

## Numerical prediction of the Orissa super cyclone (1999) : Sensitivity to the parameterisation of convection, boundary layer and explicit moisture processes

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**सार** – पी. एस. यू. / एन. सी. ए. आर. एम. एम. 5 का उपयोग करके उड़ीसा में 1999 में आए महाचक्रवात की गतिविधियों और उसकी तीव्रता के संख्यात्मक पूर्वानुमान का इस शोध-पत्र में अध्ययन किया गया है। संवहन, ग्रहीय परिसीमा स्तर और निश्चित नमी स्कीमों की प्राचलीकरण योजनाओं की भूमिका का अध्ययन करने के लिए संवेदनशीलता प्रयोग किए गए हैं। बंगाल की खाड़ी में 90, 30 और 10 कि.मी. क्षैतिज अंतरालों के तीन पारस्परिक प्रक्षेत्रों (डोमेन) का पता लगाने के लिए इस मॉडल की परिकल्पना की गई है। एक अंश के अंतराल पर उपलब्ध हुए एन. सी. ई. पी. एफ. एन. एल. आँकड़ों का उपयोग करके प्रारंभिक क्षेत्रों और भिन्न समय के परिसीमा परिवर्ती तथा 12 घंटे के अंतराल पर समुद्र सतह तापमान उपलब्ध कराए गए हैं।

संवहन, ग्रहीय परिसीमा स्तर और निश्चित नमी प्रक्रियाओं के संबंध में चक्रवात के मार्ग का पूर्वानुमान और उसकी तीव्रता की संवेदनशीलता का अध्ययन करने के लिए तीन प्रयोग किए गए हैं। इससे प्राप्त हुए परिणामों से चक्रवात के मार्ग के पूर्वानुमान में संवहनीय प्रक्रियाओं की महत्वपूर्ण भूमिका का पता चला है तथा कैन-फ्रिश 2 स्कीम से चक्रवात के मार्ग का सबसे सटीक ढंग से पता लगाया जा सका है। इसके अलावा यह पता चलता है कि ग्रहीय परिसीमा स्तर प्रक्रियाएँ मेलर-यमादा स्कीम के सहयोग से सबसे प्रचंडतम चक्रवात की तीव्रता को ज्ञात कर सकती हैं। निश्चित नमी प्रक्रियाएँ चक्रवात की गति को नियंत्रित करती हैं जो भीतरी प्रक्षेत्र (डोमेन) के 10 कि.मी. के सूक्ष्म विभेदन के फलस्वरूप संभव हो सकता है। कैन-फ्रिश 2 और मेलर-यमादा की संयुक्त चरणबद्ध योजना से चक्रवात के मार्ग और उसकी तीव्रता के संबंधों को बेहतर ढंग से प्रतिरूपित किया गया है। किसी एकमात्र प्रयोग की तुलना में सभी मिलेजुले प्रयोगों से चक्रवात के मार्ग और उसकी तीव्रता का बेहतर आकलन किया जा सका है। प्रतिरूपित चक्रवात में एकपूर्ण विकसित चक्रवात के, उष्ण क्रोड, केंद्र और केंद्र-भित्ति जैसे सभी लक्षण पाए गए हैं। मॉडल से प्रतिरूपित वर्षा वितरण और तीव्रता प्रेक्षणों के अनुरूप पाई गई है।

**ABSTRACT.** Numerical prediction of the movement and intensification of the Orissa Super Cyclone (1999) is studied using PSU/NCAR MM5. Sensitivity experiments were made to study the role of the parameterisation schemes of convection, planetary boundary layer and explicit moisture schemes. The model is designed to have three interactive domains with 90, 30 and 10 km horizontal resolutions covering the Bay of Bengal region. The initial fields and time varying boundary variables and sea surface temperatures at 12 hour interval are provided from NCEP FNL data available at 1° resolution.

Three groups of experiments were performed to study the sensitivity of the cyclone track prediction and intensification to the schemes of convection, planetary boundary layer and explicit moisture processes. The results indicate that convective processes play an important role in the cyclone track prediction and the scheme of Kain-Fritsch 2 produces the best track and the planetary boundary layer processes control the intensification with the scheme of Mellor-Yamada producing the strongest cyclone. The explicit moisture processes modulate the movement of the cyclone, which may be due to the fine resolution of the 10 km for the innermost domain. The mixed-phase scheme in combination with Kain-Fritsch 2 and Mellor-Yamada produce the best simulation in terms of the track as well as intensification. The ensemble mean of all the conducted experiments estimate the track positions and intensification better than any individual experiment. The simulated cyclone shows all the characteristics of a mature cyclone, with warm core, formation of the eye and eye wall. The model simulated rainfall distribution and intensity have good agreement with the observations.

**Key words** – Tropical cyclones, Numerical models, Track prediction, Physical processes, Structure, Rainfall, Ensemble.

## 1. Introduction

Tropical cyclones are known to cause damage and destruction along the coastal regions, around the location and time of the landfall. The destruction is due to strong gale winds, torrential rain and associated tidal wave. Though the intensity and the frequency of the tropical cyclone over north Indian Ocean are less than those over Pacific and Atlantic oceans, more devastation was caused over the coastal regions of the Indian subcontinent because of the socio-economic conditions and the coastal topography of this region. For north Indian Ocean region, prediction of the movement of the tropical cyclones is very important to initiate proper mitigation measures. Though the general behavior of the movement of the tropical cyclones is well known, it is desirable to have as much as accurate prediction as possible of the landfall for effective implementation of the disaster mitigation. For a long time, conventional synoptic methods are used for tropical cyclone prediction. Though these methods are helpful, their utility is limited due to the variability of tracks of cyclones.

Numerical models, based on fundamental dynamics and well defined physical processes, provide a useful tool for weather prediction including tropical cyclones. However, for the modeling of the tropical cyclones, all the important physical processes which play important role in the evolution are to be well defined and incorporated such as energy supply from the ocean to the atmosphere. So well formulated PBL processes may be crucial for modeling of cyclones, as convection in the free atmosphere depends on the supply through the PBL. The PBL processes and the Conditionally Instability of Second Kind (CISK) mechanism are the important physical processes for the intensification of a low pressure into a cyclonic storm. Therefore numerical models are to be designed to incorporate these processes for the simulation of the evolution of tropical cyclones. The use of numerical models is subject to the limitations of inadequate observations. As the cyclones form over remote oceanic regions where conventional observations are not available, providing accurate initial conditions for model integration is the first limitation. Availability of some data through remote sensing measurements slightly improved the definition of the initial conditions, but is still a limitation which needs improvement. Secondly, the numerical models for the study of tropical cyclones need to have a very high resolution to resolve cumulus convection. Though it is desirable to design a model which can resolve the convection explicitly, predictions on real time basis with constraints on computational power preclude such attempts. With the rapid developments of computer technology and availability of fast computing through desktop computers and parallel processing methods, it is

now possible to use the weather prediction models at high resolutions (about 10-30 km), but still not sufficient to resolve the convection explicitly (~ 1 km). Due to these reasons, the sub-grid scale processes of convection (non-resolvable) and the PBL processes are parameterized to define their interaction with grid-resolvable prognostic variables.

Tropical cyclone predictions in different countries are being operationally provided by the relevant national meteorological agencies (Iwasaki *et al.*, 1987; Mathur, 1991; Puri *et al.*, 1992; Chen *et al.*, 1995; Kurihara *et al.*, 1993, 1995). For the Indian region, the India Meteorological Department (IMD) issues forecasts of the tropical cyclones over north Indian Ocean using limited area models and with assimilation of synthetic observations (Prasad and Rama Rao, 2003). Mandal (1991) provides a good account of the forecasting methods for the prediction of tropical cyclones in the north Indian ocean region and continuous attempts are being made towards the development and application of numerical models for this purpose (Sikka, 1975; Ramanathan and Bansal, 1977; Singh and Saha, 1978; Prasad *et al.*, 1997; Prasad and Rama Rao, 2003).

NCAR MM5 is being used for tropical cyclone studies by many researchers. Liu *et al.* (1997) gives a comprehensive review of the simulation of the tropical cyclones. Their study reports the simulation of the track, storm intensity and the inner core structure of the hurricane Andrew-1992 using NCAR MM5 with triple nested grid and at a resolution of 6 km. Braun and Tao (2000) used NCAR MM5 to study the sensitivity of tropical cyclone intensification to the PBL parameterisation and reported that Burk-Thompson and Bulk Aerodynamic schemes of the PBL produced the strongest tropical cyclone where as the MRF scheme produced the weakest storm. Davis and Bosart (2001) simulated the genesis of hurricane Diana-1984 using NCAR MM5 and reported that model physics plays an important role during the transformation from marginal storm to hurricane intensity than from mesoscale vortex to marginal storm strength. Wang (2002) studied the sensitivity of tropical cyclone development to cloud microphysics using a triple nested movable mesh hydrostatic model. The study with three cloud microphysics schemes of warm rain, and two mixed ice-phase schemes, one with graupel and other with hail indicate that the intensification rate and final intensity are not sensible to cloud microphysics but only produce differences in the cloud structure. Braun (2002) simulated hurricane BOB-1991 using NCAR MM5 with the four nested domains and with 1.3 km resolution of the inner most domain to simulate the asymmetrical structure of eye and eye wall. Mohanty *et al.* (2004) simulated the Orissa

Super Cyclone using NCAR MM5 with a horizontal resolution of 30 km and with analysis nudging for 12 hr prior to the model integration starting at 0000 UTC of 26 October 1999. The results of this study indicate that the model could predict the intensity of the storm up to 48 hr, but as underestimated between 48 hr and 72 hr. The study also reports delayed landfall which is reflected as overestimation of the intensity. Rao and Bhaskarrao (2003) attempted to simulate the Orissa super cyclone using NCAR MM5 with the options of Grell, MRF and simple ice for the parameterisation schemes of convection, planetary boundary layer and explicit moisture. Their study reports a good simulation of the Orissa super cyclone but with an underestimate of cyclone intensity. Trivedi *et al.* (2002) reported the improvement of track prediction and the characteristics of Orissa super cyclone due to the assimilation of synthetic vortex in the initial analysis. Yang and Ching (2005) simulated Typhoon Toraji - 2001 using NCAR MM5 and studied the sensitivity to different parameterisation schemes. Their study indicates Grell convection scheme and Goddard Graupel cloud microphysics scheme gives the best track; where as the warm rain scheme gives the lowest central surface pressure and MRF planetary boundary layer simulates the track and intensity agreeing with the observations. They have also indicated that the ensemble mean rainfall with the 15 experiments is close to the observations than individual experiments. Ensemble and super ensemble approaches for cyclone track prediction are reported to reduce the errors in the forecasts (Zhang and Krishnamurti, 1997; Vijaya Kumar and Krishnamurti, 2003).

