Effect of cumulus and microphysical parameterizations on the JAL cyclone prediction

M Venkatarami Reddy¹,², S B Surendra Prasad¹,², U V Murali Krishna¹ & K Krishna Reddy¹,§,*

¹Semi-arid-zonal Atmospheric Research Centre (SARC), Yogi Vemana University, Kadapa 516 003, Andhra Pradesh, India
²Department of Physics, Acharya Nagarjuna University, Guntur 522 510, Andhra Pradesh, India
§E-mail: krishna.kkreddy@gmail.com

Received 19 August 2013; revised 7 November 2013; accepted 8 January 2014

Weather Research and Forecasting (WRF) model is used to predict the track and intensity of JAL cyclone, which formed during 04-08 November 2010 over the Bay of Bengal. The model has been simulated with numerous experiments using the logical/scientific combination of convection and micro-physics schemes. The model simulations have been conducted with different initial conditions to know the effective track and intensity prediction of JAL cyclone. In addition, the effect of cumulus parameterization schemes at different resolution (27 and 9 km) on the cyclone track and intensity is reported. The model simulated results showed the importance of cumulus schemes and their role at 9 km horizontal resolution. The results indicate that the track predicted by Kain-Fritsch (KF) scheme is in good agreement with the observed track in all the experiments and the land fall error is minimum (~11 km) for the combination of Ferrier and KF scheme with 0000 hrs UTC on 04 November 2010 as initial condition. Strong intensity is produced by KF, New Grell (NG) schemes and weak intensity is produced by Betts-Miller-Janjić (BMJ) scheme with all microphysics parameterization (MP) combinations. Further, the dependency of intensity of cyclone has been studied in terms of surface latent heat flux, divergence and vorticity fields. To validate the model performance, different meteorological parameters are derived from the model simulations over three different regions and are compared with the observed meteorological parameters. The model results are in good agreement with the observed parameters, but variations are observed at the landfall /dissipation of the cyclone.

Keywords: JAL cyclone, Weather Research and Forecasting (WRF model), Cumulus parameter, Microphysical parameters, Vorticity, Divergence, Convergence

PACS Nos: 92.60.Aa; 92.60.hb; 92.60.Wc

1 Introduction

Tropical cyclones (TC) form over Bay of Bengal (BOB) with strong winds, torrential rains and tidal waves¹,² during pre- and post-monsoon season and cause a severe damage to lives and property over the east coast of India and Bangladesh. The tropical storms form and develop over the warm tropical oceans under favourable environmental conditions³. The BOB in the Indian Ocean is a potentially energetic region for the development of TCs and it contributes about 7% of the global annual tropical storms. There is a need to develop a regional weather forecasting system to give the lead time forecast warnings and to mitigate the disasters. Hence, accurate prediction of the track and intensity of cyclones is essential to minimize the loss of human lives and property damage. Several models and methods have been developed to predict the accurate position of the cyclone to some extent. The improvement in prediction helps to issue the appropriate cyclone warnings to the society and disaster management.

Initially, TC forecast was carried out using a computer oriented half persistence and half climatology technique in India⁴. Later on, Mohanty & Gupta⁵ have used multi-level primitive equation models with parameterization of physical processes for the prediction of cyclone track. Prasad & Rama Rao⁶ have performed numerous sensitive experiments on Quasi-Lagrangian model (QLM) to forecast the track of cyclones. In the last few years, the rapid advancement of computing power and high resolution mesoscale models are being used for hurricane sensitivity studies to...
know the structure, intensification and movement with different physical processes\textsuperscript{22,23}. Fovell & Su\textsuperscript{24} showed that the logical combination of microphysics parameterization (MP) and cumulus parameterization (CP) schemes significantly influenced the track and land fall of Hurricane Rita using WRF model at 30 and 12 km resolution. They also reported the impact of cloud MP schemes on track forecasting. Different parameterization schemes have been developed by several researchers but all of them have certain limitations\textsuperscript{25-28}.

The TC intensity forecast varied with different microphysical processes in numerical models. Zhu & Zhang\textsuperscript{29} examined the sensitivity of the hurricanes intensity with different microphysical processes in the MM5 model. The intensity and track forecast of cyclones depend on the evolution and the distribution of the heat rates\textsuperscript{30}, which depends on the release of latent heat flux by the condensation within the system. Deshpande et al.\textsuperscript{31} studied the track and intensity prediction for cyclone Gonu using MM5 model at 90 and 30 km resolutions and concluded that track and intensity prediction were highly sensitive for convective parameterization schemes than other physical parameterization schemes. Loh et al.\textsuperscript{32} also reported that the planetary boundary layer parameterization (PBL) schemes did not show much impact on the prediction of track and intensity of near equatorial typhoons. However, the intensity forecast still remains a challenging problem in both operational and research communities\textsuperscript{7,33,34}.

Even though the CP schemes are important for the simulation of TCs, there is a limitation in usage of CP schemes in the numerical simulations at high resolutions (e.g. less than 10 km grid spacing). Liu et al.\textsuperscript{35} and Braun et al.\textsuperscript{36} simulated the TC without any CP scheme in the high resolution because it is not worthy to use CP schemes in the numerical simulations where the grid horizontal resolution is less than 10 km. Even though the domain horizontal resolution is less than 10 km, CP scheme plays a key role for the accurate prediction of TC\textsuperscript{37,38}. McFarquhar et al.\textsuperscript{40} used 6 km horizontal resolution domain and reported the change in intensity and track prediction of TC with different CP schemes.

