic storm) among the three cases considered here. Therefore, the 24 h forecasts are quite poor in quality, and the movement of cyclones in time scale also does not follow the path in a westerly direction as observed. RAMS predicts very slow movement of the centre of the cyclone towards the Indian east coast and also the predicted direction is somewhat inclined to the south. On the contrary, MM5 forecasts show a diminishing trend in their intensity and no clear cyclonic eye can be identified at the 24 h forecast time (top-right panel).

Figure 2 *c* shows the horizontal streamlines for the severe cyclonic storm with a core of hurricane wind during 15–20 May 1997. We started the simulations on 17 May 1997 at 00 UTC when the centre of the cyclonic storm was located at 11.0°N, 91.4°E and started moving in a north to north-easterly direction. The 24 h forecast of RAMS shows an elongated low pressure region in the northern part of the Bay of Bengal with the eye of the cyclone at around 14.9°N, 92.2°E. A similar behaviour is also seen in the analysed data but with the centre being located at 16.6°N, 93.1°E. The MM5 simulations did not reproduce this feature very well and it appeared from the figure that the centre of the cyclone moved at a much slower speed and in a different direction. Further, the position is found to be around 12.7°N, 94.5°E. The 48 h forecasts of both RAMS and MM5 indicate the presence of low-pressure region over the coastal area of Bangladesh which is consistent with the analysis.

In addition, outside the cyclonic region the streamlines from the analysed data and those predicted by RAMS and MM5 match very well. This is evident from the RMS errors of various meteorological parameters at all vertical levels and for the whole domain. The calculated RMS errors for zonal winds (U), meridional winds (V), and temperature (T) at 24 and 48 h forecast times are given in Table 2 for comparison. In general, most of the error values are well within the acceptable criteria identified by the model intercomparison exercise[3]. The accuracy criteria are 2 K for temperature and 2.5 m/s for the wind speeds encountered during cyclones. The only exception is the MM5 forecast for the 1997 cyclone; the higher errors in U and V arise primarily due to the difference in the cyclone track as will be discussed later in the article. It can be noticed from Table 2 that, in general, the RMS error is decreasing with height; more consistently in RAMS simulations than in MM5. This is due to the fact that physical processes and surface forcings are more important in the lower troposphere and as one moves up vertically, the effect of these forcings to the atmospheric motion reduces.

Temperature distributions

As in the case of horizontal streamlines, the temperature distributions at around 1.5 km height also indicate a similar behaviour; RAMS performs better than MM5. Simulations of temperature by RAMS and MM5 for 48 h, along with the corresponding verification analysis are depicted in Figure 3. In general, RAMS and MM5 simulations match very well with the analysed data for the absolute temperature values (see Table 2). Both the models forecasted slightly lower temperatures (a maximum difference of 2 K) when compared with the analysed data over the Bay of Bengal region. However, in the RAMS simulations every detailed feature present in the analysis, particularly the low and high values over the land, is reproduced which is not the case with MM5. This discrepancy is primarily caused by the difference in the treatment of surface energy balance between the two models.

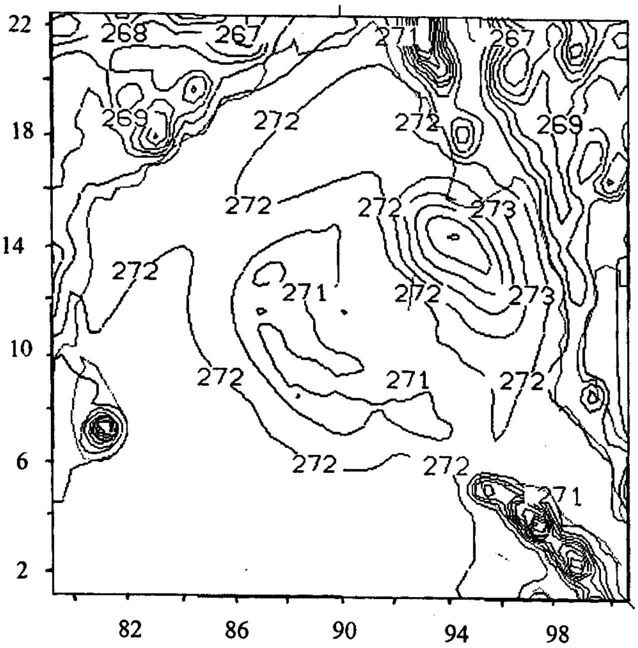


Figure 4. Horizontal cross-sections of temperature distributions after 21 forecast hours depicting the spatial extent and intensity of the warm core, typical of a tropical cyclone. However, this feature is not evident from the analysed data.

