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A Study on the Impact of Parameterization of Physical Processes on Prediction of Tropical Cyclones over the Bay of Bengal with NCAR/PSU Mesoscale Model

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Abstract. Prediction of the track and intensity of tropical cyclones is one of the most challenging problems in numerical weather prediction (NWP). The chief objective of this study is to investigate the performance of different cumulus convection and planetary boundary layer (PBL) parameterization schemes in the simulation of tropical cyclones over the Bay of Bengal. For this purpose, two severe cyclonic storms are simulated with two PBL and four convection schemes using non-hydrostatic version of MM5 modeling system. Several important model simulated fields including sea level pressure, horizontal wind and precipitation are compared with the corresponding verification analysis/observation. The track of the cyclones in the simulation and analysis are compared with the best-fit track provided by India Meteorological Department (IMD). The Hong-Pan PBL scheme (as implemented in NCAR Medium Range Forecast (MRF) model) in combination with Grell (or Betts-Miller) cumulus convection scheme is found to perform better than the other combinations of schemes used in this study. Though it is expected that radiative processes may not have pronounced effect in short-range forecasts, an attempt is made to calibrate the model with respect to the two radiation parameterization schemes used in the study. And the results indicate that radiation parameterization has noticeable impact on the simulation of tropical cyclones.

Key words: convection, intensity, mesoscale model, planetary boundary layer, radiation, track, tropical cyclone

1. Introduction

Tropical cyclones are one of the most violent and deadliest of all meteorological phenomena that form over the warm seas. The Bay of Bengal is a potentially energetic region for the development of cyclonic storms and accounts for about 7% of the global annual total number of tropical storms (Gray, 1968). These storms, in particular the post-monsoon storms, are highly devastating causing loss of life and damage to property, especially when they cross the coastal states of India and

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Bangladesh (De Angelis, 1976). Therefore, reasonably accurate prediction of the Bay of Bengal cyclones is of great importance to avoid or reduce the loss of life and damages to property.

There have been considerable improvements in the field of prediction by numerical models during last two decades. High-resolution limited area models as well as global models are now being extensively used by most of the leading operational numerical weather prediction centers of the world. With increasing computer resources, in the last half decade, many of these NWP centers started using higher resolution models for tropical cyclone prediction to reduce errors associated with finite differencing (Dudhia, 1993) and for better representation of topographical features and sub-grid scale physical processes (Mandal *et al.*, 2003).

Cumulus convection, surface fluxes of heat, moisture and momentum and vertical mixing in the Planetary Boundary Layer (PBL) and radiative heating and cooling play important roles in the development of tropical cyclones (Anthes, 1982). Convection has long been recognized as a process of central importance in the development of tropical cyclones. The scale of convective clouds are too small to be resolved by numerical models and hence need to be parameterized in terms of variables defined at the grid points. A number of parameterization schemes have been developed over the years but all of them have certain limitations (Frank, 1983; Molinari and Dudek, 1992; Emanuel and Raymond, 1993; Zhang *et al.*, 1994; Kuo *et al.*, 1997). Performance of a numerical model in tropical cyclone forecast depends on how good the convection is parameterized in the model. Wang and Seaman (1997) conducted a comparison study of four convection schemes towards simulation of six precipitation events over continental United States. Tsutsui *et al.* (1998) made a study evaluating Kuo and Relaxed Arakawa-Schubert (RAS) schemes in simulating hurricanes using their regional atmospheric model.

Surface fluxes of latent and sensible heat play a vital role in the development and maintenance of tropical cyclones (Bayers, 1944). Emanuel (1986) and Rotunno and Emanuel (1987) further demonstrated the importance of surface fluxes. They showed that the hurricanes can develop and be maintained as a result of energy derived from the surface fluxes of latent and sensible heat even if there is no initial convective potential energy in the environment. Anthes and Chang (1978) showed the sensitivity of PBL parameterization in the simulation of hurricanes. Braun and Tao (2000) presented a comparison study of four PBL parameterization schemes in simulation of hurricane Bob (1991) using MM5 model.

In the present study, PSU/NCAR mesoscale model MM5 is used to simulate two post-monsoon Bay of Bengal cyclones. The model already showed its skill in simulating hurricanes (Karyampudi *et al.*, 1998; Liu *et al.*, 1997, 1999 and Braun and Tao, 2000). A non-hydrostatic version of the model is used for better representation of the processes closely related to topography and sub-grid scale physical processes. Four cumulus parameterization schemes, two PBL parameterization schemes and two radiation schemes are evaluated to find the best combination of parameterization schemes in simulation of Bay of Bengal cyclones.

The performance of the model is also examined with the two best combinations of schemes.

A description of the model used in the study is given in Section 2. Various numerical experiments and data used are described in Section 3. Results of the model simulation and analysis maps are presented in Section 4 and the conclusions in Section 5.

2. Model Description

The non-hydrostatic version of the MM5 modeling system developed at Pennsylvania State University (PSU)/National Center for Atmospheric Research (NCAR) by Anthes, Warner, Ying-Hwa, Kuo and their colleagues is used in this study. MM5 is a primitive equation hydrostatic/non-hydrostatic limited area model. Pressure perturbation p', three velocity components (u, v, w), temperature T, specific humidity q are the prognostic variables in non-hydrostatic version of the model. Model equations in the terrain following sigma co-ordinate are written in flux form and solved in Arakawa B grid. Leapfrog time integration scheme with time splitting technique is used in model integration. In time splitting technique, the slowly varying terms are integrated with longer time step and the terms giving rise to fast moving waves are integrated with shorter time step.

The most useful feature of MM5 model is its flexibility in terms of many options that are user specified and by setting these parameters to appropriate values, the model can be used for a wide range of applications. These include number of nests, type of convection, PBL and radiation parameterization schemes etc. Another advantage of this modeling system is that it is a state-of-the-art model and is under continuous development. A detailed description of the model is provided by Dudhia (1993) and Grell *et al*. (1995). A short overview of the model is provided in Table I.

3. Numerical Experiments and Data Used

The MM5 model described in section 2 is used to simulate two Bay of Bengal post monsoon cyclones. On 7th November 1995, a deep depression formed over the Bay of Bengal intensified into a cyclonic storm by 00:00 UTC of 8 November and centered near 11.5° N and 85.0° E (Figure 1a). Thereafter it intensified into a severe cyclonic storm and moved northward to cross the north Andhra Pradesh – Orissa coast around 05:00 UTC of 9 November 1995. This is taken as case 1. A deep depression formed over the southeast Bay of Bengal on the morning of 22 November 1995 and intensified into a cyclonic storm by the evening of the same day. By 00:00 UTC of 23 November, it intensified into a severe cyclonic storm and was centered near 9.0° N and 85.5° E (Figure 1d). Thereafter it moved northward up to 24th morning and then recurved to move towards northeast. It crossed south-

Table I.

Model	Fifth-Generation Penn State/NCAR Mesoscale Model (MM5) version 2.12
Dynamics	Non-hydrostatic with three-dimensional Coriolis force
Main prognostic variables	u, v, w, T, p' and q
Map projection	Lambert conformal mapping
Central point of the domain	12° N, 84° E
Number of horizontal grid points	101, 81 grid points for x, y respectively
Horizontal grid distance	60 km
Number of vertical levels	23 half sigma levels (full sigma levels are: 1, 0.99, 0.98, 0.96, 0.93, 0.89, 0.85, 0.8, 0.75, 0.7, 0.65, 0.6, 0.55, 0.5, 0.45, 0.4, 0.35, 0.3, 0.25, 0.2, 0.15, 0.1, .05, 0.0)
Horizontal grid system	Arakawa B grid
Time integration scheme	Leapfrog scheme with time-splitting technique
Lateral boundary conditions	Nudging toward the NCEP/NCAR reanalysis
Radiation parameterization schemes	1. CCM2 2. Simple cloud
Planetary boundary layer parameterization schemes	1. Blackadar 2. MRF
Cumulus parameterization schemes	1. Kuo 2. Grell 3. Kain–Fritsch 4. Betts–Miller
Microphysics	Simple ice
Soil model	Multi-layer soil model

east coast of Bangladesh near Cox's Bazar around noon of 25 November 1995. This is taken as case 2.