TCs track and intensity simulation are sensitive to model resolution, CP, MP and PBL schemes used in the model. However, the best set of parameterization schemes in the model is not same for all the cyclones. The logical combination of schemes for one region may not be suitable for other regions. Most of the studies mainly focused on the prediction of track and intensity of the cyclones over BOB with resolutions greater than 10 km using different physical processes and few of them performed less than 10 km resolution with different MP and PBL processes. The present study focused mainly on the prediction of track and intensity of JAL cyclone using WRF model with different CP and MP schemes to find the best set of physics options. During the last decade, JAL cyclone alone passed over the semi-arid region of India. Hence, the best logical combination of parameterization schemes for JAL cyclone was reported and the results compared with observational meteorological parameters over three regions, viz. Oceanic (12.8-13.8°N, 80-90.2°E), inland (13-14°N, 79-80°E) and semi-arid (14-15°N, 78-79°E) at 3 km resolution with and without CP schemes.

2 Brief description of JAL cyclone

A severe cyclonic storm, JAL developed (04-08 November 2010) over BOB. It moved west-northwestwards and intensified into severe cyclonic storm on 06 November 2010. India Meteorological Department (IMD) reported\textsuperscript{41} that the JAL cyclone moved to the southwest of BOB having lower ocean thermal energy and high vertical wind shear in association with the strong easterlies in the upper tropospheric level. The strong wind shear led to westward shearing of convective clouds from the centre of system and the lower Ocean thermal energy caused to convection un-sustainability over the region. The severe cyclonic storm, JAL gradually weakened into a deep depression and crossed north Tamil Nadu – South Andhra Pradesh coast, close to the north of Chennai near 13.3°N and 80.3°E around 1600 hrs UTC on 07 November 2010. It continued to move west-northwestwards and further weakened into well marked low pressure area. The convective clouds were sheared to the large extent to west on the date of landfall, i.e. on 07 November 2010. During the last decade, JAL cyclone is the only cyclone, which passed over interior parts of Andhra Pradesh (semi-arid region) and it caused heavy rainfall over the coastal region as well as the interior parts of semi-arid regions.

3 Model description

The non-hydrostatic compressible WRF model was developed by National Center for Atmospheric
It has features like a fully compressible, Eulerian non-hydrostatic control equation set, a terrain-following, hydrostatic pressure vertical coordinate system with the constant pressure surface at the top level of model. The staggered grid, like Arakawa-C grid, used in the model and a third-order Runge-Kutta time integration scheme used for both horizontal and vertical directions. The WRF model incorporates several processes like MP, CP, PBL, surface layer, land surface, and long wave and shortwave radiations, with multiple options for each process. The model details and equations are available in the NCAR technical note. In the present study, WRF-ARW model is used to simulate the track and intensity of JAL cyclone. The horizontal resolutions used are 27 km, 9 km and 3 km (Fig. 1) with 27 vertical levels. The input details of the model are given in Table 1.

WRF-ARW model offers user specified options, number of physical parameterization schemes. Simulation experiments have been conducted with four CP schemes such as Kain-Fritsch (KF), Betts-Miller-Janjic (BMJ), Grell-Devenyi ensemble (GD) and New Grell (NG). KF scheme, a deep and shallow convection sub-grid scale scheme, uses a mass flux approach with downdrafts and Convective Available Potential Energy (CAPE) removal time scale. The KF convective parameterization is based on a simple cloud model of Kain & Fritsch. It includes the effects of detrainment, entrainment, simple microphysics and moist updrafts and downdrafts. The BMJ scheme derived from Betts-Miller convective adjustment scheme was commonly used in tropical cyclone simulations. The GD is a cloud ensemble scheme with 144 sub-grid members. It uses 16 ensemble members derived from 5 popular closure assumptions to obtain an ensemble-mean realization at a given time and location. The MP schemes used in the model are WRF Single Moment 6 class scheme (WSM6) ["6" stands for six classes of hydrometeors], Thompson et al. (THOMP) scheme, Lin et al. (LIN) scheme, Ferrier et al. (FERR) scheme. Dudhia scheme is used for the short-wave radiation, Rapid Radiative Transfer Model (RRTM) scheme is used for the long-wave radiation and Yonsei University (YSU) scheme is used for the PBL.

**4 Data and Experiment description**

In the present study, WRF-ARW model is initialized with the National Center for Environmental Prediction Final Analyses (FNL) data from Global Data (with every 6 hourly interval of time period)

![Model domains used for the prediction of JAL cyclone with horizontal resolution of 27 km, 9 km (D02) and 3 km (D03)](image_url)

![Table 1 — Model configuration and parameterization schemes used in the WRF model](table_url)
having the resolution of $1^\circ\times1^\circ$ Assimilation System (GDAS) for the prediction of track and intensity of tropical cyclone. The details of different types of data undergoing into the analyses, can be obtained from the Data Documentation for Data Set 6141B (NCEP Model Output—FNL archive data). The model results of track and intensity are compared with IMD observational data. For validation, the model results of meteorological parameters (sea level pressure, temperature and relative humidity) are compared with the data collected from Automatic Weather Station (AWS) located in oceanic, in land and semi-arid regions, respectively. For each region, data is collected from seven AWS located nearby to cover complete region of interest.

A detailed study on the impacts of different combinations of CP and MP schemes on track and intensity of JAL cyclone using WRF-ARW Model is carried out. For this purpose, 64-core (8 cluster + 5TB storage server) High Performance Computational (HPC) facility established at Yogi Vemana University (YVU), Kadapa is utilized. Six numerical experiments were designed and performed to investigate the characteristics of the simulated track and intensity. The details of the experiments are reported in Table 2.

5 Results and Discussion

5.1 Simulation of JAL cyclone at 27 km resolution

The JAL cyclone is simulated with different CP schemes and MP schemes at 0000 hrs UTC on 03 November 2010 (Exp-D1I3) and 0000 hrs UTC on 04 November 2010 (Exp-D1I4) as initial conditions for WRF model at 27 km resolution.