Figure 4 shows the temperature distributions at about 5 km height on 17 May at 21 UTC (equivalent to 21 forecast hours). A warm core structure can be observed in all the three simulations by using RAMS with varying intensity; the core is apparently warmer by about 5 K in this case and situated at around 14.5°N, 94°E. The vertical cross-section of the cyclone (not depicted here) shows that the vertical extent of the warm core is about 1.5 km at around 5 km height. This warm core structure is one of the salient characteristics of tropical cyclones. The spatial extent of this warm core is about the same order as that of the tropical cyclones (~ 100–200 km about the cyclone eye). Notwithstanding the fact that the analysed data do not exhibit the warm core structure, interestingly RAMS simulations generate this feature. Recently, satellite-borne passive microwave radiometers, Advanced Microwave Sounding Unit (AMSU) on NOAA-15 since early 1998, have been utilized to delineate the upper tropospheric warm core characteristics of tropical cyclones[13]. They found a maximum temperature anomaly of about 10 K for Hurricane Bonnie. It should be mentioned that the MM5 simulations also produce the warm core feature but without much clarity. In the other two cases, the warm core structure diminishes as the centre of the cyclone lies close to the land within about 24 h of the forecast time.

Total accumulated rainfall

Figure 5 shows the total accumulated rainfall during 48 h of simulation time for 7–9 November 1995 and 17–19 May 1997. Due to the cyclonic storm during 7–10 November 1995, both the models predicted very heavy rainfall in the coastal region of north Andhra Pradesh (AP) and south Orissa. RAMS produced maximum total rainfall of about 30 cm in north AP and up to about 20 cm of total rainfall in the south Orissa. The total observed rainfall between 8 November, 0300 UTC and 9 November, 0300 UTC agrees well with the RAMS simulation with a high of about 20 cm on the AP coastline to a low of about 5 cm in some districts of Orissa. During 6–8 November 1996, RAMS did not produce ample rainfall (not shown) for comparison with the IMD observations (up to 39 cm in Godavari district of AP). MM5 did simulate comparable amount of rainfall (up to 50 cm), but the location was different as the track. This discrepancy in rainfall could arise due to the differences in the convection scheme used in the models. The cyclone during 17–20 May 1997 produced heavy to very heavy rainfall with a core of maximum rainfall of about 30 cm at around 10.6°N, 90.8°E and the contour of 15 cm rainfall lying over the Andaman and Nicobar Islands (near Port Blair), all on 17 May 1997. There are no observations available to us for comparison with the simulated rainfall.