A series of ten experiments producing 48 hours forecasts (for both the cases) were carried out in two stages. In the first stage eight experiments using eight possible combinations of four convection and two PBL parameterization schemes along with CCM2 (2nd generation Community Climate Model) radiation scheme (Briegleb, 1992 and Kiehl *et al*., 1994) are performed. The four convection schemes are Grell (Grell, 1993), Betts–Miller (Betts, 1986; Betts and Miller, 1986), Kuo–Anthes (Kuo, 1974; Anthes, 1977) and Kain–Fritsch (Kain and Fritsch, 1993), which hereafter referred as GR, BM, KU and KF respectively. Two PBL schemes are Blackadar (Blackadar, 1976, 1979; Zhang and Anthes, 1982) and Hong–Pan (Hong and Pan, 1996) as implemented in NCEP MRF model, which hereafter referred as B and M respectively. The experiments using MRF PBL scheme in combination with GR, BM, KU and KF convection schemes are referred as experiments M–GR, M–BM, M–KU and M–KF respectively. Similarly experiments

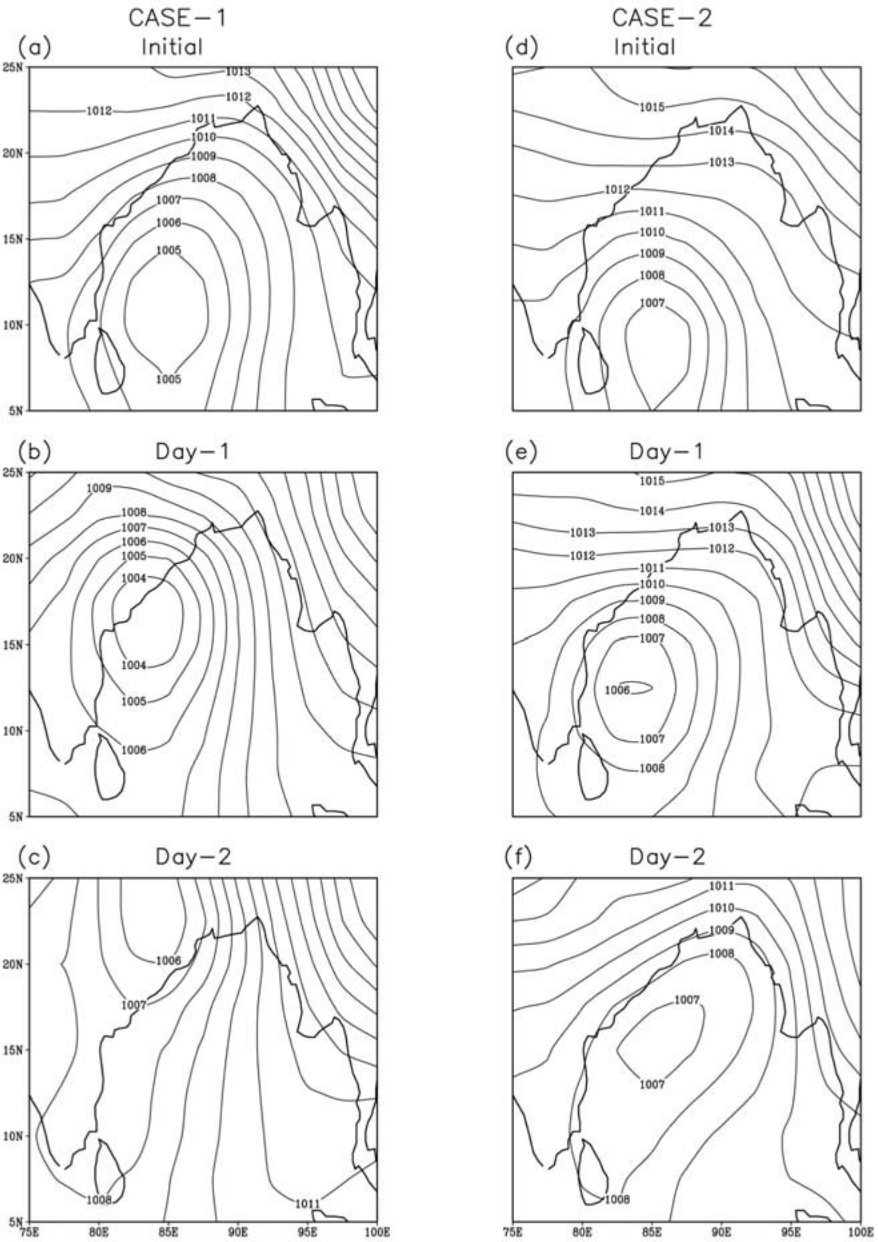

Figure 1. Mean sea level pressure as obtained from NCEP/NCAR reanalysis (all at 00:00 UTC) (a) Analysis valid on 8 November 1995 (b) Verification analysis valid on 9 November 1995 (c) Verification analysis valid on 10 November 1995 (d) Analysis valid on 23 November 1995 (e) Verification analysis valid on 24 November 1995 (f) Verification analysis valid on 25 November 1995.

using Blackadar PBL scheme in combination with GR, BM, KU and KF convection schemes are referred as experiments B–GR, B– BM, B–KU and B–KF respectively. Results obtained from these experiments are examined by comparing with the verification analysis and observations to find the best combinations towards forecasting the track and intensity of the cyclones. In the second stage two more experiments are performed with the two best combinations of PBL and convection schemes obtained from the first stage along with Dudhia's (1989) long- and short-wave radiation scheme also known as Simple Cloud scheme (SC).

In the present study, the initial and boundary conditions for model integration are obtained from NCEP/NCAR reanalysis (2.5° × 2.5° horizontal resolution) interpolated to model grids. Simply interpolating the coarse resolution reanalysis to high-resolution model grids cannot reproduce small-scale features, which have already been smoothed out in the large-scale reanalysis. In general, reanalysis datasets are enhanced through data assimilation. In this study, 12 hours analysis nudging is performed before the start of actual forecast. Analysis nudging means nudging the model simulation to an available analysis. This is done by adding an extra forcing term (known as analysis-nudging term) to the dynamical equations of the model. The analysis-nudging term for a variable is proportional to the difference between the model simulation and the analysis at every grid point. Analysis nudging will allow the model to generate some small-scale features during the nudging period and also the input fields will be initialized.

4. Results and Discussions

As discussed in Section 3, as many as eight experiments producing 48 hours forecasts (for both the cases) are performed to examine the performance of the four convection and two PBL schemes mentioned earlier. In case 1 and case 2 the model is integrated from 00:00 UTC of 8 and 23 November 1995 respectively.

Figure 1 shows the sea level pressure (SLP) at the initial time, day 1 and day 2 for both the cases as extracted from NCEP/NCAR reanalysis dataset. As shown in Figure 1, in case 1 the storm moved almost northward from (11.5° N, 85.0° E) to (17.5° N, 83.5° E) in first 24 hours during which central SLP changed from 1,005 hPa to 1,004 hPa. During next 24 hours it moved in the north of northeasterly direction and was centered at (22.5° N, 84.5° E) with central SLP 1,006 hPa. This shows that the intensity of the storm is poorly represented in the reanalysis. The situation is similar in case 2 as well. This is attributed to the coarse resolution (2.5° × 2.5°) of the reanalysis and sparsity of data over the oceans. The initial and subsequent positions of the storm are also in error in comparison to the best-fit track. In case 1 and case 2, initial positional errors are 415 km and 156 km respectively.

4.1. EVALUATION OF PBL SCHEMES

Day 1 (24 hours) forecast of SLP for case 1 from all the eight experiments are presented in Figure 3. Left panel shows simulation results with MRF PBL scheme and right panel with Blackadar scheme. Comparison of the figures in the left panel to the corresponding figures in the right panel indicate that the position and central SLP of the storm is better predicted by the MRF PBL scheme in combination with almost all the convection schemes except the Betts-Miller (Figure 3b, 3f) scheme. With this convection scheme, both the PBL schemes produce same central SLP of 995 hPa. But the location of the storm is better predicted by the MRF scheme. Use of MRF PBL scheme causes positional improvements of 46 km, 80 km, 132 km and 76 km with GR, BM, KU and KF convection schemes respectively (Table II). Similar to Figure 3, Figure 4 represents day 2 (48 hours) forecasts of SLP for case 1. Comparison between the figures in the left panel to that in the right panel shows that the central SLP and location of the storm are again better predicted by MRF PBL scheme in combination with all the four convection schemes. Positional improvements with the four convection schemes GR, BM, KU and KF are 360 km, 128 km, 76 km and 146 km respectively (Table II).

Figure 5 and Figure 6 illustrate respectively day 1 (24 hours) and day 2 (48 hours) forecast of SLP for case 2. A comparative study similar to case 1 indicates better performance of the MRF PBL scheme in combination with all the convection schemes with the exception of day 1 forecast with Grell scheme, which gives almost same location and better central SLP with Blackadar scheme. Positional improvements of 5 km, 164 km, 92 km and 108 km in day 1 forecasts and 50 km, 550 km, 232 km and 378 km in day 2 forecasts are observed using MRF PBL scheme with GR, BM, KU and KF convection schemes respectively.