5.1.1 Track

The track of the cyclone is predicted with different CP and MP schemes using the WRF model. Figure 2(a) shows the comparison of predicted tracks with the India Meteorological Department (IMD) track using the combination of LIN MP scheme with four CP schemes in 27 km resolution experiment Exp-D1I3. According to the IMD observations, the cyclone JAL was formed over the South Andaman Sea near $8.0^\circ$N and $92.0^\circ$E (Fig. 2(a)) and moved to west-northwest, whereas in LIN+KF scheme the cyclone formed over the South Andaman Sea near $8.5^\circ$N and $91.5^\circ$E, moved to northwest and then moved in the direction of west-northwest. In LIN+NG scheme, the storm developed near $8.5^\circ$N and $91.5^\circ$E and follows the observed track up to 1800 hrs UTC on 06 November 2010 ($12^\circ$N, $83.8^\circ$E) and deviated thereafter. Also, the LIN+BMJ scheme shows more or less similar behaviour with genesis point near to $8.5^\circ$N and $91.5^\circ$E and follows the path up to 0000 hrs UTC on 06 November 2010 ($10.8^\circ$N, $86^\circ$E) and then deviated more thereafter. In LIN+GD scheme, the storm developed near $8.5^\circ$N and $91.5^\circ$E and followed the track up to 0000 hrs UTC on 06 November 2010 ($11^\circ$N, $85.8^\circ$E). The distance between the IMD observed and model predicted tracks are considered as track errors and are shown in Fig. 3(a). The track error lies in the range 35-140 km, 55-280 km, 65-245 km and 20-165 km for KF, BMJ, GD and NG schemes, respectively. The track error is minimum for FERR MP scheme with KF, GD

![Table 2 — Description of the performed numerical experiments](image-url)

<table>
<thead>
<tr>
<th>Experiment name</th>
<th>Horizontal resolution, km</th>
<th>No of grid points</th>
<th>Initial time, Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exp-D1I3</td>
<td>27</td>
<td>123x135</td>
<td>0000 hrs UTC, 03 November 2010</td>
</tr>
<tr>
<td>Exp-D2I3</td>
<td>9</td>
<td>193x151</td>
<td>0000 hrs UTC, 03 November 2010</td>
</tr>
<tr>
<td>Exp-D3I3</td>
<td>3</td>
<td>154x139</td>
<td>0000 hrs UTC, 03 November 2010</td>
</tr>
<tr>
<td>Exp-D1I4</td>
<td>27</td>
<td>123x135</td>
<td>0000 hrs UTC, 04 November 2010</td>
</tr>
<tr>
<td>Exp-D2I4</td>
<td>9</td>
<td>193x151</td>
<td>0000 hrs UTC, 04 November 2010</td>
</tr>
<tr>
<td>Exp-D3I4</td>
<td>3</td>
<td>154x139</td>
<td>0000 hrs UTC, 04 November 2010</td>
</tr>
</tbody>
</table>
and NG schemes compared to all other MP combinations [Fig 3(a-d)]. Among all the CP schemes, KF scheme followed the track well in all MP schemes. The KF combination showed minimum track errors compared to the other combinations. From the above experimental results, it is clear that in the combination of KF scheme with different MP schemes, FERR and LIN has minimum track error. In the combination of BMJ with all MP schemes, LIN and WSM6, in GD scheme FERR and THOMP and in NG scheme FERR and LIN has minimum track error.

Similar to the above experiment, the cyclone is simulated in the experiment Exp-D1I4 with 27 km resolution using the same MP and CP schemes. In this experiment (Exp-D1I4), the track simulated with LIN MP scheme [Fig. 2(e)] shows small variations compared to observed track simulated in Exp-D1I3. Here also, LIN+KF scheme followed the observed track well compared to other CP schemes. The track error simulated using LIN MP scheme with 4 different CP schemes in Exp-D1I4 is shown in Fig. 3(e). The track error in LIN+KF decreased initially and then increases compared to LIN+KF in Exp-D1I3, but the track error for LIN+BMJ, LIN+GD and LIN+NG are similar to Exp-D1I3. Simulated track and track error using FERR MP scheme with 4 CP schemes in Exp-D1I4 are shown in Fig. 2(f) and
Fig. 3(f), respectively. Track simulated in Exp-D1I4 using FERR MP scheme followed the track simulated in Exp-D1I3. The track error decreased in FERR+KF and FERR+GD schemes, whereas in FERR+NG, the track error increased in Exp-D1I4 compared to Exp-D1I3. Track simulated using WSM6 and THOMP in Exp-D1I4 are comparable with the track simulated in Exp-D1I3 for the respective schemes (figure not shown). The landfall error for all CP and MP combinations in all the experiments is shown in Table 3.

5.1.2 Intensity

The intensity of the tropical cyclone is discussed in terms of minimum central sea level pressure (MSLP) and maximum surface wind (MSW). Figure 4(a and b) shows the model predicted MSLP and MSW using LIN MP scheme with 4 CP schemes in the experiment (Exp-D1I3) along with observed MSLP and MSW by IMD. The observed MSLP decreased from 1002 to 988 hPa; and then increased to 1004 hPa during the passage of cyclone; thereafter, the cyclone is weakened. LIN+BMJ scheme predicted the MSLP very well up to 1800 hrs UTC on 06 November 2010 and deviated thereafter from IMD observations. Whereas the LIN+GD scheme predicted the MSLP well up to 0600 hrs UTC on 06 November 2010. The MSW are predicted well by LIN+BMJ and LIN+GD up to 1800 hrs UTC on 06 November 2010 and deviated thereafter. Among these two, LIN+GD scheme followed the MSW well compared to LIN+BMJ scheme. From these observational studies, LIN+KF and LIN+NG are not able to represent the true intensity of the cyclone. The minimum variations in predicted MSLP in BMJ, GD, KF and NG schemes are 3, 13, 18 and 28 hPa, respectively and the MSW are 5, 9, 14 and 15 ms\(^{-1}\) for the respective schemes.
The experimental results show that the strongest storm is produced by KF and NG schemes and the weakest storm produced by BMJ and GD schemes.