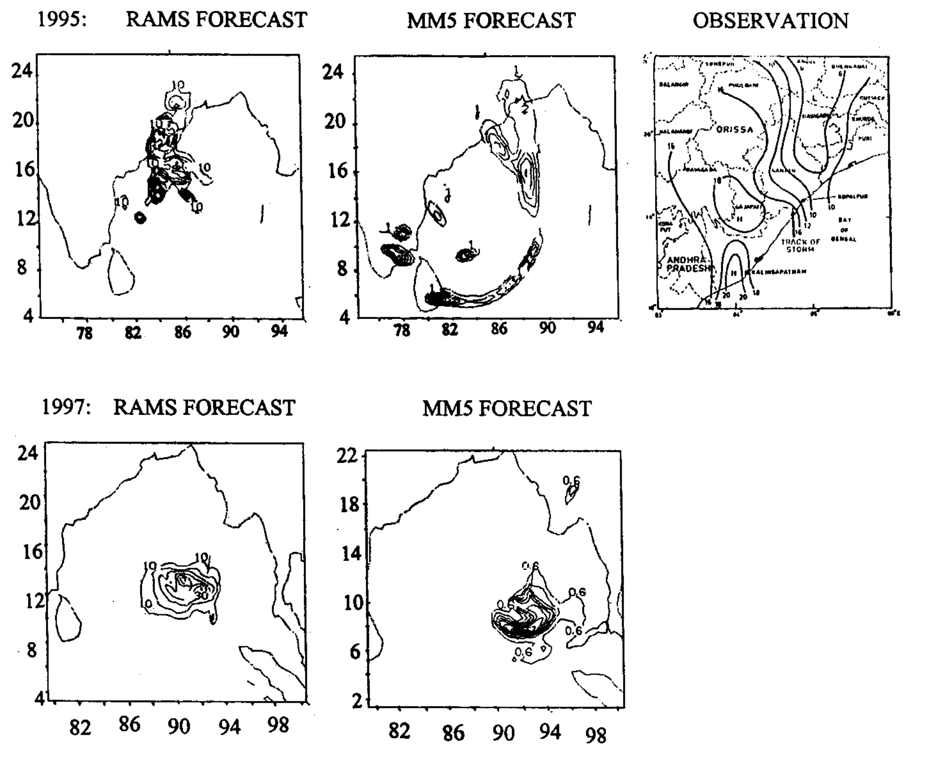


Figure 5. Contour diagrams of the total accumulated rainfall as predicted by the RAMS (unit: cm) and MM5 (unit: cm/h) simulations for the 1995 (top) and 1997 (bottom) cyclones. Observed rainfall is available only for the 1995 case and is shown (top-right).

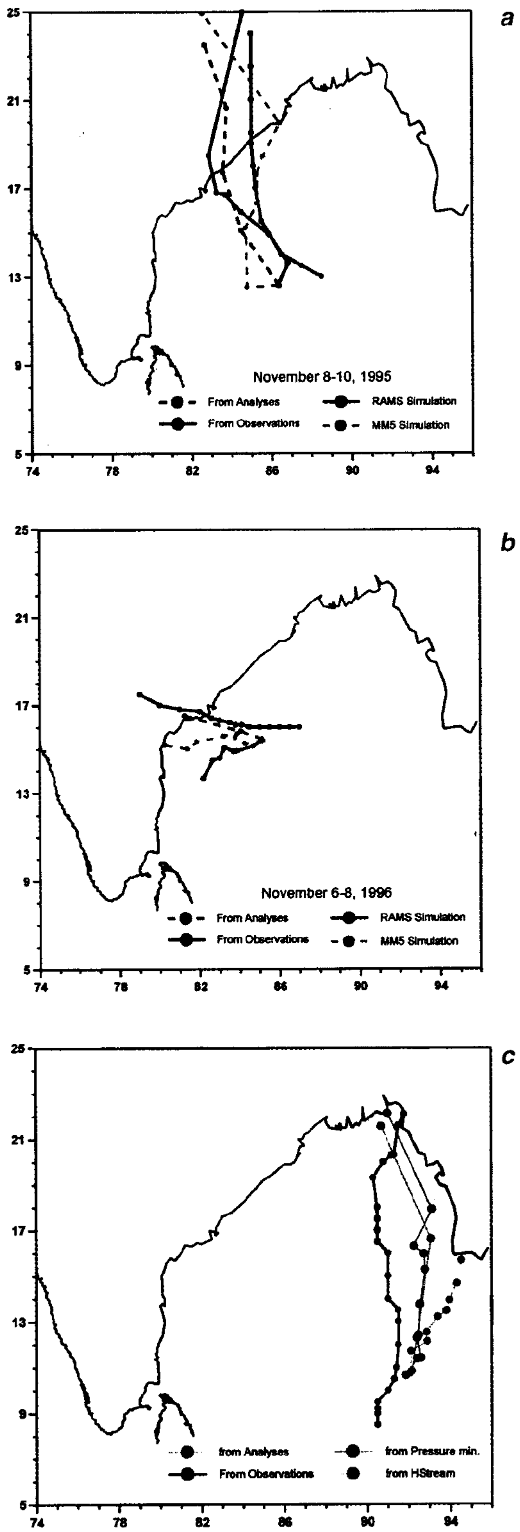


Figure 6. Observed (source: India Meteorological Department), analysed (calculated from NCMRWF analyses), and predicted (using RAMS and MM5) cyclone tracks during (***a***) 8–10 November 1995; (***b***) 6–8 November 1996; and (***c***) 17–19 May 1997.