Figures 2(a,b) present the analyzed 24 hours accumulated precipitation valid at 03:00 UTC of 9 and 10 November 1995 respectively as obtained from National Center for Medium Range Weather Forecasting (NCMRWF), India (Mitra *et al.*, 1997). Figure 2a shows rainfall over Andhra Pradesh, Orissa, West Bengal and over a large area of Bay of Bengal. Maximum precipitation of 11.3 cm is located close to Bhubaneswar in Orissa (20.5° N, 86.0° E). India meteorological Department (IMD) recorded a maximum precipitation of 27 cm at Kalingpatnam in Andhra Pradesh and 13 cm precipitation was recorded over Bhubaneswar and Gopalpur region in Orissa. Figure 2b shows rainfall over Orissa, West Bengal, Bihar, Northeastern states and over a large area of the Bay of Bengal. Maximum precipitation of 18.1 cm is located at about 20° N and 89° E. IMD observations show precipitation of 20 cm, 27.5 cm and 13 cm at Krishnanagar, Sandheads and Jamshedpur respectively.

Figures 7 and 8 illustrate 24 hours accumulated precipitation forecast valid at 03:00 UTC of 9 and 10 November 1995 respectively. These figures show that the magnitudes of precipitation differ substantially in the two PBL schemes. Use of MRF scheme has improved 24 hours accumulated precipitation forecasts in the range of 6–7 cm in day 1 and 10–18 cm in day 2 (Table III). Maximum surface

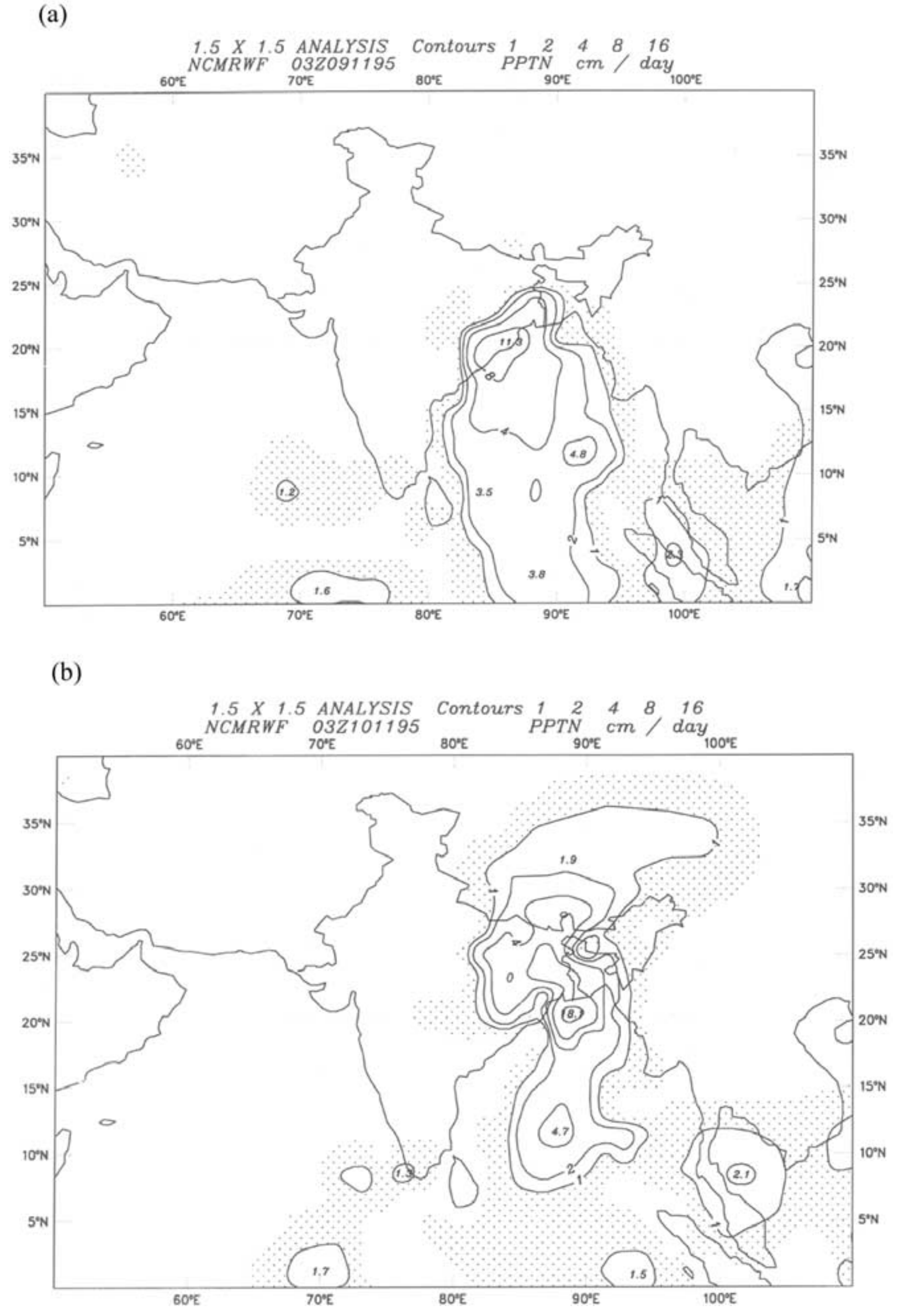

Figure 2. Verification analysis of 24 hrs accumulated rainfall as obtained from NCMRWF (a) Day 1 (b) Day 2.

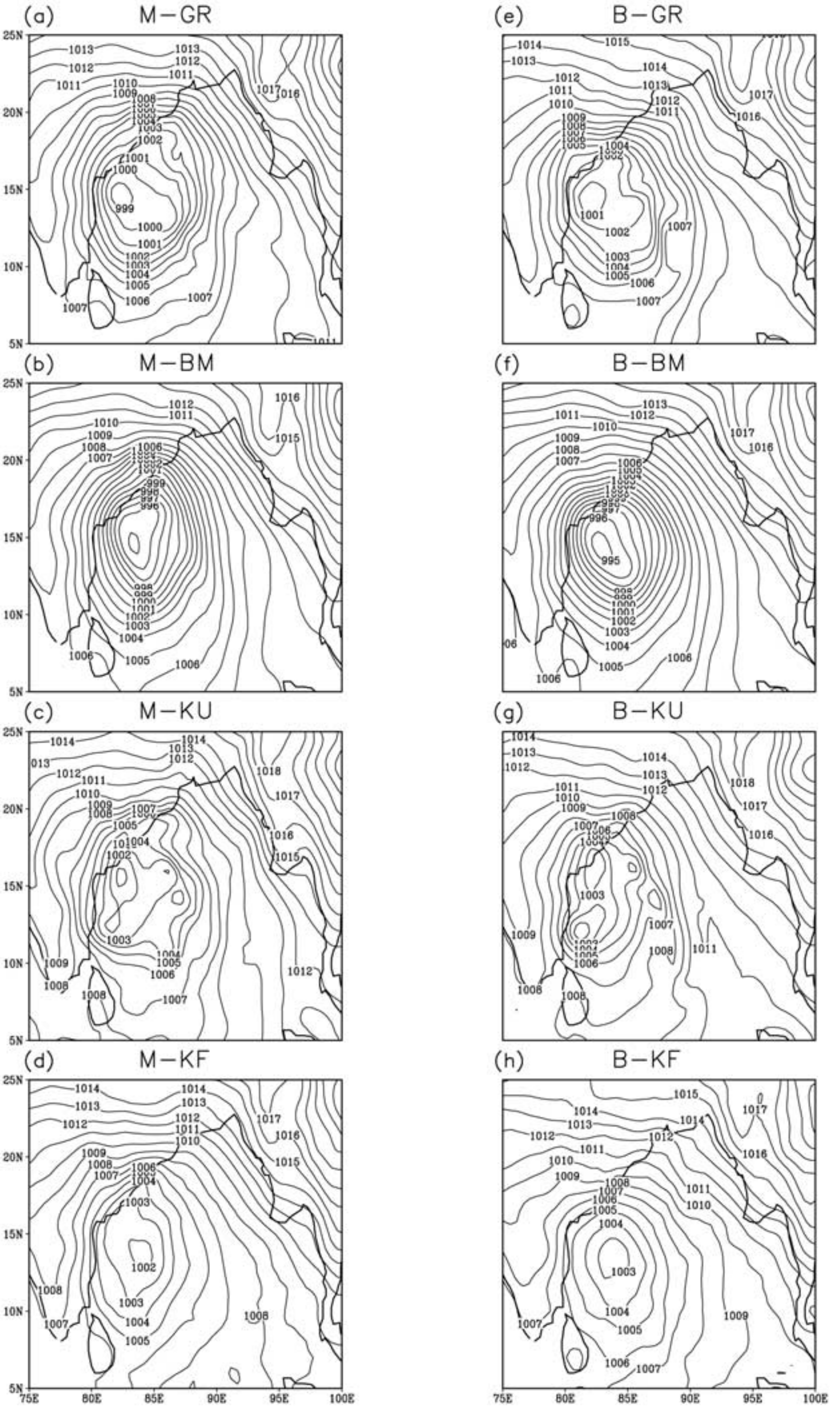

Figure 3. 24-hrs forecasts of sea level pressure valid at 00:00 UTC on 9 November 1995 (a) Experiment M–GR. (b) Experiment M–BM. (c) Experiment M–KU. (d) Experiment M–KF. (e) Experiment B–GR. (f) Experiment B–BM. (g) Experiment B–KU. (h) Experiment B–KF.