In this study, an attempt has been made to simulate the movement of Orissa super cyclone using NCAR MM5, a high resolution mesoscale model. A case study of Orissa super cyclone is chosen as it is the most intense cyclone of the past century and caused enormous damage and destruction to the coastal regions of the Orissa state. A brief description of the Orissa cyclone is given in section 2 followed by the details of the model in section 3; initial and boundary conditions in section 4 and the description of the experiments and results in section 5.

## 2. Description of Orissa Super Cyclone (1999)

The Orissa Super Cyclone (OSC-99), as referred by the IMD, is the most intense cyclonic storm experienced over Bay of Bengal since the false point cyclone of 1885, with an estimated minimum central sea level pressure of 912 hPa and associated maximum wind of 140 knots. This storm had its genesis over the Gulf of Thailand, located as a low-pressure area on 24 October 1999. This low pressure moved westwards and was identified as a well-marked low pressure over north Andaman Sea at

0000 UTC of 25 October and was later identified as a depression at 1200 UTC of 25 October. The depression then moved in westnorthwesterly direction and was reported as cyclonic storm at 0300 UTC of 26 October and then as a severe cyclonic storm at 0300 UTC of 27 October. It continued to move in northwesterly direction attaining the stage of very severe cyclonic storm with hurricane intensity at 1500 UTC of 27 October. Satellite imagery show clear eye formation at 0300 UTC of 28 October, indicating its hurricane force intensity. The system continued to intensify and move west northwesterly and attaining the intensity of super cyclonic storm at 1500 UTC of 28 October. Rapid intensification of the storm with an estimated fall of the central surface pressure of 60 hPa, between 0600 UTC and 1800 UTC of 28 October indicate rapid development. At this stage the lowest central surface pressure was estimated as 912 hPa with an associated maximum wind speed of 140 knots. The cyclone had its landfall near Paradip ( $20.5^{\circ}$  N,  $86^{\circ}$  E) on the east coast of India between 0430 UTC and 0530 UTC on 29 October. Satellite observations indicate slight weakening of the cyclone just before landfall and continued to loose its intensity rapidly after the landfall to the stage of cyclonic storm at 0300 UTC of 30 October and depression at 0300 UTC of 31 October 1999. After crossing the coast, the system moved northeasterly during 1200 UTC of 29 October and 0300 UTC of 30 October and then southeasterly between 0300 UTC of 30 October and 0300 UTC of 31 October. In some analysis (Kalsi 2005 in this volume) the storm is thought to have remained stationary between 29 to 31 October, 1999. Heavy rainfall was recorded along the Orissa coast with reports of 53, 25, 22, 25, 43, 18 and 25 cm at Paradip, Chandbali, Balasore, Cuttack, Bhubaneswar, Puri and Gopalpur respectively on 30 October and rainfall of 26, 36, 10, 12 and 15 cm at Paradip, Chandbali, Bhubaneswar, Puri and Gopalpur respectively on 31 October. A storm surge estimated to vary between 6-9 m caused enormous damage inundating the coastal regions. At the end, the Orissa super cyclone caused extensive damage and destruction with a loss of life of 10,000 people and perished lives stock of 450,000, damage to 200,000 hectares of crop area etc.

## 3. Model

NCAR MM5, a non- hydrostatic primitive equation model, developed by Pennsylvania State University (PSU)/ National Center for Atmospheric Research (NCAR) is used in the present study. A detailed description of the NCAR MM5 is given by Grell *et al.* (1994). This model has versatility to choose the domain region of interest; horizontal resolution; interacting nested domains and with various options to choose parameterisation schemes for convection, planetary

TABLE 1

Details of NCAR MM5 model

Model Name	PSU/ NCAR MM5 V3.6		
Model type	Primitive equation, Non- hydrostatic		
Vertical resolution	23 sigma levels		
Horizontal resolution	90 km	30 km	10 km
Domain of integration	64. 1668° E – 103.832° E 4. 16439° S – 31. 3731° N	77.6588° E – 98.4334° E 4. 46226° N – 26. 6558° N	80. 2672° E- 93. 932° E 9.1942° N - 24.055° N
Radiation scheme	Dudhia scheme for short wave radiation Rapid Radiative Transfer Model for long wave radiation		
Surface scheme	OSU/Eta Land- Surface Model		
Sea surface temperature	Real sea surface temperatures		
Convection scheme	Anthes-Kuo (AK); Grell (GR); Betts - Miller (BM); Kain - Fritsch 1 (KF1), Kain - Fritsch 2 (KF2)		
PBL scheme	Medium Resolution Forecast (MRF); Mellor -Yamada (MY); Blackadar (BL); Pleim - Xiu (PX)		
Explicit moisture scheme	Warm Rain (WR); Simple Ice (SI), Mixed Phase (MP); Goddard Microphysics (GM)		

boundary layer (PBL), explicit moisture; radiation and soil processes. For the present study, the model is designed to have three interactive nested domains with horizontal resolutions at 90, 30 and 10 km covering the Bay of Bengal and neighborhood as shown in Fig. 1. Different sensitivity experiments have been conducted to simulate the development stages of the Orissa super cyclone. The details of the options used in this study are given in Table 1. For all these experiments, the model is integrated for 120 hours starting from 0000 UTC of 25 October 1999.

#### 4. Data

The initial conditions for the three model domains have been interpolated from NCEP FNL data available at  $1^\circ \times 1^\circ$  resolution corresponding to 0000 UTC of 25 October 1999. The model topography for the 90, 30 and 10 km domain regions are obtained from the USGS topography data at  $30'$ ,  $10'$  and  $5'$  resolutions.

The time varying lateral boundary conditions are derived at every 12 hr interval during the period 0000 UTC of 25 October 1999 to 0000 UTC of 30 October 1999 from NCEP FNL analysis. The time varying SST data are also prescribed at 12 hr interval taken from NCEP data interpolated for the three model domains.

The intensity and the position of the Orissa super cyclone are taken from the reports on the India Meteorological Department (2000) for comparison with