Cyclone track prediction

The trajectories of the centre of the cyclones have been traditionally called cyclone tracks and are identified from the point of lowest sea-surface pressure and the location of minimum surface wind speed. Figure 6 *a*–*c* shows the tracks for 1995, 1996 and 1997 cyclones, respectively. In each of these figures, cyclone tracks as obtained from NCMRWF analysis and model simulations are compared with the observed tracks. During 7–10 November 1995 the observed cyclone tracks are quite different from those simulated by the RAMS (see Table 3 for details), but they appear to be moving in parallel. More interestingly, we find that the track calculated from the analysed data matches fairly well with the simulations (Figure 6 *a*). In contrast, MM5 simulations show deviations from the analysed track but follow the observed track quite closely. For the 1996 cyclone, while the observed and the analysed tracks show good agreement, the simulation using RAMS is not satisfactory. An angular separation of about 40 degrees between the observed/analysed track and RAMS simulated track is estimated at the start of model integration and the angular separation worsens towards the end of the 24 h forecast (Figure 6 *b*, see Table 3 for linear distances). The MM5 simulation resulted in a better agreement between the tracks. Finally, for the 1997 cyclone the tracks obtained from the analysed data sets and RAMS simulations deviate significantly from the observed tracks after about 21 h forecast time (i.e. around 2100 UTC on May 17), but the simulation predicted the location quite correctly where the cyclone finally struck the land (Table 3). For this case, an angular deviation of about 20 degrees is estimated between the track obtained using MM5 simulation and the analysed data sets in the first 24 h.

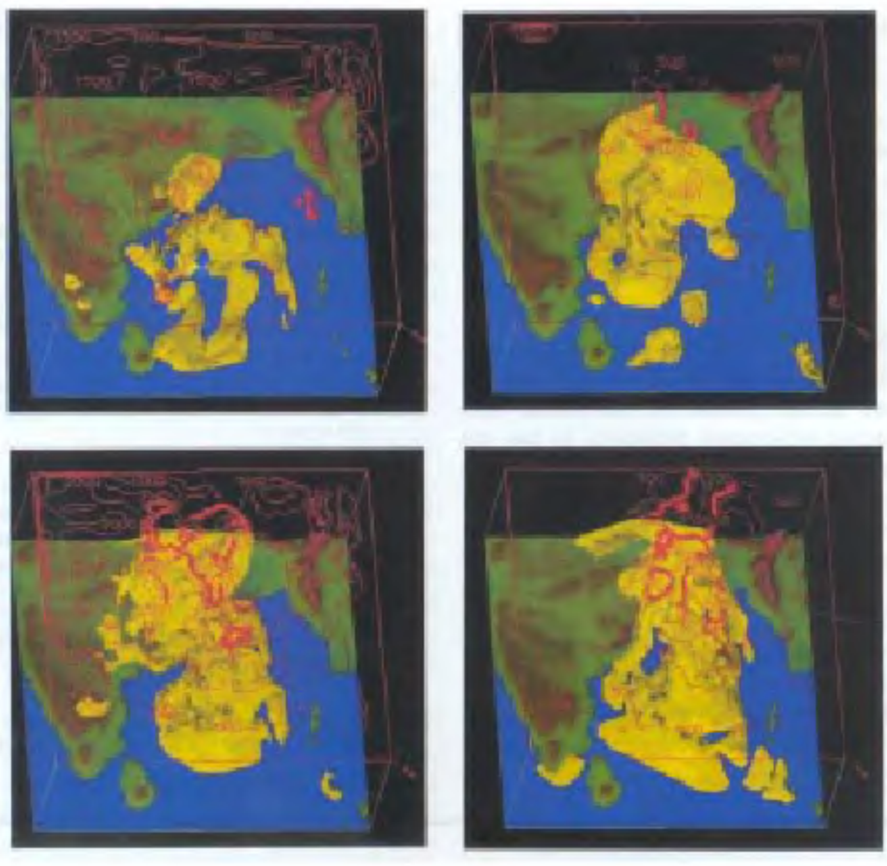
Moisture convection and planetary boundary layer