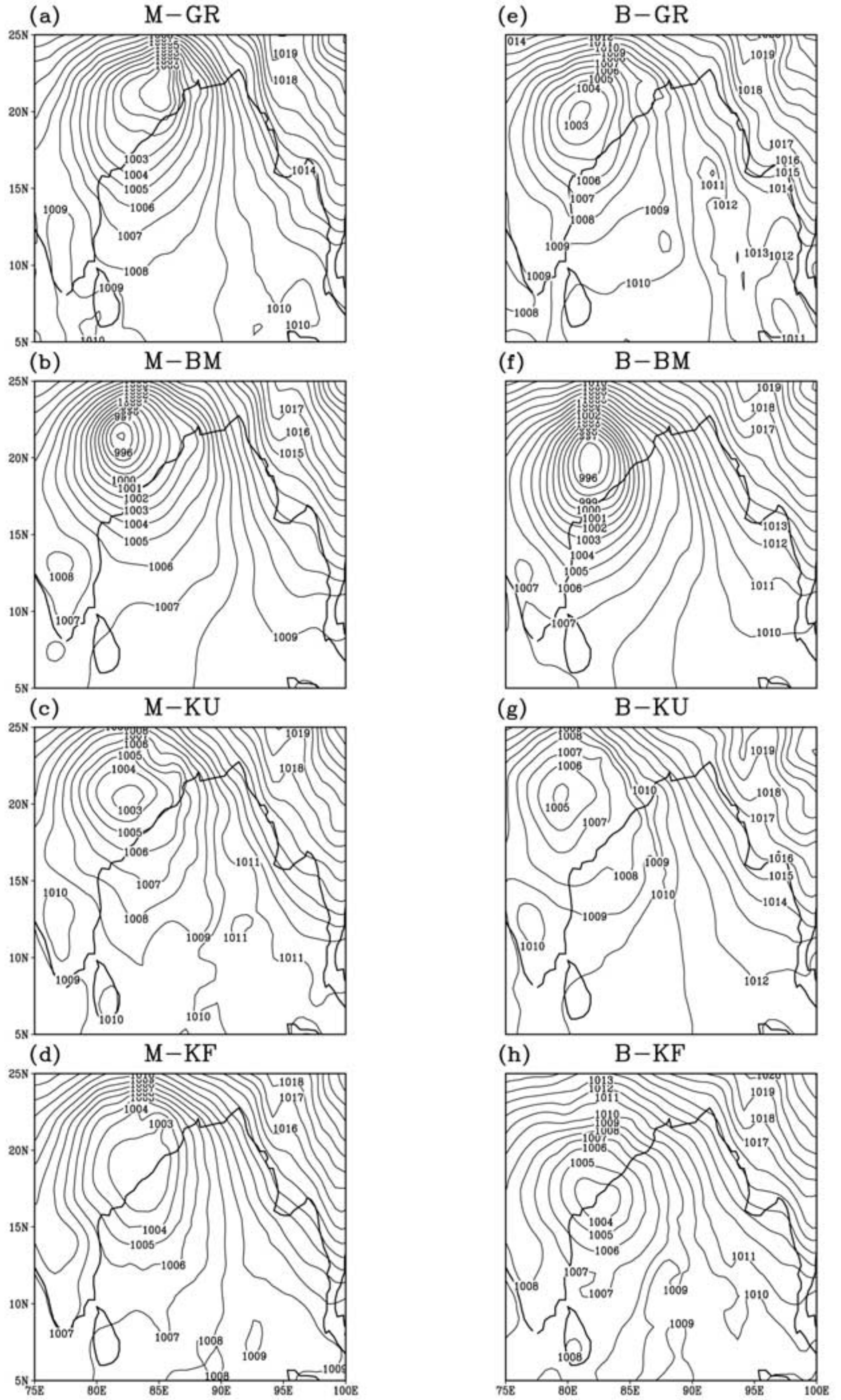

Figure 4. Same as Figure 3 but 48-hrs forecasts of sea level pressure valid at 00:00 UTC on 10 November 1995.

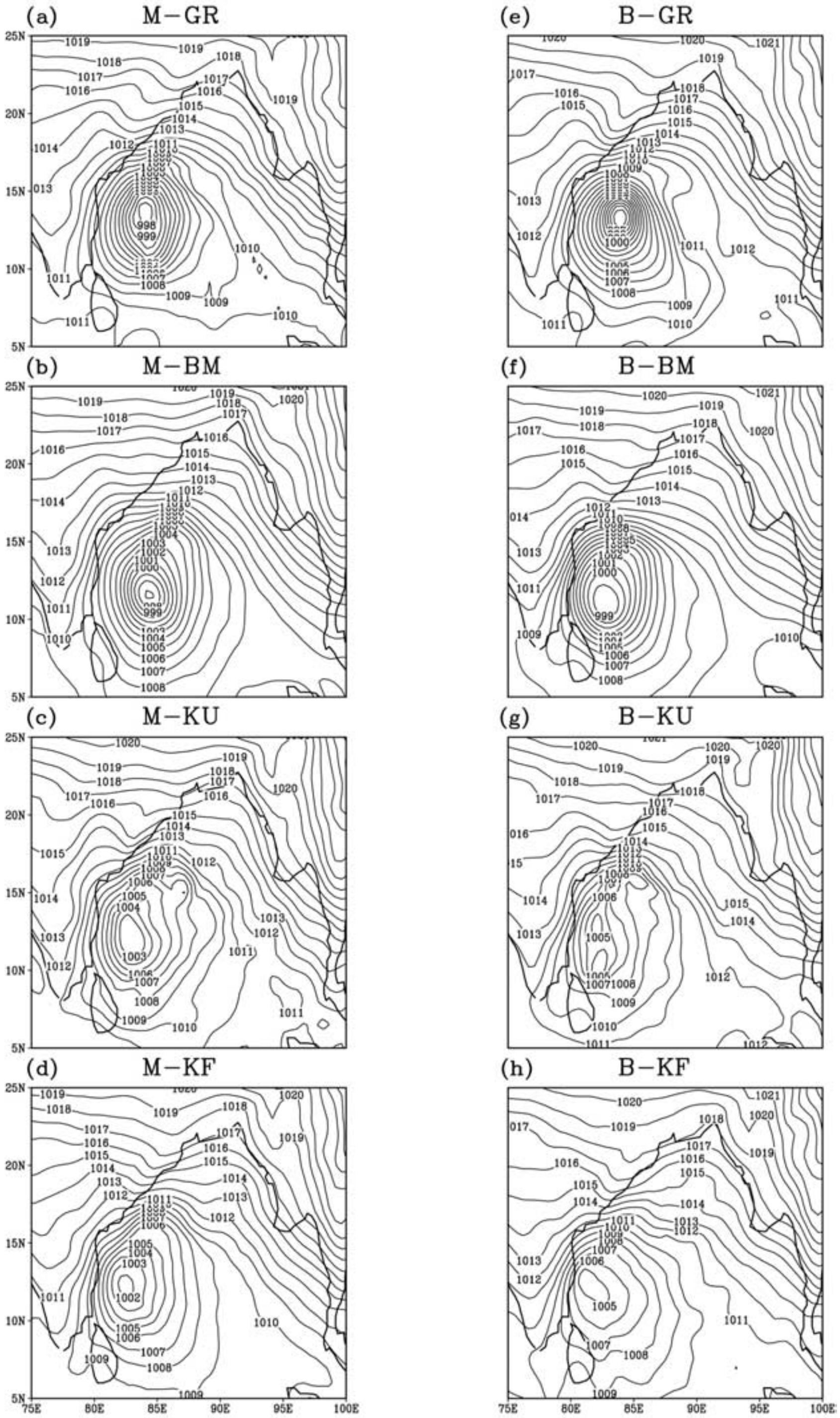

Figure 5. Same as Figure 3 but 24-hrs forecasts of sea level pressure valid at 00:00 UTC on 24 November 1995.