Intensity of the cyclone is simulated using FERR, WSM6 and THOMP MP Scheme with four CP schemes in Exp-D1I3. In FERR MP scheme, BMJ scheme predicted the MSLP and MSW well up to 1800 hrs UTC on 05 November 2010 and decrease until 0000 hrs UTC on 07 November 2010 and then increased thereafter compared to observed MSLP and MSW [Fig. 4(c and d)]. The FERR+GD scheme followed the LIN+GD scheme until 0600 hrs UTC on 07 November 2010 and then deviated. Whereas, KF and NG schemes shows similar intensity compared with LIN+KF and LIN+NG schemes. The minimum variations in the predicted MSLP in BMJ, GD, KF and NG schemes are 3, 19, 18 and 23 hPa, respectively and the MSW are -5, 9, 14 and 11 ms$^{-1}$ for the corresponding schemes. WSM6 and THOMP schemes predicted the intensity similar to LIN MP scheme with 4 CP schemes [Fig. 4(e-h)]. The minimum variations in predicted MSLP by BMJ, GD, KF and NG schemes are -2, 1, 13, 28 and -2, 16, 13, 23 hPa and the MSW are 1, 1, 11, 15 and 3, 7, 11, 15 ms$^{-1}$ in both MP schemes, respectively. But in both MP schemes, the BMJ scheme shows less MSW compared to the observed value.

Figure 4(i and j) shows the intensity simulated by LIN MP scheme with 4 different CP schemes in the experiment Exp-D1I4. The intensity simulated in Exp-D1I4 is similar to those simulated in Exp-D1I3 with a small variation in MSLP and MSW. In LIN+KF and LIN+GD schemes, the MSLP decreased and in LIN+BMJ and LIN+NG schemes, the MSLP remains almost same compared to Exp-D1I3. Here, also the strongest storm was simulated by KF and NG schemes, whereas weakest storm was simulated by BMJ scheme. The intensity simulated using FERR MP scheme with 4 CP schemes in Exp-D1I4 is shown in Fig. 4(k and l). Initially, MSLP increased in FERR+KF scheme, decreased in the remaining combinations and finally became almost same in all combinations compared to Exp-D1I3. Whereas, MSW initially decreased in KF scheme and increased in GD scheme and then became almost equal in both the combination compared to Exp-D1I3. But the variations in MSW in BMJ and NG schemes are not uniform.

<table>
<thead>
<tr>
<th>Experiments</th>
<th>Landfall errors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Schemes</td>
<td>Exp-D1I3</td>
</tr>
<tr>
<td>KF+ LIN</td>
<td>79 -1</td>
</tr>
<tr>
<td>BMJ+ LIN</td>
<td>288 4</td>
</tr>
<tr>
<td>GD+ LIN</td>
<td>234 5</td>
</tr>
<tr>
<td>NG+LIN</td>
<td>123 1</td>
</tr>
<tr>
<td>KF+FERR</td>
<td>-22 -2</td>
</tr>
<tr>
<td>BMJ+FERR</td>
<td>400 7</td>
</tr>
<tr>
<td>GD+FERR</td>
<td>57 1</td>
</tr>
<tr>
<td>NG+FERR</td>
<td>90 5</td>
</tr>
<tr>
<td>KF+WSM6</td>
<td>90 0</td>
</tr>
<tr>
<td>BMJ+WSM6</td>
<td>370 4</td>
</tr>
<tr>
<td>GD+WSM6</td>
<td>244 6</td>
</tr>
<tr>
<td>NG+WSM6</td>
<td>178 3</td>
</tr>
<tr>
<td>KF+THOMP</td>
<td>79 0</td>
</tr>
<tr>
<td>BMJ+THOMP</td>
<td>536 5</td>
</tr>
<tr>
<td>GD+THOMP</td>
<td>211 3</td>
</tr>
<tr>
<td>NG+THOMP</td>
<td>90 1</td>
</tr>
<tr>
<td>KF+MMS</td>
<td>256 2</td>
</tr>
<tr>
<td>BMJ+MMS</td>
<td>545 0</td>
</tr>
<tr>
<td>GD+MMS</td>
<td>326 -1</td>
</tr>
<tr>
<td>NG+MMS</td>
<td>299 0</td>
</tr>
</tbody>
</table>
5.2. Simulation of JAL cyclone at 9 km resolution

The effect of CP schemes on the cyclone track and intensity predicted are investigated using Exp-D2I3 and Exp-D2I4 with 9 km resolution.

5.2.1 Track

The track and track error simulated by LIN MP scheme with four CP schemes in Exp-D2I3 is shown in Fig. 5(a) and Fig. 3(g). The track simulated in Exp-D2I3 is similar to those simulated in Exp-D1I3. The track error simulated using LIN+KF scheme decreased initially, then increased and finally became comparable to Exp-D1I3. Whereas, the tracks for LIN+BMJ, LIN+GD and LIN+NG schemes are comparable to the respective combination in Exp-D1I3. The simulated track and track error using FERR MP scheme with 4 CP schemes are shown in Fig. 5(b) and Fig. 3(h). The track simulated by FERR MP scheme in Exp-D2I3 is similar to those simulated in Exp-D1I3. The track error decreased initially and became comparable afterwards for FERR+KF and FERR+GD combinations. Whereas the track error does not show much variation in FERR+BMJ and FERR+NG schemes compared to Exp-D1I3. The track simulated by WSM6 and THOMP schemes in Exp-D2I3 are comparable to Exp-D1I3 (figure not shown).