Many more features can be studied in special atmospheric events like cyclones and have to be estimated separately by user-defined programmes, but are beyond the scope of this article. However, with the help of advanced visualization softwares we can analyse atmospheric parameters like planetary boundary layer (PBL) heights, turbulent kinetic energy, heat fluxes, dew point temperature, etc. on a task-specific basis with moveable vertical or horizontal cross-sections for any 3-dimensional meteorological parameter. Figure 7 shows an approximate topography of the model domain, and the isosurfaces of relative humidity (RH) for 99.08% and contour plots PBL heights in 12 h time interval during the cyclonic storm in 1995. At the start of the model (8 November, 00 UTC), RH values more than 99% were not seen. But as time progressed, the RH values crossed the 99% mark at 12 UTC of 8 November, and then large masses of moist air converged and the colliding air masses were forced upward. The figures for 9 November, 1200 UTC and 10 November, 00 UTC clearly depict that high moisture levels also prevail over the land (up to the northern-most boundary of the model domain), along the cyclone track. The typical PBL heights over oceans are around 500 m during the day, and less than that during the night, but the diurnal variations over the land are significantly higher, ranging from less than 500 m during the night to 2000 m at mid-day. The contour diagrams in Figure 7 reveal that in and around the cyclone-affected areas, the PBL height crosses 3000 m. These results also indicate that large amounts of momentum,

Table 3. Deviations of the RAMS and MM5 simulations from the observed and analysed cyclone tracks

	Deviations (in km) between			
Date and time	Observations and RAMS simulations	Analyses and RAMS simulations	Observations and MM5 simulations	Analyses and MM5 simulations
08 November 1995, 00 UTC	238	8.8	241	6
09 November 1995, 00 UTC	210	110.0	48	186
10 November 1995, 00 UTC	114	118.0	197	231
06 November 1996, 00 UTC	92	9.5	103	9
07 November 1996, 00 UTC	328	285.0	279	239
08 November 1996, 00 UTC	Weakened	Weakened	Weakened	Weakened
17 May 1997, 00 UTC	65	37.0	81	12
18 May 1997, 00 UTC	214	151.0	406	375
19 May 1997, 00 UTC	237	73.0	629	722

8 November 1995; 12:00:00 UT   9 November 1995; 00:00:00 UT



9 November 1995; 12:00:00 UT   10 November 1995; 00:00:00 UT

Figure 7. Advanced visualization of the moisture convection (isosurface at RH = 99%) and the planetary boundary layer heights (contours) simulated by RAMS during the cyclonic storm in November 1995 using Vis5d software.

heat, moisture, and chemical constituents with intermediate lifetime (~ a few months) can be transferred from the earth's surface to the free/upper troposphere during a cyclonic storm.

In view of the above results, it is desirable to consider possible improvements in the model physics and data assimilation. For instance, the sea-level pressures (not shown here) obtained from the analysed data did not show sufficient intensity at the eye of the cyclone. The minimum sea-level pressure was only about 1004, 1008 and 1004 mb from the analysed data, whereas the observed pressures were as low as 980, 990 and 975 mb during the cyclones in 1995, 1996 and 1997, respectively. Our simulations showed good agreement with the analysis. Hence, with better analyses the model performance is likely to improve. In addition, both these models are equipped with data ingestion systems, i.e. the rawinsonde and/or surface observations. These can be utilized in conjunction with the presently available analysis to improve the model initialization and in turn the model forecast. In the areas of insufficient measurements such as in the oceanic regions, introduction of bogus data and satellite data assimilation into the numerical models may also improve the forecast. Another important area which needs a better understanding is the model physics. For example, the RAMS simulation using Kuo's convection scheme failed to produce rainfall during the 1996 cyclone. On the other hand, MM5 based on Grell's scheme could produce realistic rainfall for the same event. However, from this result we cannot judge the relative performance of these two convection schemes.