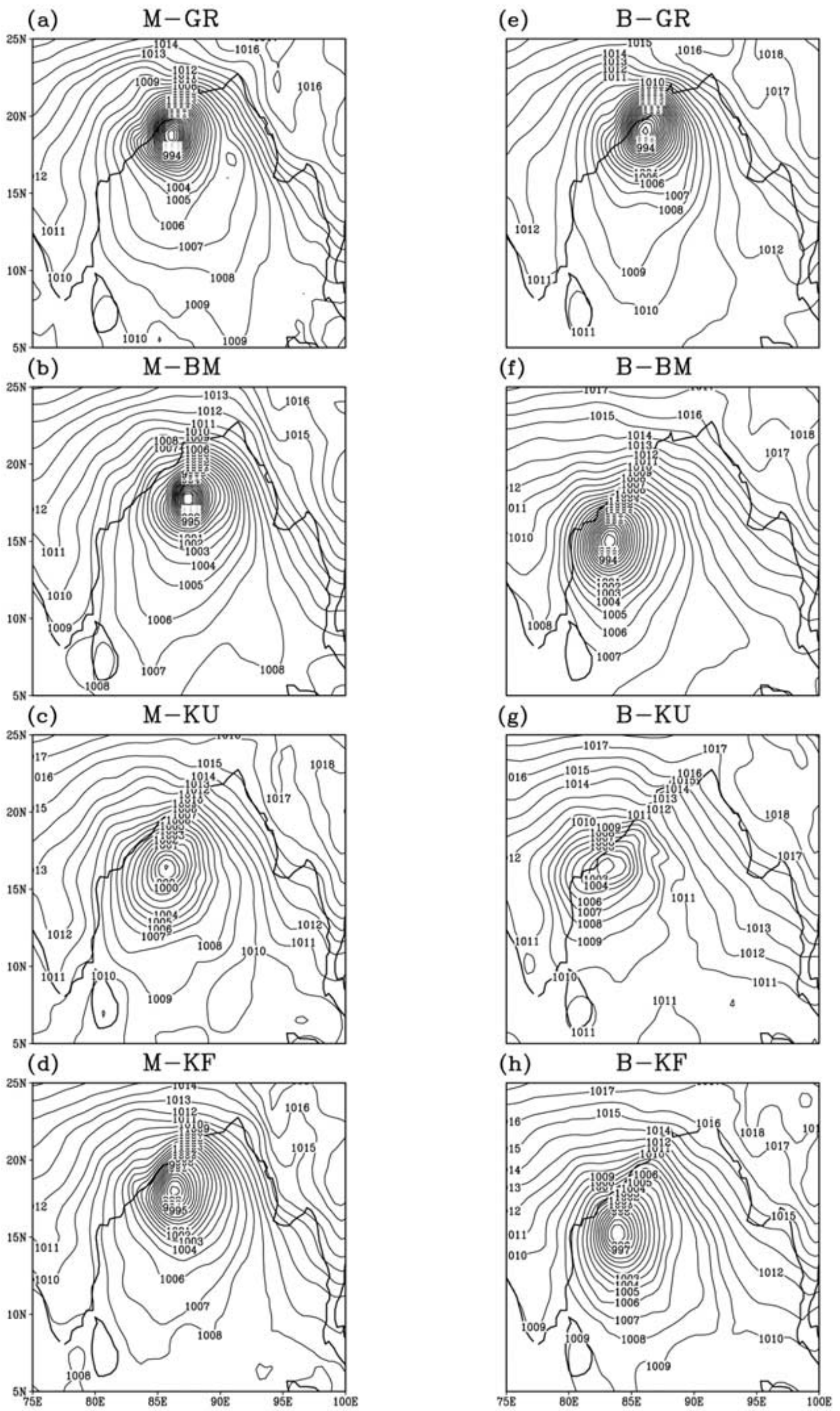

Figure 6. Same as Figure 3 but 48-hrs forecasts of sea level pressure valid at 00:00 UTC on 25 November 1995.

Table II. Vector displacement error in km

Case-1

Experiment	Day 1*		Day 2*	
	w.r.t analysis	w.r.t observation	w.r.t analysis	w.r.t observation
M-GR-CCM2	298	478	174	333
M-BM-CCM2	278	425	281	414
M-KU-CCM2	198	392	304	466
M-KF-CCM2	370	492	503	675
B-GR-CCM2	341	524	532	693
B-BM-CCM2	329	505	380	542
B-KU-CCM2	350	524	521	642
B-KF-CCM2	393	568	646	821
M-GR-SC	337	460	403	558
M-BM-SC	403	504	191	346

* Day 1 and day 2 corresponds to 00:00 UTC of 9 and 10 November 1995 respectively.

Case-2

Experiment	Day 1**		Day 2**	
	w.r.t analysis	w.r.t observation	w.r.t analysis	w.r.t observation
M-GR-CCM2	155	108	217	265
M-BM-CCM2	186	207	235	200
M-KU-CCM2	056	274	081	461
M-KF-CCM2	064	307	134	315
B-GR-CCM2	133	113	229	315
B-BM-CCM2	189	371	331	750
B-KU-CCM2	122	366	272	693
B-KF-CCM2	172	415	274	693
M-GR-SC	114	181	215	225
M-BM-SC	172	268	123	461

** Day 1 and day 2 correspond to 00:00 UTC of 24 and 25 November 1995 respectively.

wind is also better predicted with the MRF scheme. Similar results were obtained in case 2 as well.

Better simulation results obtained using the MRF PBL scheme is probably due to stronger vertical mixing allowed in this scheme, which facilitates convection and hence development of the storm. It is to be noted here that the surface fluxes are parameterized in the same manner in both the schemes.

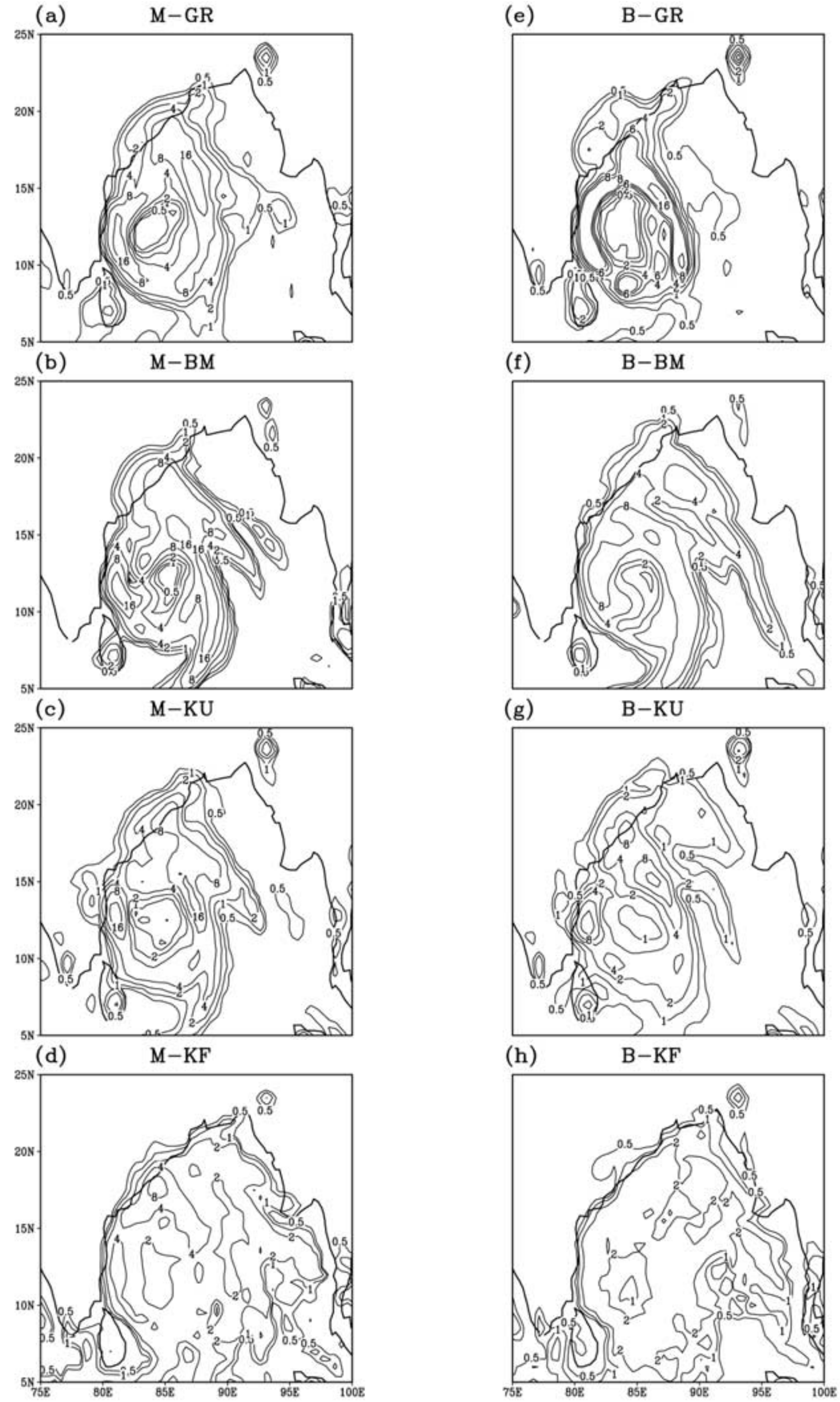

Figure 7. Same as Figure 3 but forecasts of 24-hrs accumulated precipitation valid at 03:00 UTC on 9 November 1995.