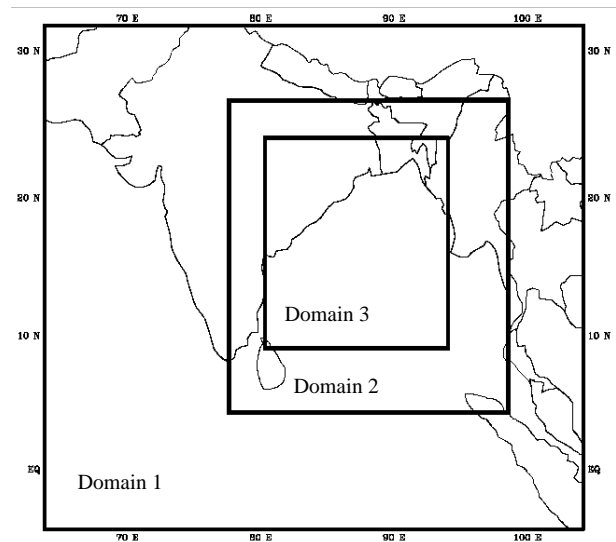
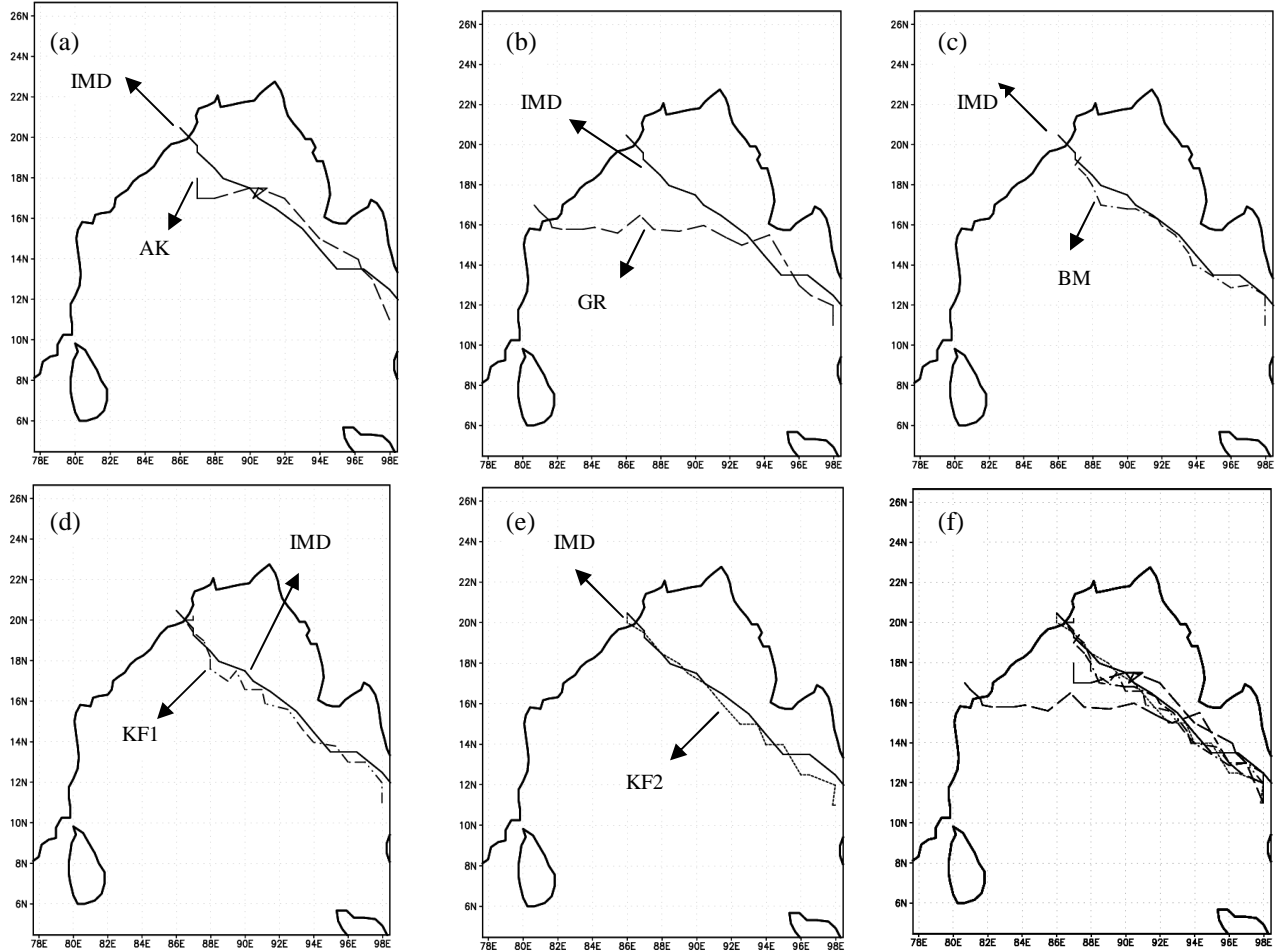


Fig. 1. Model domains with 90, 30 and 10 km resolutions

the model results. The observations of rainfall recorded at the coastal stations are collected from IMD reports for comparison with model derived rainfall.

#### 5. Results

In this study several model prediction experiments of the OSC-99 were carried out using NCAR MM5 with



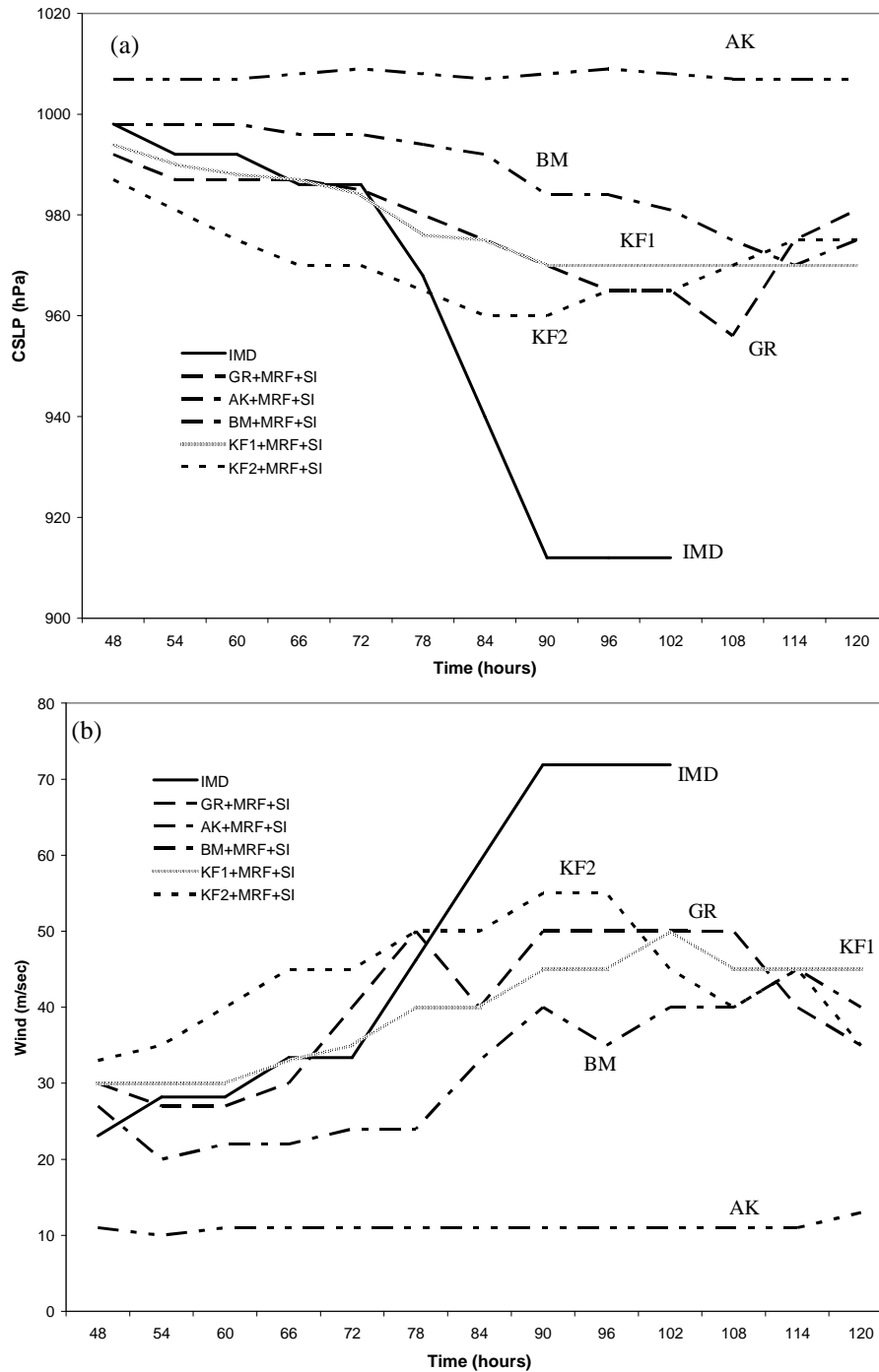
**Figs. 2(a-f).** Model simulated track positions of the Orissa super cyclone along with the IMD observations for the experiments with different convection schemes of (a) Anthes-Kuo (b) Grell (c) Betts-Miller (d) Kain-Fritsch 1 (e) Kain-Fritsch 2 and (f) All together in combination with MRF and simple Ice schemes for PBL and explicit moisture

three nested domains of horizontal resolution at 90, 30 and 10 km. The experiments were categorized in to three groups, choosing different parameterisation schemes of convection, planetary boundary layer and explicit moisture processes to study their role in the movement and intensification of the OSC-99 under study. Though model results are available for the three domains, model predicted track positions are shown and discussed for the 30 km domain only, whereas the model intensity estimates are presented for the 10 km domain. This is due to the stronger intensity with the 10 km domain, which covers the passage of the OSC-99 only from 0000 UTC of 27 October and that the track positions from 30 and 10 km domains are almost the same.

#### 5.1. Sensitivity experiments with convection schemes

In this group, five experiments were performed with the variation of the parameterisation scheme for

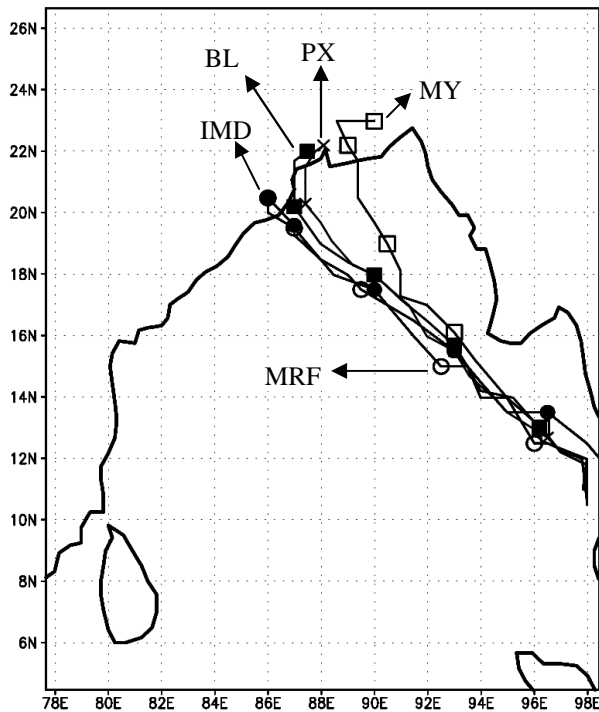
convection as Anthes-Kuo (AK), Grell (GR), Betts-Miller (BM), Kain-Fritsch 1 (KF1) and Kain-Fritsch 2 (KF2) in combination with Medium Range Forecast (MRF) scheme for PBL and Simple Ice (SI) for explicit moisture processes. The model predicted track positions are presented individually for each of the experiments [Figs. 2(a-e)] and together [Fig. 2(f)] to facilitate the evaluation. The results indicate that the experiments with AK [Fig. 2(a)] give the worst simulation, considering both the estimates of intensity and track errors. The scheme of GR [Fig. 2(b)] provides reasonable estimates of the track positions up to 48 hours (*i.e.*, 0000 UTC of 27 October) and the error increases thereafter. The BM scheme [Fig. 2(c)] gives good track position agreeing with the observations, but with an underestimation of the cyclone motion. The schemes of KF1 [Fig. 2(d)] and KF2 [Fig. 2(e)] give very good estimate of the track position agreeing with the observations. Though 24 hr prediction errors are higher in these schemes, the error reduces from 48 hr to 120 hr, particularly in KF2 scheme. It is difficult