The experiment Exp-D2I4 was simulated with 9 km resolution using all the MP and CP combinations. The track simulated using LIN MP scheme in Exp-D2I4 is shown in Fig. 5(c). In LIN MP scheme, the track simulated is comparable to the observed track as in Exp-D1I4. The track error in LIN+KF scheme [Fig. 3(i)] decreased, whereas in LIN+BMJ, LIN+GD and LIN+NG schemes, no much variation in track error is observed. Similarly, the track simulated using FERR MP scheme followed the observed track well as in Exp-D1I4 [Fig. 5(d)]. Also, the track error decreased in FERR+NG scheme.

Fig. 4 — Estimated MSLP (hPa) and estimated MSW (ms⁻¹) of the cyclone: (a and b) LIN, (c and d) FERR, (e and f) WSM6, and (g and h) THOMP MP scheme, with four CP schemes (KF, BMJ GD and NG) in experiment (Exp-D1I3); (i and j) LIN, (k and l) FERR scheme, with four CP schemes (KF, BMJ GD and NG) in experiment Exp-D1I4.
[Fig. 3(j)] and the variation are not uniform in the remaining schemes. Even in the 9 km resolution experiment also, variation in track error is comparable to variations in track error in 27 km resolution experiment when the initial condition is changed from 0000 hrs UTC on 03 November to 0000 hrs UTC on 04 November 2010. The landfall error for all the schemes in Exp-D2I3 and Exp-D2I4 is given in Table 3. From the observations, it is clear that there is no much variation in the landfall error and track error simulated in 27 km and 9 km resolution experiments.

From these experiments, one can notice that all the schemes followed the observed track well until 0000 hrs UTC on 07 November 2010 and deviated thereafter. But the track simulated with FERR+KF schemes initially moved to west until 1200 hrs UTC on 06 November 2010 and then to north-west, whereas the observed track moved to north-west from the beginning. In all experiments, the combination of KF scheme with all the MP schemes followed the observed track well compared to other CP schemes because of its moist updraft and downdrafts, detrainment, entrainment and simple microphysics along with the widespread triggering of convection. Pattanaik & Rama Rao observed a decrease in landfall error when the initial conditions change from 30 April to 01 May for the cyclone Nargis. However, in the present study, when the initial conditions change from 03 November to 04 November, the landfall error is decreased in some MP and CP combinations and increased in other MP and CP combinations both in 27 and 9 km resolutions.

5.2.2 Intensity

Figure 6(a and b) shows the model simulated MSLP and MSW using LIN MP scheme with four CP schemes in Exp-D2I3 along with observed MSLP and MSW by IMD. The minimum variations in predicted MSLP using BMJ, GD, KF and NG schemes are 6, 15, 18 and 37 hPa, respectively and the MSW are 11, 13, 14 and 27 ms$^{-1}$ for the corresponding schemes. In this experiment, the strongest intensities are shown by LIN+NG and LIN+KF; and weakest intensities by LIN+BMJ and LIN+GD schemes. In FERR MP scheme, the simulated intensity followed the observed intensity as in Exp-D1I3 [Fig. 6(c and d)]. But in Exp-D2I3, all the MP and CP combinations show lower MSLP and higher MSW compared to Exp-D1I3. Hence, the intensity simulated using LIN and FERR MP schemes is stronger in Exp-D2I3 compared to Exp-D1I3. The intensity simulated using LIN and FERR MP schemes with all CP schemes in Exp-D2I4 is shown in Fig. 6(e-h). The intensity simulated by both MP schemes are stronger compared to Exp-D1I4 in all the CP schemes.

Fig. 5 — Track simulated using: (a) LIN and (b) FERR MP scheme, with four CP Schemes (KF, BMJ, GD and NG) in experiment Exp-D2I3 along with observed track; (c) LIN and (d) FERR MP scheme, with four CP Schemes (KF, BMJ, GD and NG) in experiment Exp-D2I4
The prediction of track and intensity of tropical cyclone depends on choice of MP schemes used in the model. Deshpande et al. observed that the track and intensity of TC are very sensitive to the choice of convective parameterization schemes compared to other physical parameterization schemes using 90 and 30 km resolutions in the MM5 model. It is clear from the present study also that the predicted track and intensity are sensitive to CP schemes rather than MP schemes even at high resolutions (9 km). Hence, for the accurate prediction of TC, high resolution models with a better choice of CP schemes are essential. To investigate further, the impact of the different MP and CP schemes on numerical simulations of intensity of the cyclone, surface latent heat flux, convergence and divergence and vertical structure of wind speed and temperature over the storm core region are examined for the simulations at 1200 hrs UTC on 06 November and 0000 hrs UTC on 07 November 2010, when the cyclone was intensified.

5.3 Predictions of surface latent heat fluxes

The observations show that the intensity of cyclone is strong from 1200 hrs UTC on 06 November to 0000 hrs UTC on 07 November 2010. To explain the strong intensity observed at 1200 hrs UTC on 06 November 2010, the latent heat flux at 1200 hrs UTC on 06 November and 0000 hrs UTC on 07 November 2010, when the cyclone was intensified.

Fig. 6 — Estimated MSLP (hPa) and estimated MSW (ms⁻¹) of cyclone: (a and b) LIN, (c and d) FERR MP scheme, with 4-different CP schemes (KF, BMJ, GD and NG) in experiment Exp-D2I3; (e and f) LIN, (g and h) FERR MP scheme, with 4-different CP schemes (KF, BMJ, GD and NG) in experiment Exp-D2I4.
cyclone increases and is more in GD scheme (figure not shown). Moreover, at 1200 hrs UTC on 07 November 2010, the intensity and surface latent heat flux are stronger in NG scheme and weaker in GD scheme, whereas it is moderate in both KF and BMJ schemes [Fig. 8 (a-d)].