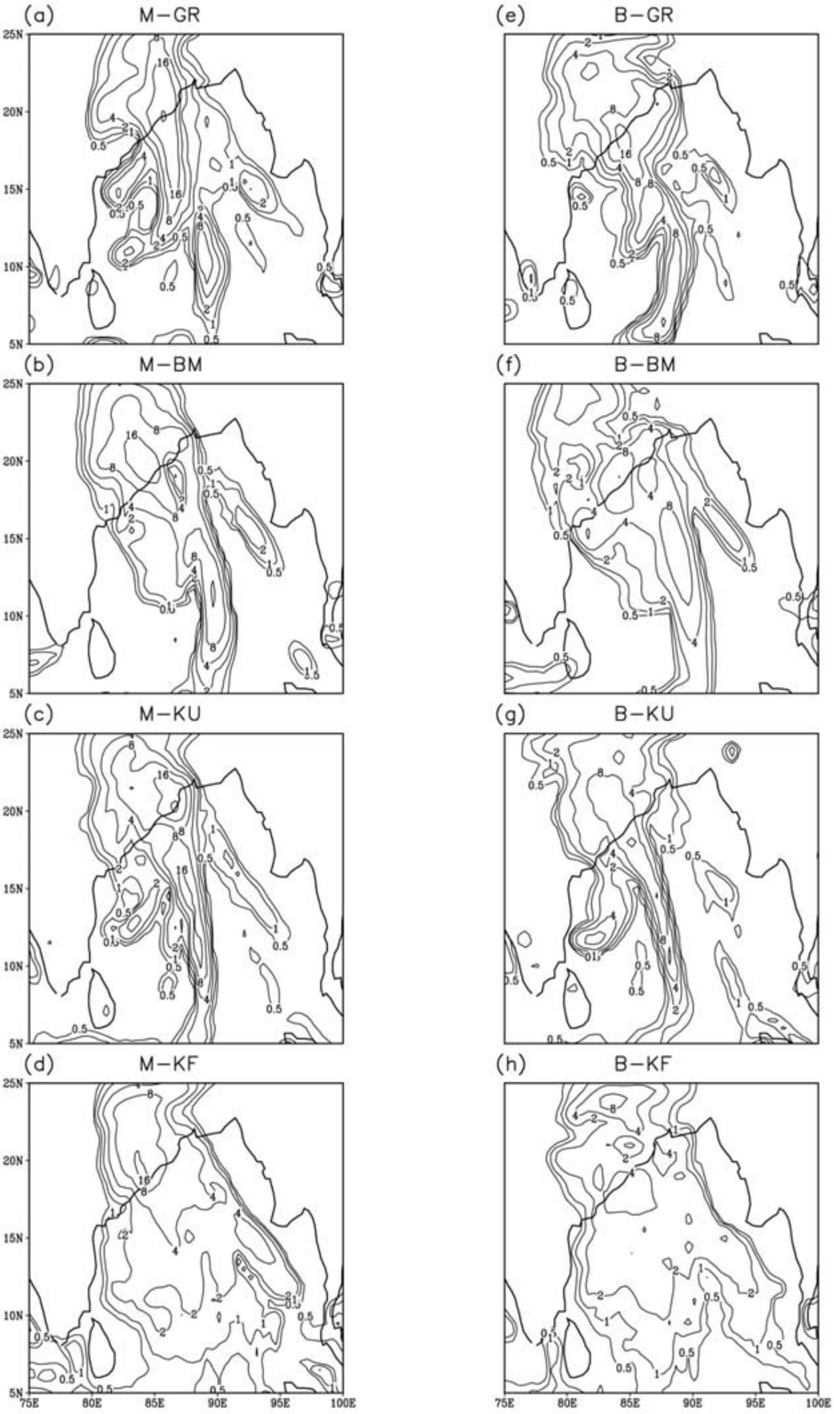

Figure 8. Same as Figure 3 but forecasts of 24-hrs accumulated precipitation at 03:00 UTC on 10 November 1995.

Table III. Maximum rainfall (in cm.) and maximum surface wind (in m/sec.)

Case 1

Experiment	Day 1**		Day 2**	
	Rainfall#	Wind	Rainfall#	Wind
Observed	27	25	27.5	18
M-GR-CCM2	26	24	32	22
M-BM-CCM2	25	25	30	22
M-KU-CCM2	23	21	35	19
M-KF-CCM2	11	16	18	18
B-GR-CCM2	19	19	23	19
B-BM-CCM2	18	21	21	19
B-KU-CCM2	23	20	17	19
B-KF-CCM2	04	16	10	19
M-GR-SC	23	23	35	22
M-BM-SC	23	23	32	22

* Day 1 and day 2 corresponds to 00:00 UTC of 9 and 10 November 1995 respectively.
# 24 hrs accumulated rainfall is from 03:00 UTC to 03:00 UTC next day.

4.2. EVALUATION OF CONVECTION SCHEMES

As discussed in Section 4.1, Figures 3 and 4 present day 1 and day 2 forecast of SLP respectively for case 1. Simulation results show significant sensitivity to convection schemes with minimum central SLP, maximum surface wind and maximum precipitation varying up to 9 hPa, 8 m/sec. and 22 cm respectively. The BM scheme produces strongest storm while KU and KF produce weakest storm in both day 1 and day 2 forecasts. But the location of the storm is better predicted by the GR scheme, particularly in day 2. Intensity of the storm is also well predicted by GR scheme, particularly in combination with MRF PBL scheme. In day 2 forecast, intensity of the storm is over predicted by BM scheme. Figure 5 and 6 present day 1 and day 2 forecast of SLP respectively for case 2. Similar to case 1, intensity of the storm is better simulated by GR and BM schemes. KU and KF schemes produce weaker storm. The location of the storm with respect to analysis is better simulated by KU and KF, however compared to observations once again GR scheme gives better results both on day 1 and day 2.

The model simulated 24 hours accumulated precipitation for day 1 and day 2 (Figures 7 and 8) show that the magnitude and distribution of rainfall is reasonably well simulated by GR, BM and KU schemes. GR, BM and KU produce 26 cm, 25 cm and 23 cm of maximum precipitation respectively compared to 27 cm in the observation on day 1. On day 2, GR and BM give a maximum precipitation of 32 cm and 30 cm in comparison to an observed value of 27.5 cm. Maximum precipitation is over predicted by KU scheme. The release of latent heat from cumulus convection seems to be well represented in these three schemes. Although the precipitation is distributed almost over the same area in these three schemes, distribution of the magnitudes of precipitation varies with the scheme. This difference indicates that a cumulus convection scheme produces, in general, a rather distinct characteristic spectrum of precipitation rates. KF scheme produces less precipitation in wider area. Wang and Seaman (1997) conducted a comparison study of these four convection schemes towards simulation of six precipitation events over continental United States using a very high-resolution model. Their results show that the KF scheme gives better results compared to other schemes.

4.3. EVALUATION OF THE PERFORMANCE OF THE MODEL

Discussions in sections 4.1 and 4.2 indicate that GR and BM schemes in combination with MRF PBL scheme are the two most efficient combinations. Forecast skill of the model is examined by comparing the simulation results from these two combinations with the verification analysis and observations. Figures 1b and 1c represent verification analysis of SLP valid at 00:00 UTC of 9 and 10 November 1995 respectively. Comparison of these figures with Figures 3a and 3b show the storm to move slower but in the same direction as in the analysis. Model simulations show the storm to be more intense than in the analysis with a central SLP of 999 hPa and 995 hPa in M–GR and M–BM respectively. These values are closer to the observed central SLP of 984 hPa. Large difference in intensity forecast compared to the observation is due to the poor initial vortex specification in the model. Similar comparison for day 2, (Figures 1c, 4a and 4b) shows that the intensity of the storm is well simulated by M–GR (1,000 hPa compared to 1,002 hPa in the observation). Intensity is over predicted by M–BM. Location of the storm is still in error due to a large error of 415 km in the initial condition.