**Figs. 3(a&b).** Time variation of model simulated (a) central sea level pressure (hPa) and (b) maximum wind ( $\text{msec}^{-1}$ ) for the experiments with different convection schemes in combination with MRF and simple Ice schemes for PBL and explicit moisture processes along with IMD estimates

to assess at this stage, from a single case study, the probable reasons for this drastic reduction in error from 24 hr to 120 hr forecast with KF2 scheme. These results indicate that the movement of the tropical cyclone is sensitive to the convective processes and that the Kain-

Fritsch2 scheme gives the best representation based on this single study. The time variation of the CSLP and maximum wind for this group of experiments are shown in Fig. 3. As noted earlier, these results correspond to 10 km resolution and are presented from 0000 UTC of 27

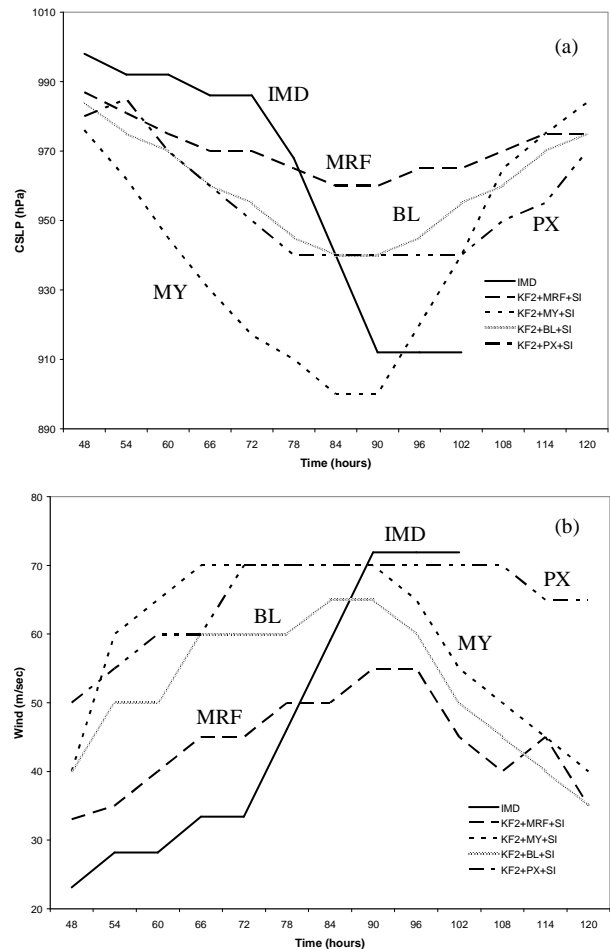


**Fig. 4.** Model simulated track positions of the Orissa super cyclone for the experiments with different PBL schemes in combination with KF2 and simple Ice schemes for convection and explicit moisture processes along with IMD estimates

October to 0000 UTC of 30 October. The results indicate that the schemes of KF2 and GR give a minimum CSLP of 960 hPa where as KF1 and BM gives 970 hPa and AK scheme does not show any intensification. Correspondingly the attained maximum wind speeds are 55 m sec<sup>-1</sup> with KF2; 50 m sec<sup>-1</sup> with GR and KF1 and about 45 m sec<sup>-1</sup> with BM. Though KF2 and GR seem to yield the same intensity, KF2 performs better as the time occurrence of the minimum CSLP and maximum wind occurs at about 90 hr coinciding with the observations, where as GR experiment attains the maximum intensity at 108 hr (*i.e.*, with a lag of 18 hr). In any case the intensity predicted falls short of the observed intensity by 50 to 60 hPa even with KF2 and GR and KF1 and BM. Perhaps the intensity simulated may correspond better with the observed if the resolution is further reduced below 10 km.

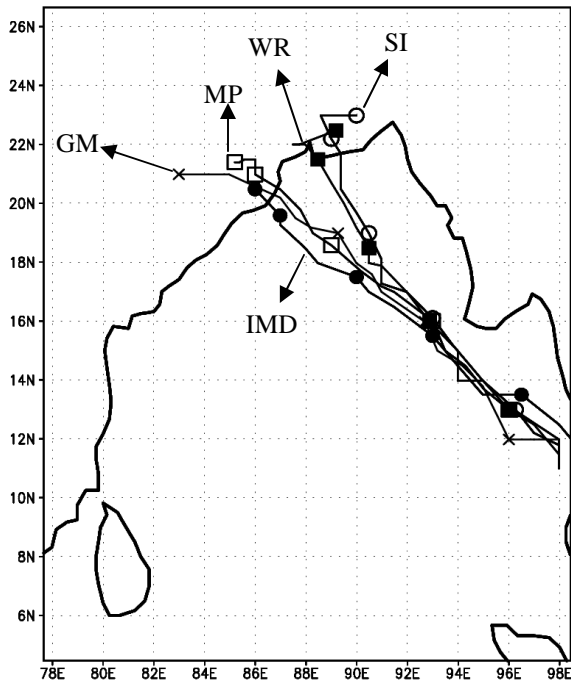
**5.2. Sensitivity experiments with PBL schemes**

As per the results noted in the previous section, KF2 convection scheme gave the best prediction of the track and the attained intensity. So the second group of experiments was carried out with KF2 and SI for the convection and explicit moisture processes and with the choice of four PBL schemes as of MRF, Blackadar (BL),



**Figs. 5(a&b).** Time variation of model simulated (a) central sea level pressure (hPa) and (b) maximum wind (m sec<sup>-1</sup>) for the experiments with different PBL schemes in combination with KF2 and simple Ice schemes for convection and explicit moisture processes along with IMD estimates

Mellor-Yamada (MY) and Pleim-Xiu (PX). The predicted track positions from these four experiments along with IMD observations are presented in Fig. 4. It is noted that all the four experiments give good prediction of the track up to 48 hr and with increasing errors there after. Specifically, MRF provides the least track error up to 120 hr and MY provides the worst error beyond 48 hr.; BL and PX slightly deviating to the right of the observations and with an error range of 50-200 km from 48 to 120 hr. MY gives good track prediction up to 48 hr, later with deviation farther to the right of observations and gradual increasing to an error of 300 km at 120 hours. The model predicted CSLP and maximum wind from 0000 UTC of 27 October (48 hr) to 0000 UTC of 30 October (120 hr) are presented in Figs. 5(a&b). The distribution of the CSLP indicate that MY scheme gives the maximum storm intensification with a CSLP of 900 hPa attained at

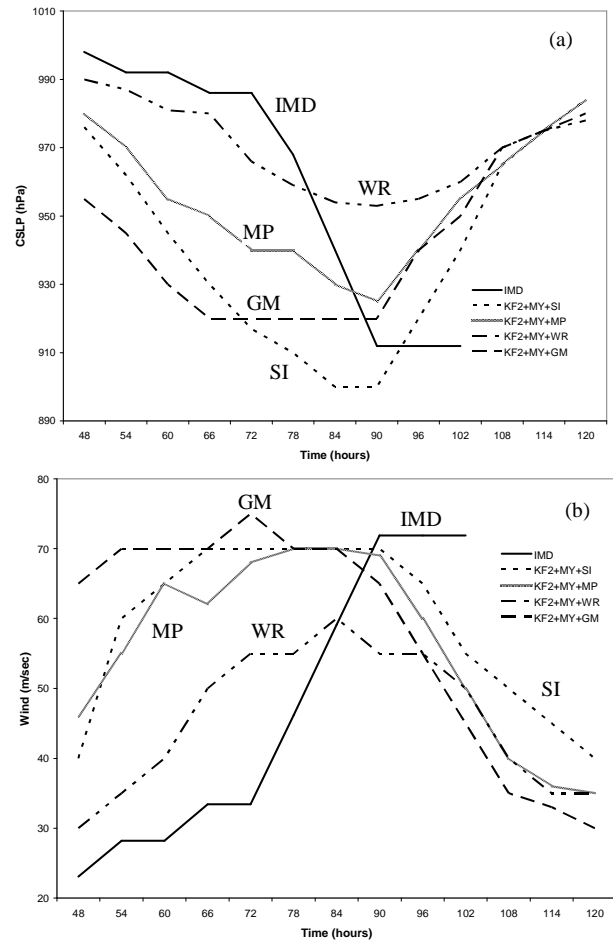


**Fig. 6.** Model simulated track positions of the Orissa super cyclone for the experiments with different explicit moisture schemes in combination with KF2 and Mellor-Yamada schemes for convection and PBL processes along with IMD estimates

around 84 hr. Contrastingly the schemes of BL and PX give a CSLP of 940 hPa, where as MRF gives only 965 hPa. All the four schemes give the maximum intensity 6 hr earlier than the observations. The distribution of the maximum attained wind show  $70 \text{ m sec}^{-1}$  for MY and PX;  $65 \text{ m sec}^{-1}$  for BL and  $55 \text{ m sec}^{-1}$  for MRF. The schemes of MY, PX and BL produce early intensification ahead of 24, 30 and 12 hr; where as MRF prediction coincides with IMD observations. These results indicate that the combination with MRF scheme gives the best track but with large underestimation of the intensification, where as MY scheme gives good prediction of the intensification but with larger error in track prediction during 48-120 hours than of MRF scheme. It is also to be noted that PX scheme gives maximum wind of  $70 \text{ m sec}^{-1}$  associated with 950 hPa which may indicate model storm quite smaller than the observation.