Similar to Exp-D1I3, the surface latent heat flux is simulated in Exp-D2I3 using LIN MP scheme with all CP schemes at 1200 hrs UTC on 06 November 2010. In Exp-D2I3, the stronger intensity is predicted by NG and KF schemes, but the strong surface latent heat flux is predicted by KF and NG scheme, respectively. However, BMJ and GD schemes show weakest intensity along with surface latent heat flux [Fig. 7 (e-h)]. Further, at 1200 hrs UTC on 07 November 2010, the stronger intensity is predicted by NG and KF; whereas the stronger surface latent heat flux is predicted by KF and NG schemes, respectively. However, BMJ and GD schemes show the same intensity and surface latent heat fluxes [Fig. 8 (e-h)]. The surface latent heat flux in Exp-D2I3 is more in all schemes compared to Exp-D1I3.

Previous studies by Zhu & Zhang and Li & Pu showed that the intensity of cyclone depends on the latent heat flux released. From the observations of JAL cyclone, it is clear that the intensity of the cyclone depends not only on the current surface latent heat flux but also on the preceding surface latent heat flux.

---

**Fig. 7** — Predicted surface latent heat flux (Wm$^{-2}$, shaded), wind speed (ms$^{-1}$, thick black line) and sea level pressure (hPa, solid red lines) at 1200 hrs UTC on 06 November 2010 using LIN MP scheme with: (a) KF, (b) BMJ, (c) GD, and (d) NG CP scheme, in experiment Exp-D1I3; (e) KF, (f) BMJ, (g) GD, and (h) NG CP scheme, in experiment Exp-D2I3

**Fig. 8** — Predicted surface latent heat flux (Wm$^{-2}$, shaded), wind speed (ms$^{-1}$, thick black line) and sea level pressure (hPa, solid red lines) at 1200 hrs UTC on 07 November 2010 using LIN MP scheme with: (a) KF, (b) BMJ, (c) GD, and (d) NG CP scheme, in experiment Exp-D1I3; (e) KF, (f) BMJ, (g) GD, and (h) NG CP scheme, in experiment Exp-D2I3
5.4 Prediction of cyclone structure using divergence and vorticity fields

According to Willoughby, air flows in a tropical cyclone work in an in-up-and-out pattern. At low levels of the atmosphere, the air flows toward the storm center. This inward air brings heat and moisture from the ocean surface into the storm. At the upper troposphere, outflow exists to compensate the inflow at the low troposphere. It is a critical factor for maintenance and development of a storm eye-wall. To elucidate this, the divergence field and vorticity of the TC are considered. Integrated between 950 and 850 hPa levels and divergence field integrated between 200 and 100 hPa levels in Exp-D1I3 and Exp-D2I3.

Figure 9 shows the divergence field integrated between 950 and 850 hPa levels in Exp-D1I3 using LIN MP scheme with all CP schemes at 1200 hrs UTC on 06 November 2010. The negative values in the figure represent convergent flows; and positive values represent divergent flows. A strong convergent inflow between 950 and 850 hPa levels and a strong and well organized divergent outflow between 200 and 100 hPa and strong vorticity at the eye of the cyclone explains the more intense storm produced by the KF and NG schemes. Meanwhile, weaker convergent flows between 950 and 850 hPa, less divergent flows between 200 and 100 hPa and weak vorticity at the eye of the cyclone corresponds to weaker storm intensity predicted by BMJ and GD schemes. Also, the intensity predicted in Exp-D2I3 is stronger than predicted in Exp-D1I3 at 1200 hrs UTC on 06 November 2010. This is due to the strong convergent inflow, divergent outflow at the eye-wall region and strong vorticity observed at the eye of the cyclone in the Exp-D2I3 [Fig. (10)] compared to Exp-D1I3.

To explain further the dependency of intensity of cyclone on the vorticity, low level convergence and upper level divergence, the following three cases are considered with different MP and CP schemes. In THOMP+NG scheme, the MSLP and MSW are smaller compared to THOMP+KF scheme at 1200 hrs UTC on 06 November 2010. This can be explained by the stronger vorticity predicted by NG scheme compared to KF scheme. A strong convergent inflow between 950 and 850 hPa levels is observed in KF scheme compared to NG scheme. In THOMP+GD scheme, MSLP is almost equal to KF scheme; hence, the vorticity predicted by GD scheme is comparable to KF scheme. Whereas, MSW predicted by GD scheme is smaller than KF scheme. Hence, a weak convergent inflow between 950 and 850 hPa levels is observed in GD scheme compared to KF scheme [Fig. 11(a-i)]. FERR+KF, FERR+NG and FERR+GD schemes predicted the same intensity at 0000 hrs UTC on 07 November 2010. Because the convergent field and vorticity integrated between 950 and 850 hPa levels at 0000 hrs UTC on 07 November 2010 show almost similar values for FERR+KF, FERR+NG and FERR+GD schemes [Fig. 11(d-l)]; so, a strong convergent inflow in the lower troposphere and a strong divergent outflow in the upper troposphere and strong vorticity at the eye of the cyclone explain the strong intensity of the cyclone. Similarly, weaker convergent flows in the lower troposphere, less divergent outflow in the upper troposphere and weak vorticity at the eye of the cyclone correspond to weaker storm intensity.