Figures 1e and 1f represent verification analysis of day 1 and day 2 respectively for case 2. In this case, location of the storm is predicted reasonably well in both day 1 and day 2. In the model simulation, the storm is found to be more intense than in the analysis and close to the observed intensity. On day 1, model simulated central SLP in experiments M–GR and M–BM are 998 hPa and 997 hPa respectively against 1,006 in the analysis and 976 in the observation. On day 2, central SLP of 986 hPa is simulated by both M–GR and M–BM compared to 1,007 hPa in the analysis and 970 hPa in the observation. The error in the intensity forecast is believed to be due to the poor initial vortex specification as discussed earlier.

Figures 7a and 7b presenting model simulated 24 hours accumulated precipitation valid on day 1 show heavy precipitation around the storm. Precipitation is found to spread over the same area as shown in the analysis (Figure 2a). Maximum precipitation of 26 cm is simulated by M–GR near 15.5° N and 87° E compared to 27 cm located at 18° N, 84° E in the observation. Model simulation shows 6 cm and 13 cm of rainfall compared to 11.3 cm and 13 cm in the observation at Bhubaneswar and Gopalpur respectively. Model simulated 24 hours accumulated precipitation valid for day 2 (Figures 8a and 8b) is found to be heavier and spread almost over the same area as in the analysis (Figure 2b). A maximum precipitation of 32 cm was simulated at 19.5° N, 86° E compared to 27.5 cm at 22° N, 88° E in the observation. The error in location of maximum precipitation is due to the error in the location of the storm. It is to be mentioned here that the model-simulated precipitation for case 2 could not be verified due to lack of adequate observations.

As discussed earlier, maximum surface wind was reasonably well simulated by the model. Figure 9 illustrates the difference in model simulated and analyzed wind vector at 850 hPa valid at 00:00 UTC of 9 November 1995. This shows that the model has easterly bias in simulating wind vector in all the eight experiments. In addition, the model simulates stronger vortex compared to the analysis, particularly with the GR and BM convection schemes. With KU and KF convection schemes, the easterly bias is mainly confined in the northeastern and northern sector of the storm respectively. Also the vortex is little weak with these two schemes. Similar results were obtained in case 2 as well (not shown).

Tracks of the cyclones for both case 1 and case 2 are compared with the track obtained from NCEP/NCAR reanalysis and the best-fit track obtained from IMD. Tracks obtained from model simulation using the two most efficient combinations are considered here. Figure 10a gives the track of the cyclone for case 1 with the location of the storm in every 12 hours. During the first 24–30 hours, the simulated tracks are closer to the analyzed track and during the next 18–24 hours the track simulated by M–GR comes closer to the best-fit track. The track simulated by M–BM gets deviated from both analyzed and best-fit track during the last 12 hours. The track simulated by M–GR follows the same trend as the analyzed and best-fit tracks, though there is large error due to large initial positional error. Figure 10b illustrates the track of the cyclone for case 2. In this case, track simulated by M–GR is found to move in between the analyzed and the best-fit track. The re-curvature of the storm is also well simulated by the model particularly with M–GR. The track simulated by M–BM, closely follows the analyzed track during the first 6 hours, but thereafter it follows the best-fit track closely. In both the cases the simulated tracks are found to be to the west of the best-fit track. This is due to the easterly bias of the model in simulation of the wind vector.

Sensitivity of the model to radiation parameterization is examined with the two most efficient combinations mentioned earlier. Figure 11 presents simulation results obtained using simple cloud radiation scheme for both the cases. Figures 11a and 11b present day 1 and day 2 forecasts of SLP for case 1 using simple cloud radiation scheme along with M–GR combination of PBL and convection schemes. Figures 11c and 11d represent the same with M–BM combination. A comparative study of Figures 11a and 11c with Figures 3a and 3b respectively show that the location and intensity of the storm is sensitive to radiation parameterization. Similar comparison of Figures 11b and 11d with Figures 4a and 4b indicates that

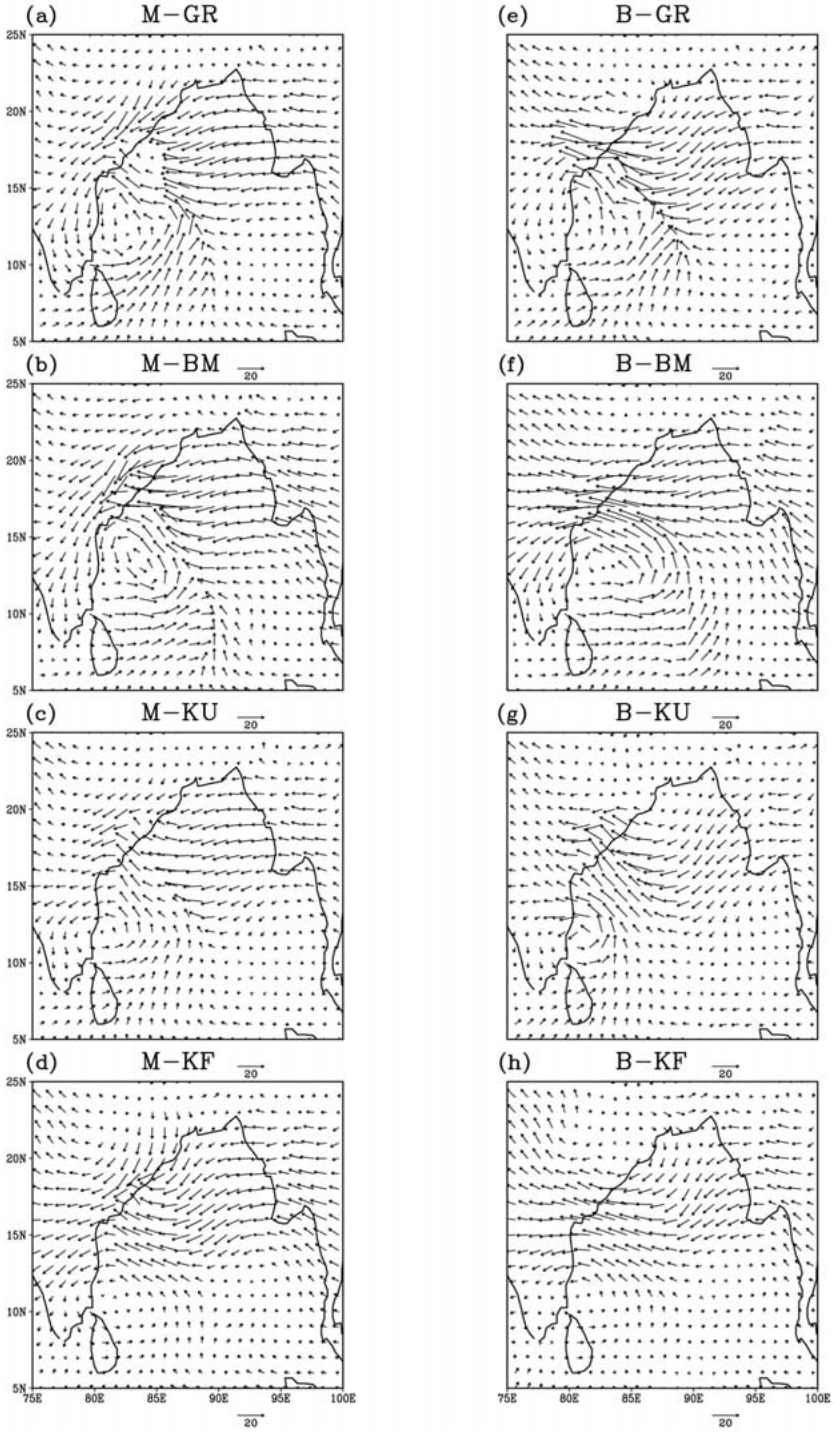

Figure 9. Same as Figure 3 but the difference in model simulation and analyzed wind vector at 850 hPa valid at 00:00 UTC of 9 November 1995.