### 5.3. Sensitivity experiments with explicit moisture schemes

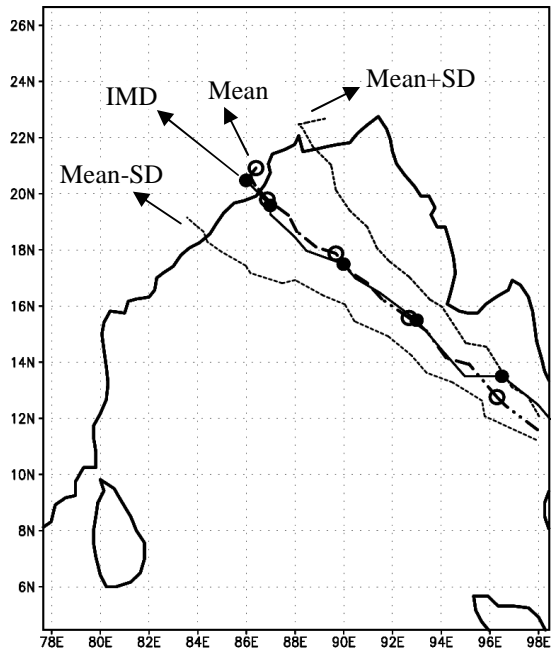
It was inferred, from the results discussed in the previous two sections, that the combination of KF2 scheme for convection and MY for PBL produce the best simulation for the OSC-99. So four simulation



**Figs. 7(a&b).** Time variation of model simulated (a) central sea level pressure (hPa) and (b) maximum wind ( $\text{msec}^{-1}$ ) for the experiments with different explicit moisture schemes in combination with KF2 and Mellor-Yamada schemes for convection and PBL processes along with IMD estimates

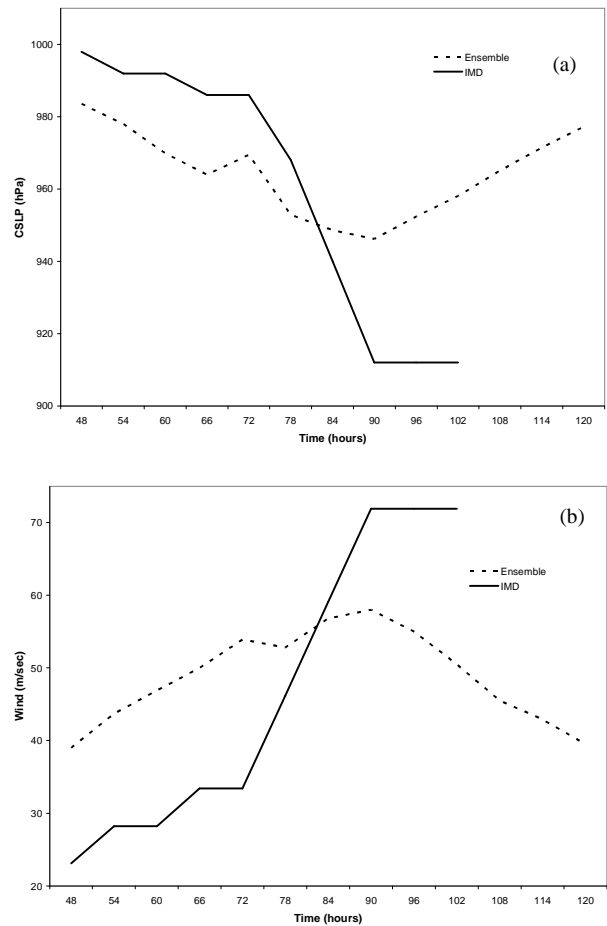
experiments were performed with the options for explicit moisture processes as SI, Warm rain (WR), Mixed-Phase (MP) and Goddard Microphysics (GM) along with KF2 and MY. The model simulated track positions are shown in Fig. 6 along with the IMD estimates. It is noted that, though the initial positions of the model and observations are slightly different, the track positions are predicted well from 24 – 60 hr and the errors gradually increase there after. The combination with MP scheme gives the best simulation where as GM overestimates the cyclone motion and the schemes of WR and SI have larger errors than of MP. The time variation of CSLP and maximum wind are shown in Figs. 7(a&b). As noted earlier the combination with SI produces the strongest cyclone with CSLP of 900 hPa where as GM produces slightly weaker than SI. However the time of attainment of the maximum intensity





**Fig. 8.** Ensemble mean values of the model simulated track positions (along with  $\pm$  SD) and along with IMD estimates

occurs earlier than the observations, a head of 6 hr for SI scheme and 24 hr for GM scheme. MP also gives an intense storm with CSLP of 925 hPa where as WR produces the weakest storm with a CSLP of 950 hPa and these two schemes have the time of maximum intensity coinciding with the observations. The time variation of the maximum wind show features consistent with CSLP variation. The maximum wind obtained by the different schemes is  $75 \text{ msec}^{-1}$  by GM;  $70 \text{ msec}^{-1}$  by MP and SI schemes and  $60 \text{ msec}^{-1}$  by WR scheme. The GM scheme produces the maximum much earlier than the observations where as the schemes of MP, SI and WR have the occurrence of the maximum agreeing with the observations. These results indicate that explicit moisture processes modulates the intensification through the PBL processes which may be due to the fine resolution of 10 km for the innermost domain. It may also be inferred from the above discussion that the combination of KF2 for convection, MY for PBL and MP for explicit moisture produce the best track where as the schemes of GM, MP and SI support stronger intensification than WR. It is difficult to conclude the reasons for the best tracks from experiments with GM and MP based on only one case study. It can however be inferred that the explicit moisture schemes of GM and MP contribute to modulate the cyclone movement in combination with the KF2 convection scheme with the resolution as 10 km. Some experiments with higher resolution of less than 5 km may indicate the specific role of explicit moisture processes. Also many such experiments are needed to bring out



**Figs. 9(a&b).** Ensemble mean values of the model simulated (a) central sea level pressure (hPa) and (b) maximum wind along with IMD estimates

statistically (if at all) the best combination of different schemes for producing optimum track and intensity predictions.

#### 5.4. Ensemble experiment

The results presented in the previous three sections show the sensitivity of the cyclone track model prediction to different schemes of convection, PBL and explicit moisture processes. Keeping in view of the dispersive nature of the predicted track, a simple ensemble mean of the track positions at different time points are computed (excluding Anthes- Kuo experiment) and are shown in Fig. 8. The ensemble mean produces a very good prediction for this case study with almost an identical track from 24 – 120 hr. These results seem to support the use of ensemble method for improvement in track predictions. The ensemble mean of CSLP and maximum wind are presented in Figs. 9(a&b). It is noted that the

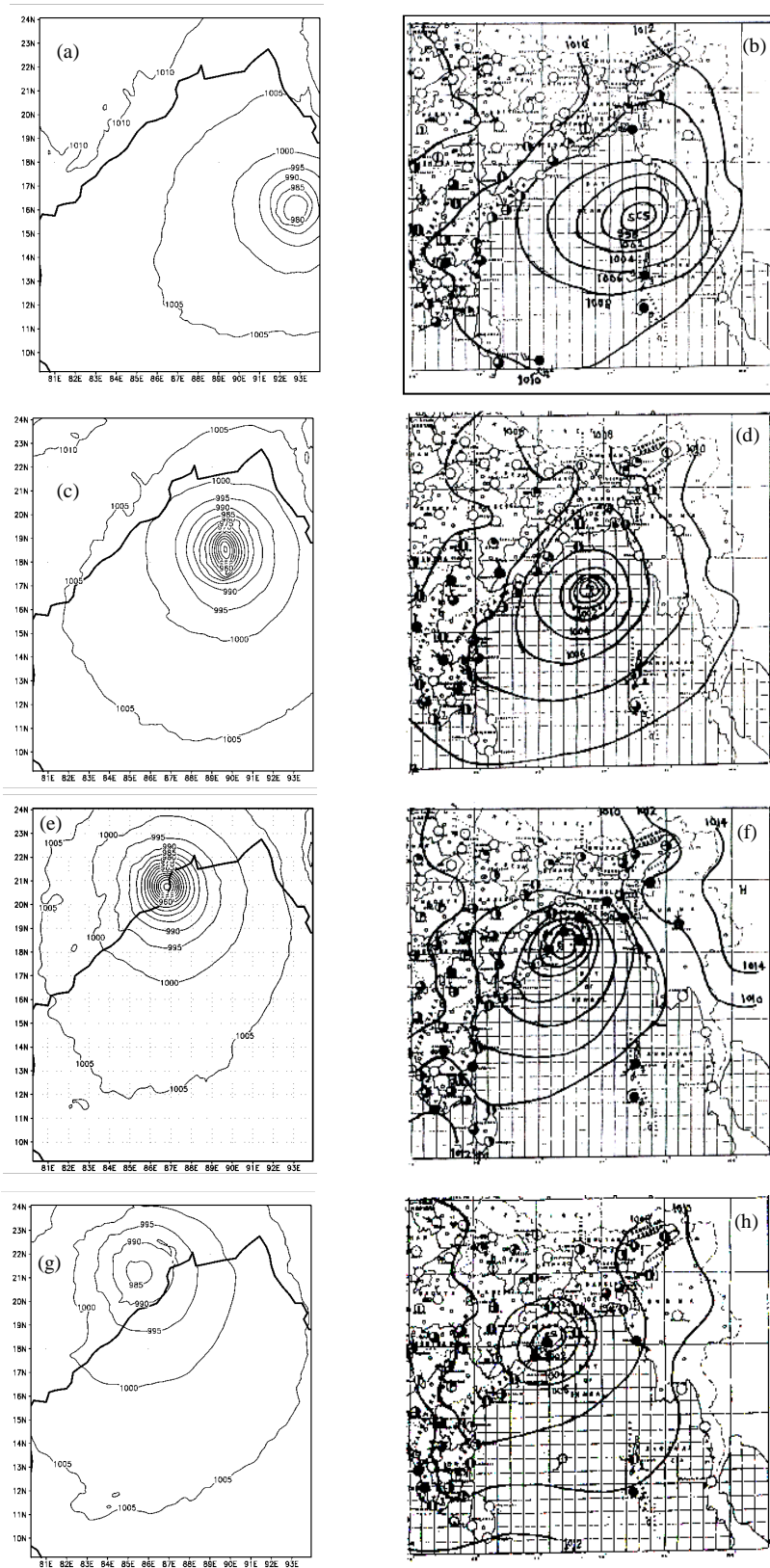
**TABLE 2**  
**Errors of track positions (km) for different sensitivity experiments**