5.5 Vertical cross sections of wind speed and temperature

Environmental vertical wind shear is another important factor that could influence cyclone structure, development and maintenance. Figure 12(a-d) shows the vertical cross sections of meridional wind speed and temperature at 1200 hrs UTC on 06 November 2010 for LIN MP scheme with different CP schemes in the experiment Exp-D1I3. The temperature field has a warm core above the cyclone because of compensating descending inside the cyclone. Among all the schemes, KF and NG schemes show maximum temperature at the eye of the cyclone because KF and NG schemes show strong intensity (MSW). A vertical column of low speed is observed in all the schemes. The distribution of the wind is symmetric around the eye-wall region in KF and NG schemes. Also, the maximum wind is observed in the low levels in all the schemes. A minimum wind is observed at the eye of the cyclone (width of the eye) in BMJ, KF and GD schemes and it is more pronounced in BMJ scheme. This is because BMJ scheme shows weak intensity and the MSLP predicted by KF is less than GD scheme. Figure 12(e-h) shows the vertical cross sections of meridional wind speed and temperature at 1200 hrs UTC on 06 November 2010 in the experiment Exp-D2I3 using LIN MP scheme with different CP schemes. The temperature and meridional wind speed observed at the eye of the cyclone is less in Exp-D2I3 compared to Exp-D1I3. The vertical wind is more symmetric about eye wall region in Exp-D2I3 compared to Exp-D1I3. Hence, the intensity (MSLP and MSW) of the cyclone depends on vertical cross section of wind speed and temperature.
Validation

To validate the model results, the meteorological parameters like sea level pressure (slp), temperature and relative humidity are compared with the observed parameters. For this, simulation of JAL cyclone is carried out using different microphysical parameterization schemes with and without CP schemes in WRF model using Exp-D3I3 at 3 km resolution.

Fig. 9 — Divergence $(10^{-5} \text{ s}^{-1})$ field integrated between lower level (950-850 hPa), upper level (200-100 hpa) and lower level (950-850 hPa) vorticity $(10^{-5} \text{ s}^{-1})$ using LIN MP scheme with: (a, b and c) KF; (d, e and f) BMJ; (g, h and i) GD; (j, k and l) NG CP scheme, at 1200 hrs UTC on 06 November 2010 in experiment Exp-D1I3
Fig. 10 — Divergence ($10^{-5}$ s$^{-1}$) field integrated between lower level (950-850 hPa), upper level (200-100 hpa) and lower level (950-850 hPa) vorticity ($10^{-5}$ s$^{-1}$) using LIN MP scheme with: (a, b and c) KF; (d, e and f) BMJ; (g, h and i) GD; (j, k and l) NG CP scheme, at 1200 hrs UTC on 06 November 2010 in experiment Exp-D2I3
Fig. 11 — Divergence ($10^{-5}$ s$^{-1}$) field integrated between lower level (950-850 hPa) and lower level (950-850 hPa) vorticity ($10^{-5}$ s$^{-1}$) - using THOMP MP scheme with: (a and d) KF, (b and e) GD, and (c and f) NG CP scheme, at 1200 hrs UTC on 06 November 2010; using FERR MP scheme with: (g and j) KF, (h and k) GD, and (i and l) NG CP scheme, at 0000 hrs UTC on 07 November 2010 in experiment Exp-D113
Figure 13 shows the meteorological parameters (slp, temperature, relative humidity and rainfall) observed using Automatic Weather Station (AWS) and meteorological parameters (slp, temperature and relative humidity) simulated in Exp-D3I3 between 0000 hrs UTC on 06 November 2010 (before landfall) and 0000 hrs UTC on 09 November 2010 (after landfall) over Oceanic region using different MP schemes with KF CP scheme and without any CP schemes. Figure 13(a) shows the observed pressure and slp predicted in Exp-D3I3 in the Oceanic region.

During the landfall, observed slp decreases and it increased after landfall. The observed slp and the slp predicted by all the schemes remain the same up to 0300 hrs UTC on 07 November 2010 and after 0000 hrs UTC on 08 November 2010. The predicted slp varied much compared to the observed slp during the landfall of the cyclone. The variation is maximum for FERR and LIN and is minimum for WSM6 MP scheme. Even in the same experiment, without any CP scheme [Fig. 13(b)] also shows the same behaviour before and after landfall of the cyclone. But
during the landfall of the cyclone, the slp decreased considerably compared to the same experiment with CP scheme. Figure 13(c) shows the observed temperature and temperature simulated in Exp-D3I3 over Oceanic region. Observed temperature increases first and then decreases until 0300 hrs UTC on 07 November 2010. After this, the temperature increases slightly and remains constant up to landfall of the cyclone. After landfall, the temperature decreases (0000 hrs UTC on 08 November 2010) and again increases following the diurnal pattern. The predicted temperature followed the observed temperature before 0300 hrs UTC on 07 November 2010 and after 0000 hrs UTC on 08 November 2010. The temperature simulated in Exp-D3I3 without CP scheme [Fig 13(d)] also shows the same pattern as in Exp-D3I3 with CP scheme. Figure 13(e) shows the observed and simulated relative humidity for Exp-D3I3 in the Oceanic region. The observed relative humidity increased before landfall and decreased during landfall and again increased after landfall. In this case, the relative humidity predicted in all the MP schemes deviated more compared to the observed relative humidity. Also, relative humidity simulated in Exp-D3I3 without CP scheme [Fig. 13(f)] shows similar behaviour as in Exp-D3I3 with CP scheme.