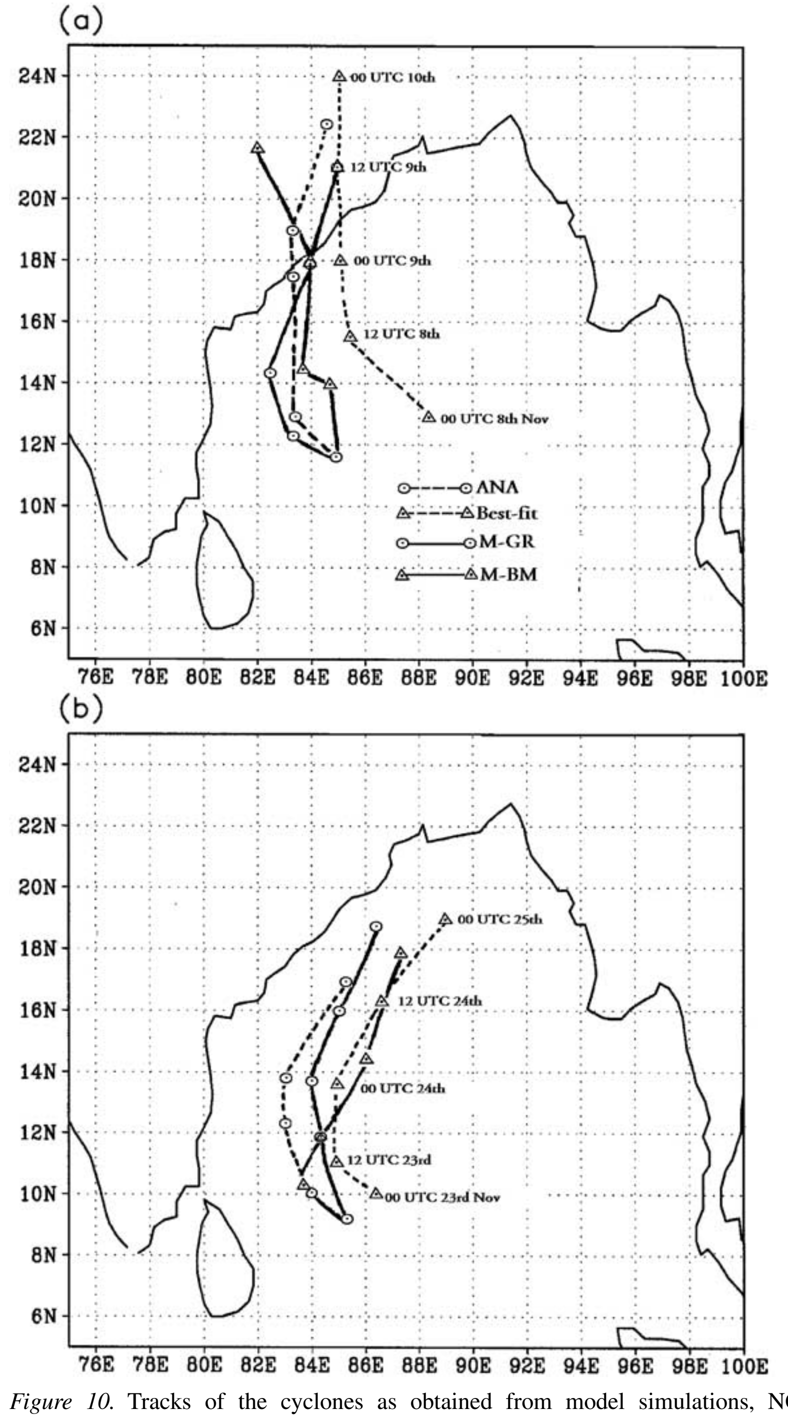

Figure 10. Tracks of the cyclones as obtained from model simulations, NCEP/NCAR reanalysis and the best-fit track provided by IMD (a) Case 1 (b) Case 2.

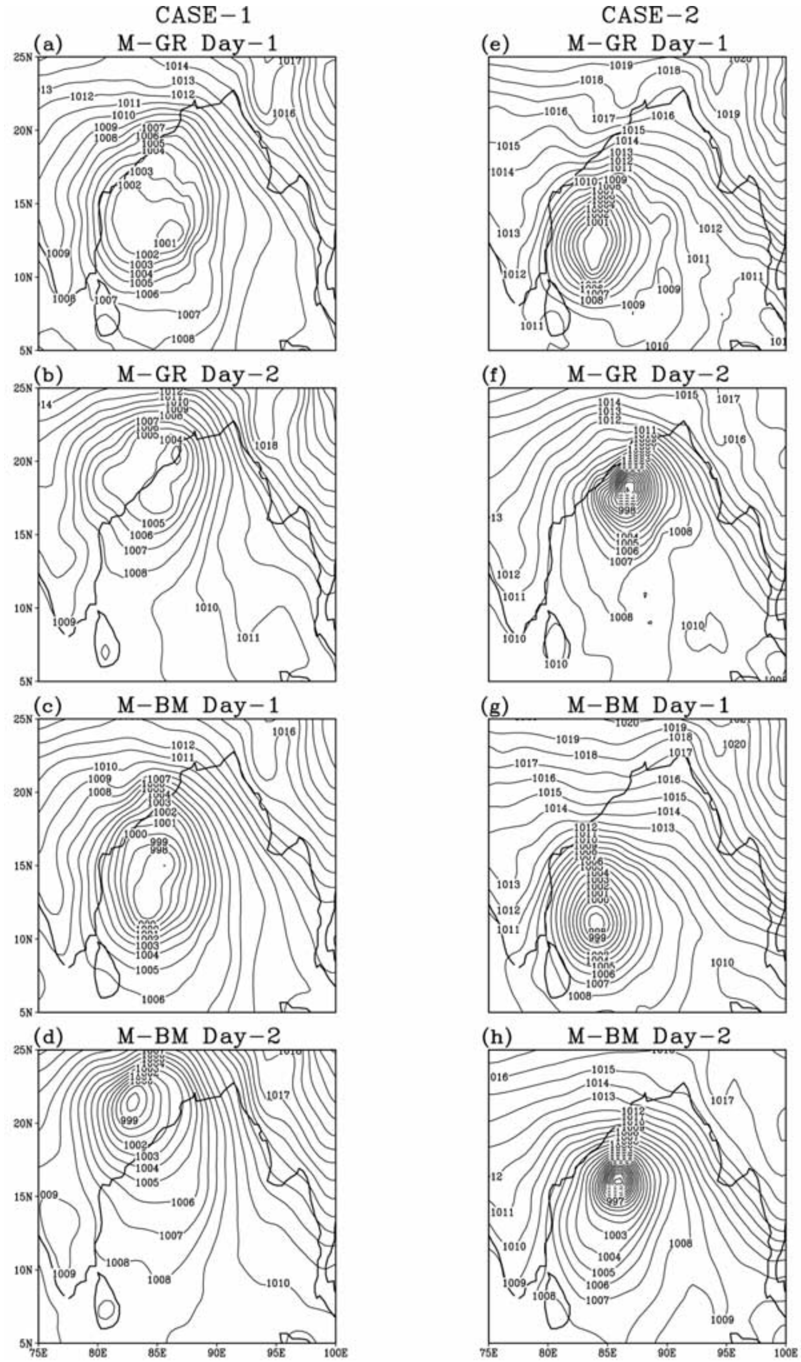

Figure 11. Forecasts of sea level pressure using simple cloud radiation scheme (a) 24-hours with M–GR. (b) 48-hours with M–GR. (c) 24-hours with M–BM. (c) 48-hours with M–BM. (e) Same as (a). (f) Same as (b). (g) Same as (c). (h) Same as (d).

the sensitivity is even more in day 2 forecast. In case 1, minimum central SLP is found to vary up to 3 hPa in day 1 and 5 hPa in day 2 with CCM2 radiation scheme showing more intense storm. Similarly in case 2 (Figures 11e–h), the intensity of the storm is better represented by CCM2 scheme with minimum central SLP varying up to 3 hPa in day 1 and 6 hPa in day 2 forecast.

5. Conclusions

This paper presents the results obtained from a number of sensitivity experiments with convection, PBL and radiation parameterization schemes towards simulation of two post-monsoon Bay of Bengal cyclones. Some important inference that can be drawn from these results are as follows.

The model is sensitive to planetary boundary layer and convection parameterization schemes. The combination of MRF and Grell (or Betts–Miller) for PBL and convection schemes respectively gives consistently better results than the other combinations. The model is reasonably successful in simulating track and intensity of the storms up to 48 hours. The performance of the model can be improved by better initial vortex specification (both location and intensity wise) of the storm. The model shows easterly bias in simulation of horizontal wind.

Radiation parameterization schemes also have perceptible impact in model simulation of the storms. Intensity of the storms is better simulated with the CCM2 radiation scheme compared to the simple cloud scheme.

Grell convection scheme performs slightly better than Betts–Miller scheme in combination with MRF PBL scheme but need to be examined with more cases.

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