	Hours (Valid on dates at 0000 UTC)				
	24 (26 Oct)	48 (27 Oct)	72 (28 Oct)	96 (29 Oct)	120 (30 Oct)
<b>Sensitivity of convection schemes with MRF and SI combination</b>					
Convection scheme					
AK	64	352	0	333	404
GR	7	176	372	607	894
BM	200	188	240	209	191
KF1	78	56	55	94	116
KF2	124	78	55	11	0
<b>Sensitivity of PBL schemes with KF2 and SI combination</b>					
PBL schemes					
MRF	124	78	55	11	0
MY	59	66	175	364	523
BL	64	22	55	433	235
PX	89	0	55	89	188
<b>Sensitivity of explicit moisture schemes with KF2 and MY combination</b>					
Explicit moisture scheme					
SI	59	66	175	364	523
MP	78	55	149	190	134
WR	78	56	124	269	397
GM	78	78	184	157	337
Ensemble mean	73	37	55	42	153

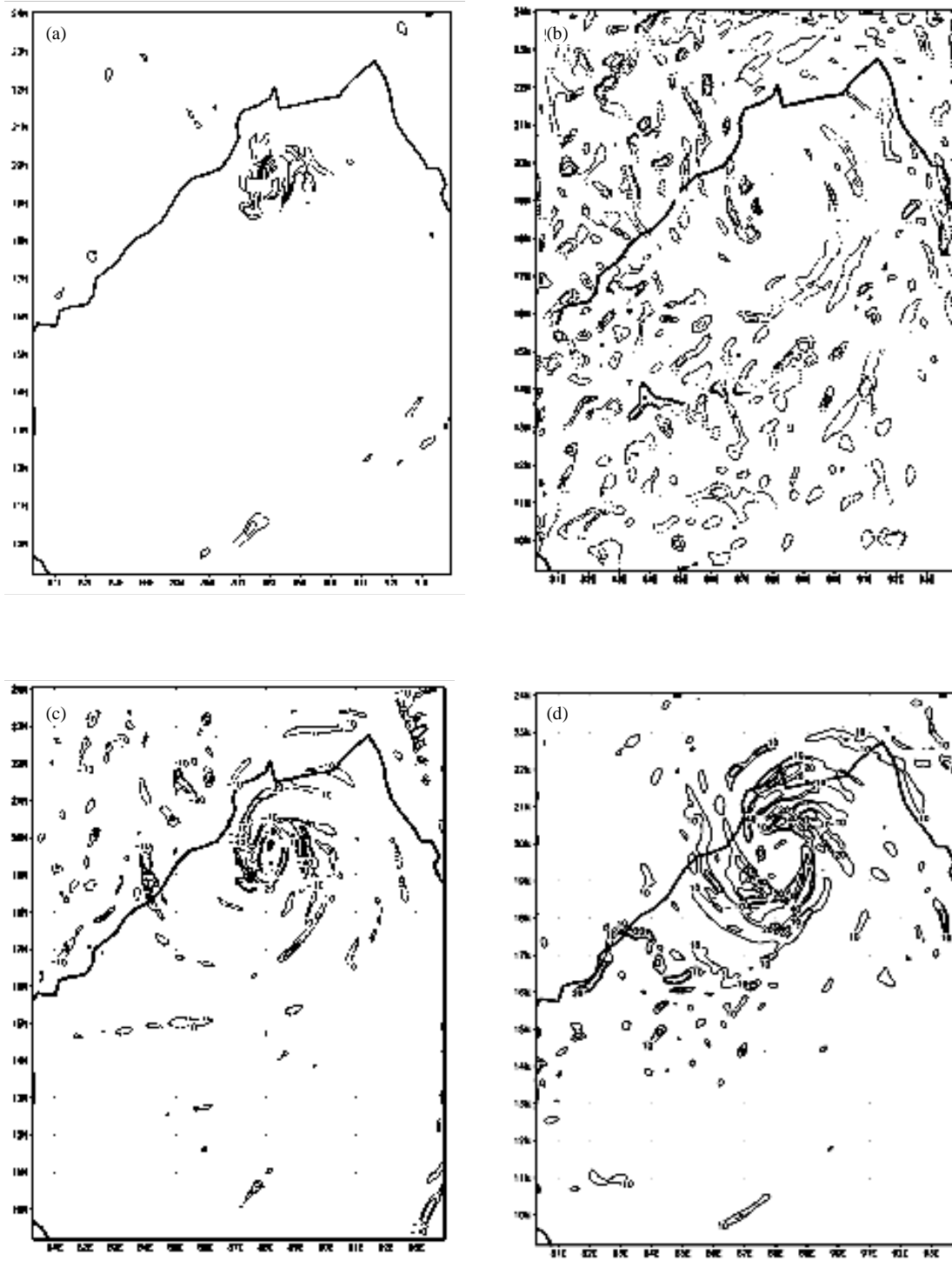
ensemble mean produces a strong cyclonic storm with a CSLP of 945 hPa and maximum wind of 55 msec<sup>-1</sup>. The ensemble mean estimates of the CSLP and maximum wind have an error of 33 hPa and 15 m/sec respectively, which are better than majority of the experiments. The ensemble mean can never be superior to all the experiments as it minimises the error due to dispersion of different experiments as some not so good forecast cancel out with some excellent forecast. Though the ensemble average is an underestimate of the observed intensity, the time of attainment of the maximum intensity coincides with the observations. For operational purpose to make an ensemble average based on different combinations, each experiment is to be run individually which would need huge computing resource as the forecast has to be issued within certain time slots. There is also a possibility that the prediction may be sensitive to initial conditions too, which aspect has not been examined in this study though it is quite important.

### 5.5. Errors in track prediction

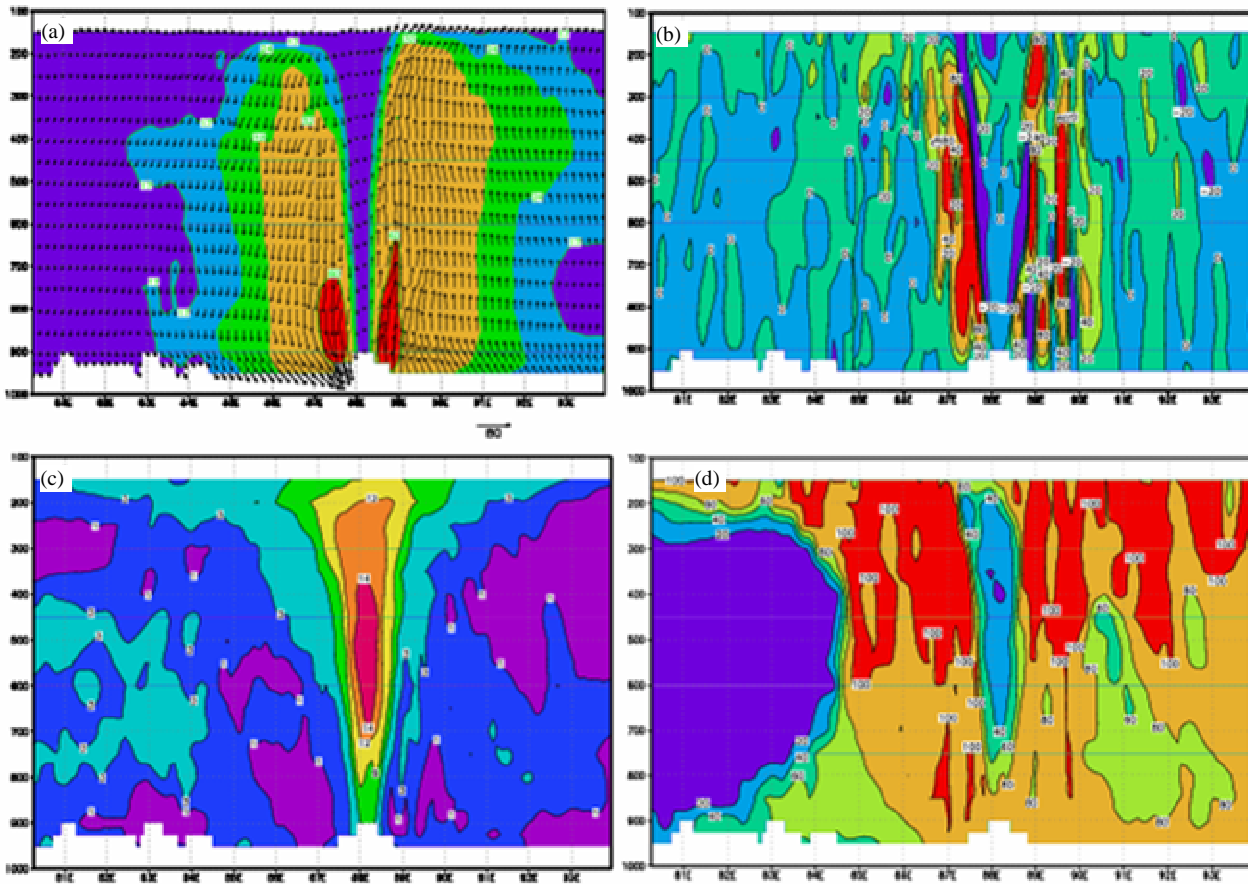
The vector errors of the model simulated cyclone for different experiments conducted in this study are computed and presented in Table 2. It is to be noted, from the sensitivity experiments with different convection schemes that KF1 and KF2 schemes have the smallest error varying from 50 to 120 km and KF2 scheme has smaller error than KF1. BM scheme follows with error varying from 180 – 250 km where as GR has errors increasing from 150 to 900 km. AK scheme does not produce intensification of the cyclone and with an erratic track prediction. The track produced with this scheme shows faster movement than the observations during the 24 – 48 hour period, with an error of 352 km at 48 hours and then slowing down with stationary position up to 72 hours and then retarded motion. The zero error noted at 72 hours should not be mistaken for a good prediction as it is due to the stationary position and looping of the cyclone