Figure 14 shows the comparison of observed and simulated meteorological parameters in Exp-D3I3 between 0000 hrs UTC on 06 November 2010 and 0000 hrs UTC on 09 November 2010 over in land and semi-arid region using different MP schemes without

Fig. 13 — Observed and simulated (a) slp (hPa), (b) temperature (°C), and (c) relative humidity (%), of the cyclone using 4 MP schemes (LIN, FERR, WSM6 and THOMP) with KF CP scheme from 0000 hrs UTC on 06 November 2010 to 0000 hrs UTC on 09 November 2010 in the Oceanic region; (d) slp (hPa), (e) temperature (°C), and (f) relative humidity (%), of the cyclone using 4 MP schemes (LIN, FERR, WSM6 and THOMP) with KF scheme from 0000 hrs UTC on 06 November 2010 to 0000 hrs UTC on 09 November 2010 in the Oceanic region [vertical bars represent the observed rainfall (mm)]
any CP schemes. Figure 14(a) shows the observed and simulated slp using Exp-D3I3 without any CP scheme in the inland region. The slp predicted in the inland region shows higher values compared to the oceanic region. The simulated slp decreased 6-hours before the dissipation of the cyclone in Exp-D3I3. All the schemes deviated from the observed slp between landfall and dissipation time and followed well in the remaining time. The variation is maximum for FERR and LIN and is minimum for THOMP MP scheme. Figure 14(b) shows the observed and simulated temperature in Exp D3I3 in the inland region. During 07 November 2010, the temperature remained constant throughout the day and increased after the dissipation of cyclone. The FERR scheme deviated from observed temperature between landfall and dissipation time, whereas the remaining schemes deviated during the dissipation time. Figure 14(c) shows the observed and simulated relative humidity for Exp-D3I3 in the inland region. The simulated relative humidity deviated a little as compared to the observed relative humidity.

Figure 14(d) shows the observed and simulated slp using Exp-D3I3 without any CP scheme in the semi-arid region. The observed slp decreased during the landfall of the cyclone and then increased after landfall. Again the slp decreased during the dissipation of the cyclone and increased afterwards. The decrement in the slp was more during dissipation compared to landfall time. All the schemes deviated from the observed slp between landfall and dissipation time and followed well in the remaining time. The
variation was maximum for LIN MP scheme. Figure 14(e) shows the observed and simulated temperature in Exp-D3I3 in the semi-arid region. During 07 November 2010, the temperature remained constant throughout the day and increased after the dissipation of cyclone. The temperature increased slightly before landfall and then decreased during landfall. All the schemes deviated between landfall and dissipation time. Figure 14(f) shows the observed and simulated relative humidity for Exp-D3I3 in the semi-arid region. The simulated relative humidity deviated from the observed relative humidity.

As the cyclone approached, the slp increased in the inland and semi-arid regions. However, during the dissipation of cyclone, the observed temperature remained the same throughout the day in both in land and semi-arid regions, whereas in the oceanic region, it varied during the landfall of the cyclone. The observed rainfall was maximum over the oceanic region (83 mm) compared to inland (79 mm) and semi-arid (65 mm) regions. The relative humidity increased before the landfall of the cyclone in both oceanic and inland region. However, in semi-arid region, relative humidity increased during dissipation of the cyclone. After dissipation, the relative humidity decreased in all the regions at the same time.

7 Summary and Conclusions

The prediction of the tropical cyclone JAL formed over Bay of Bengal is carried out using WRF model with different CP and MP schemes. The result shows that the simulated track and intensity are sensitive to the choice of the CP and MP schemes used in the model.

The track/landfall error decreased in some MP and CP combinations and increased in other MP and CP combinations when the initial conditions change from 0000 hrs UTC on 03 November 2010 to 0000 hrs UTC on 04 November 2010. The track error is more sensitive to the choice of initial conditions, CP and MP schemes. Even, there is no much variation in the track predicted using 27 km and 9 km resolutions, model simulates stronger intensity in 9 km resolution compared to 27 km resolution. The track predicted using KF scheme with all MP schemes is in good agreement with the observed track in all the experiments. The land fall error is minimum (-11 km) for the combination of FERR+KF scheme in Exp-D1I4.

The cyclone intensity simulations are performed in terms of the MSLP and MSW in the model. The BMJ scheme predicted weak intensity and KF and NG schemes predicted strong intensity with all MP schemes in all the experiments. The KF and NG schemes predicted stronger intensity with minimum track error. Whereas, BMJ scheme predicted weak intensity with maximum track errors. Intensity (MSLP and MSW) of the cyclone depends on surface latent heat flux, convergent inflow in the lower troposphere, divergent outflow in the upper troposphere, vorticity, vertical cross section of wind speed and temperature.

The decrease in slp, temperature and increase in relative humidity is observed during the landfall of the cyclone with AWS at oceanic, in land and semi-arid regions. The model simulations well predicted the variation in meteorological parameters before/after the depression/landfall of cyclone without using CP schemes, but significant variations have been observed during cyclone period using the CP Schemes. The model simulations clearly indicated the importance of MP and CP schemes in the simulations of JAL cyclone.

Acknowledgement

The authors acknowledge the support of India Meteorological Department (IMD), Govt of India, for providing the JAL cyclone track information. They are thankful to Indian Space Research Organization (ISRO) for providing AWS data through MOSDAC website. They acknowledge the assistance of NOAA/OLR/ESRL PSD, Boulder, Colorado, USA, for providing FNL data at their website at http://www.esrl.noaa.gov/. Two of the authors (MVR and SBSP) greatly acknowledge the financial support extended by Atmospheric Science Program (ASP), Indian Space Research Organization (ISRO), Govt of India. One of the authors (UVMK) acknowledges the support of Ministry of Earth Sciences (MoES), New Delhi, Govt of India for providing the fellowship in carrying out this work.

References
1. Asnani G C, Tropical meteorology (Indian Institute of Tropical Meteorology, Pune, India), 2005.
41 Indian Meteorological Department, Cyclone Annual report 2010 (Indian Meteorological Department, Delhi), 2011.