Conclusions

Both the regional weather prediction models (RAMS and MM5) appear promising for the simulations of tropical cyclones, and more studies should be undertaken with critical cases involving recurvature dynamics. In two out of three cases the cyclone track predictions and total accumulated rainfall simulations are quite satisfactory on an average. This is evident from the fact that the errors in the cyclonic tracks obtained in this study are of the order of the average track error of 325 km for the 48 h forecasts given by National Hurricane Centre, USA during the period 1990–96 (ref. 14). Similarly, a mean track error of 230–270 km has been reported for the 1995 Atlantic hurricane season[15] from a study of several operational models. In general, horizontal distributions of horizontal winds and temperature have been predicted satisfactorily for all the cyclones with both the models, which is evident from the RMS errors. These models are also able to reveal the salient features of the tropical cyclones like strong surface winds, the warm core in the troposphere and organized moisture convergence, etc.

1. Miller, B. I., *ESSA Tech. Mem.*, ERL TM-NHRL-85, 1969, 28.
2. Anthes, R. A., *Meteorol. Monogr.*, 1982, **41**, 208.
3. Cox, R., Bauer, B. L. and Smith, T., *Bull. Am. Meteorol. Soc.*, 1998, **79**, 265–283.
4. Krishanamurti, T. N., Xue, J., Bedi, H. S., Ingles, K. and Oosterhof, D., *Tellus*, 1991, **AB43**, 53–81.
5. Mureau, R., Molteni, F. and Palmer, T. N., *Q. J. R. Meteorol. Soc.*, 1992, **119**, 299–323.
6. Krishnamurti, T. N., Kishtawal, C. M., LaRow, T. E., Bachiochi, D. R., Zhang, Z., Williford, C. E., Gadgil, S. and Surendran, S., *Science*, 1999, **285**, 1548–1550.
7. Holland, G. J., *The Global Guide to Tropical Cyclone Forecasting*, WMO, 1993, p. 337.
8. Tremback C. J., Ph D thesis, Atmos. Sci. Paper No. 495, Colorado State Univ., Fort Collins, CO, USA, 1990.
9. Walko, R. L., Tremback, C. J. and Hertenstein, R. F. A., *RAMS Version 3b User Guide*, ASTER Division, Fort Collins, CO, USA, 1995.
10. Grell, G. A., Dudhia, J. and Stauffer, D. A., Report, NCAR/TN-398 + SAT, Colorado, December 1994, p. 122.
11. Parrish, D. F. and Derber, J. C., *Mon. Weather Rev.*, 1992, **120**, 1747–1763.
12. Dvorak, V. F., NOAA Tech. Rep. NESDIS 11, 1984, p. 47.
13. Velden, C. S. and Brueske, K. F., AMS Proc. on 23rd Conf. on Hurricanes and Tropical Meteorology, Dallas, 1999, pp. 182–185.
14. Goerss, J. S., *Mon. Weather Rev.*, 2000, **128**, 1187–1193.
15. Kurihara, Y. *et al.*, *Mon. Weather Rev.*, 1998, **126**, 1306–1322; Goerss, J. S. *et al.*, *ibid.*, 1219–1227.
16. Mellor and Yamada, *J. Atmos. Sci.*, 1974, **31**, 1791–1806.
17. Chen, S. and Cotton, W. R., *J. Atmos. Sci.*, 1988, **45**, 3897–3910.
18. Dudhia, J., *J. Atmos. Sci.*, 1989, **46**, 3077–3107.
19. Tremback, C. J. and Kessler, R., 7th Conference on Numerical Weather Prediction, 17–20 June, Montreal, 1985.
20. Klemp, J. B. and Durran, D. R., *Mon. Weather Rev.*, 1983, **111**, 430–444.
21. Klemp, J. B. and Wilhelmson, R. B., *J. Atmos. Sci.*, 1978, **35**, 1070–1096.

ACKNOWLEDGEMENTS. RAMS was developed under the support of the National Science Foundation (NSF) and the U. S. Army Research Office (ARO). P.K.P. is grateful to Craig Tremback for providing a great deal of insight on the working and engineering aspects of the RAMS. MM5 was developed in cooperation with the Pennsylvania State University (Penn State) and the University Corporation for Atmospheric Research (UCAR). We are also thankful to NCMRWF, New Delhi for providing the analysed data sets to K.V.J.P. for further research.

Received 14 September1999; revised accepted 19 May 2000