**Figs. 10(a-h).** Distribution of sea level pressure. Left panel shows model predicted fields and right panel shows IMD charts at 0300 UTC of 27 October (a,b); 28 October (c,d); 29 October (e, f) and 30 October 1999 (g, h)



**Figs. 11(a-d).** Model derived vorticity and divergence fields ( $10^{-5} \text{ sec}^{-1}$ ) at 1200 UTC of 28 October 1999. (a) Low level (850 hPa) cyclonic vorticity (b) Upper level (150 hPa) anticyclonic vorticity (c) Low level (850 hPa) convergence and (d) Upper level (150 hPa) divergence



**Figs. 12(a-d).** Vertical section along 19.5° N at 1200 UTC of 28 October 1999 of (a) wind ( $\text{m sec}^{-1}$ ) (b) temperature anomaly ( $^{\circ}\text{C}$ ) (c) vertical velocity ( $\text{cm sec}^{-1}$ ) and (d) relative humidity (%)

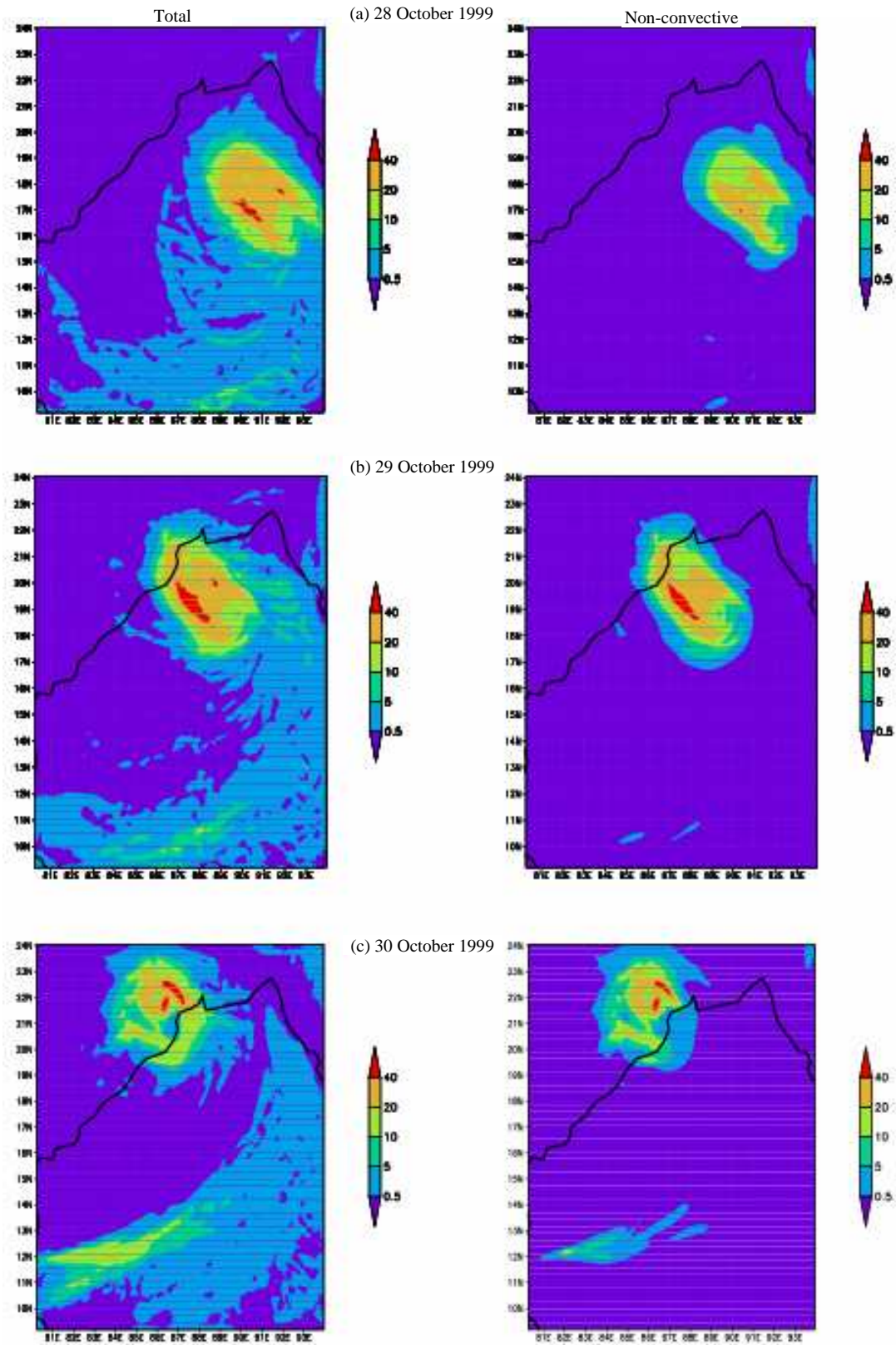
from 48 to 72 hours. The errors corresponding to the second group of experiments *i.e.*, with different PBL schemes indicate that MRF has the smallest errors ranging from 0-124 km; followed by PX with error of 0-188 km; BL with 22-433 km and MY with 59-523 km. These numbers indicate that MY has good prediction up to 48 hr but with increasing errors there after. The third set of experiments with different explicit moisture schemes show that the combination of KF2, MY and MP show the best track with errors of 50 to 190 km.

It is of interest to note that all the four schemes for explicit moisture, in combination with KF2 and MY show very good prediction up to 48 hr with an error of 50-80 km only. Beyond 48 hr, MP scheme gives the best prediction followed by GM; WR and SI respectively. Though the combination of KF1, MRF and SI seem to have slightly smaller track errors than KF2, MY and MP, the model intensification is better with the later combination. These results indicate that the combination

of KF2, MY and MP have smaller errors than any other combination established through the consideration of model predicted track and intensity.

In view of the result that KF2+MRF+SI has smaller track errors, for this case study, than the experiments with KF2 + MY + MP but with less attained intensity, another experiment was carried out with the combination of KF2 + MRF + MP. The results (not shown) of this experiment indicate that the track errors are more than of KF2 + MRF + SI but with little change in the attained intensity. Considering these results, it is concluded that KF2 + MY + MP seem to produce the best simulation amongst all the performed experiments for this case study. Many such experiments are needed to produce statistically the best combination of schemes.

The ensemble mean produces the best track positions with errors in the range of 30-150 km, less than any individual experiment.



Figs. 13(a-c). The model simulated total precipitation (left panel) and non-convective precipitation (right panel) in cm/day corresponding to 0000 UTC of 28 October (b) 29 October and (c) 30 October 1999



### 5.6. Characteristics of the model simulated cyclone

For the experiment with the combination of KF2, MY and MP schemes, the development of the cyclone as predicted by the model and its structure at the mature stage are analysed and presented.

The model simulated CSLP distribution at 0300 UTC of 27, 28, 29 and 30 October along with IMD analysis are presented in Figs. 10(a&b). It is noted that the model produces the development of the low pressure system at 0000 UTC of 25 October (not shown), into a severe cyclonic storm at 0300 UTC of 27 October with CSLP of 975 hPa. IMD reports indicate a severe cyclonic storm with estimated CSLP of 990 hPa. The simulated location of the storm is to the northeast of the IMD estimates at a distance of 104 km. At 0300 UTC of 28 October, the model simulated a very severe cyclonic storm with a CSLP of 940 hPa and maximum wind of  $65 \text{ msec}^{-1}$ . Correspondingly IMD also identifies the system as a very severe cyclonic storm with estimated CSLP of 978 hPa and maximum wind of  $38 \text{ msec}^{-1}$ . The location of the model storm is slightly north of IMD estimate. At 0300 UTC of 29 October, the model simulation shows that the cyclonic storm just crossed the coast with its center at  $20.8^\circ \text{ N}$ ,  $86.5^\circ \text{ E}$  where as IMD analyses indicate its position right on the coast at  $19.9^\circ \text{ N}$ ,  $86.7^\circ \text{ E}$  indicating an error of about 102 km. The simulated storm still shows a CSLP of 940 hPa and maximum wind of  $60 \text{ msec}^{-1}$ ; where as IMD reports indicate the CSLP of 912 hPa and maximum wind of  $70 \text{ msec}^{-1}$ . The model storm lost its intensity to become a cyclonic storm at 0300 UTC of 30 October, which agrees with the IMD observations. The results indicate that the model could simulate the intensification of the OSC-99, the trend agreeing with the IMD estimates. The model simulates a pressure fall of 55 hPa in 36 hours as compared to 86 hPa from 0000 UTC of 27 October to 1800 UTC of 28 October in the IMD estimates. This is a good simulation within the constraints of model resolution.

The cyclonic/anticyclonic vorticity and the convergence/divergence corresponding to the lower (850 hPa)/ upper (150 hPa) tropospheric levels at 1200 UTC of 28 October are presented in Figs. 11(a-d). The low level cyclonic vorticity Fig. 11(a) shows strong cyclonic circulation concentrated within a radius of 150 km indicating a fully evolved storm. The upper level anticyclonic vorticity Fig. 11(b) shows weak anticyclonic circulation around the region of the low level cyclonic circulation. The low level convergence Fig. 11(c) pattern shows strong spiraling inflow regions towards the center of the storm. Upper level divergent flow indicates Fig. 11(d) outflow regions, concentrated in the forward-right and rear-left quadrants around the region of low level convergence.

The structure of the model simulated cyclone for the experiment with the combination of KF2, MY and MP schemes, at its mature stage *i.e.*, 1200 UTC of 28 October is analysed. The vertical sections of the wind flow; temperature anomaly; vertical wind and relative humidity at the Latitude  $19.5^\circ \text{ N}$  are presented in Figs. 12(a-d). The distribution of the wind flow Fig. 12(a) shows cyclone intensity winds throughout the troposphere within a radius of about 400 km. Super cyclone winds exceeding  $60 \text{ msec}^{-1}$  are found up to about 700 hPa level. The calm region at the center slowly expands upward associated with decreasing intensity of the cyclonic circulation and outflow at higher levels. The temperature anomalies Fig. 12(b) indicate warm core with a maximum heating of  $14^\circ \text{ C}$  in the 700-400 hPa layer. The region of warming also slowly expands outward at higher levels. The distribution of the vertical velocities Fig. 12(c) shows downward motion at the center which also expands upward conforming to the wind and temperature distributions. Strong vertical motion is observed within the 30-60 km radius coinciding with the radius of maximum wind. Small regions of downdrafts are observed, which are due to subsidence associated with convection. Beyond the dry region Fig. 12(d) of 50 km radius, highly moist region prevails up to about 400 km radius throughout the troposphere. Saturated atmosphere at higher levels above 600 hPa level shows the outflow region associated with the convection. Strong cyclonic winds throughout the troposphere with the radius of maximum wind at 50 km; warm, dry, subsidence regions at the center; strong upward motion with high humidity expanding upward indicate the distinct characteristics of a mature cyclonic storm.

### 5.7. Model simulated rainfall

The model predicted rainfall computed for the preceding 24 hr period, from the experiment with the combination of KF2, MY and MP schemes, is analysed for 0000 UTC of 28, 29 and 30 October 1999. The total rainfall, sum of the contribution from convective and non-convective processes and for the non-convective rainfall (grid scale condensation) alone are shown separately Figs. 13(a-c) to assess the respective contributions. At 0000 UTC of 28 October, rainfall was observed over north central Bay of Bengal with precipitation exceeding 20 cm/day. It is noted that much of the rainfall associated with the active storm region is contributed by the grid-scale precipitation. Rainfall around the storm region is from the sub-grid scale convective processes. At 0000 UTC of 29 October, the rainfall maximum moved northwest coinciding with the storm motion. Non-convective precipitation contributes to most of the rainfall over the storm region where as sub-grid scale convection contributes in the outer region. On both 28 and 29

October, the precipitation distribution shows northwest-southeast elongation with the rainfall maximum (40 cm/day) located to the left side of the storm motion. At 0000 UTC of 30 October, the precipitation distribution becomes more circular, as the storm crosses the coast. The region of high precipitation reduces in horizontal extent but still with the maximum exceeding 40 cm/day. As observed earlier, non-convective precipitation dominates the storm region where as sub-grid scale precipitation contributes for the meager rainfall in the outer region. It is to be noted that the precipitation maximum (40 cm/day) shifted to the right half of the storm motion, contrary to the trend before the landfall. The model simulated precipitation exceeding 20 cm/day with isolated maxima of 40 cm/day over the regions near the landfall point are comparable with the rainfall observations of 43, 25, 22, 18 and 15 cm/day recorded at Bhubaneswar, Chandbali, Cuttack, Puri and Paradip respectively.

## 6. Summary and conclusions

The present study reports results from numerical prediction experiments of the Orissa Super Cyclone (1999) as sensitive to the parameterisation schemes of convection, planetary boundary layer and explicit moisture. The case study of OSC-99 is chosen as it is the most intense cyclone reported during the past century. The model simulated movement and the development of the OSC-99 during its evolution from a low pressure system to a super cyclone are studied using NCAR MM5. Three sets of experiments have been carried out with varying options of the parameterisation schemes, first for convection, then for PBL and for explicit moisture processes.

The results from sensitivity experiments with different schemes for convection, in combination with MRF for PBL and SI for explicit moisture process, indicate that the movement of the cyclone is quite sensitive to the convection processes. The schemes of KF1 and KF2 produce the best track positions agreeing with the observations. The schemes of KF2 and GR produce the maximum cyclone intensification with CSLP of 960 hPa, better than the other two schemes. These results indicate that KF2 scheme performs better than other convection schemes as evaluated from the track positions and time and strength of maximum attained intensity.

Following the results from the first set of experiments, the second set of experiments was carried out for KF2 scheme for convection, SI for explicit moisture and with different schemes for PBL processes. These results indicate that PBL processes play crucial role in the intensification of the storm. MY scheme produces the maximum intensification with a CSLP of 900 hPa and

maximum wind of  $70 \text{ msec}^{-1}$  followed by BL and PX giving 940 hPa and MRF only 965 hPa. All the four schemes give good track prediction up to 48 hours and MRF scheme gives the better track positions as compared to the other three schemes. These results indicate that MY scheme gives the best intensification though the errors in the track position with MY scheme are slightly more than MRF. Of the PBL schemes, MY produces the maximum intensification, where as MRF shows the weakest, but the intensification starts from the 48 hr itself both for MY and MRF schemes where as the steep fall of pressure occurs from about 72-86 hr in the IMD reports.

The third group of experiments with KF2 scheme for convection, MY for PBL and with different options for explicit moisture processes indicate that the MP scheme gives the best simulation in terms of track as well as intensity. Though SI scheme produces the strongest cyclone the track errors are higher. The experiment with SI produces the strong intensification with the deepening stage from 48 to 84 hr while the rapid intensification taking place 72-86 hrs in the observations and WR produces the worst.

From the above model simulations it is to be noted that different schemes produce different intensification characteristics and that none of the experiments could exactly predict the rapid intensification from 72-86 hrs as of the observations.

A simple ensemble mean of the experiments carried out, excluding Anthes-Kuo, gives a very good estimate of the track positions with errors less than any single experiment. The ensemble mean also produces a strong cyclonic storm with a minimum CSLP of 945 hPa. Though this is a slight underestimation of the observed intensity, the time of attainment coincides with the observations.

The computed errors of the track positions of the different experiments show that the experiments with the combination of KF2+MY+MP and KF1+MRF+SI have the minimum errors in the range of 30-150 km, less than the other experiments.

The model simulated development and the characteristics of the cyclone at the mature stage for the experiment with KF2 for cumulus convection, MY for PBL and SI for explicit moisture is examined. The model simulated development clearly indicates the different stages from depression to the super cyclone. The model could simulate a steep pressure fall of 55 hPa in 36 hours as compared to 86 hPa of the IMD reports. The characteristics of the simulated cyclone agree with those of earlier studies. The model simulates strong low-level



convergence within 150 km radius; upper-level divergence over a wider region; warm core aloft, dry and subsidence motions at the center within the 50 km radius; strong upward motion in the 50-100 km radius throughout the troposphere indicate the distinct characteristics of a mature cyclonic storm.

The model predicted rainfall distribution and intensity agree with the observations. The model could simulate asymmetrical distribution of the rainfall, with maximum exceeding 40 cm/day, located towards the left of the storm track before landfall and towards right after the landfall. Precipitation from cloud resolvable processes contributes for most of the rainfall associated with the cyclone where as sub-grid scale convection contributes in the outer environment.

The results of this study clearly indicate the role of the convection, PBL and explicit moisture processes on the movement and intensification of the tropical cyclone. It may be concluded from these experiments that sub-grid scale and grid scale convective processes modulate the movement of the tropical cyclone and PBL processes are important for the development and intensification. As the model innermost domain has 10 km resolution, grid resolvable convection dominates the rainfall over the active cyclone region where as sub-grid scale convection contributes in the outer environment. Though difficult to conclude from one case study, 10 km resolution seems to be sufficient to resolve the convection inside the cyclone. As expected, the different experiments performed in this study show dispersion of the predicted track. However, ensemble mean seems to be a very good approximation of the best track. As the results of this study are concerned with a single case of the Orissa super cyclone, several case studies of different types of cyclones with different tracks and attained intensities are to be made to arrive at definite conclusions.

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