

The evaluation of Kain-Fritsch scheme in tropical cyclone simulation

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सार — इस अध्ययन में 25–30 अक्टूबर 1999 तक की अवधि में उड़ीसा में आए महाचक्रवातों के मूल्यांकन का प्रतिरूपण करने के लिए कैन फ्रिश् के कपासी प्राचलीकरण योजना के साथ एन. सी. ए. आर. एम. एम. 5 का उपयोग किया गया है। 25 अक्टूबर 1999 के 0000 यू टी सी पर 90, 30 और 10 कि.मी. के द्विपथी आधारित क्षैतिज प्रक्षेत्रों (डोमेन) वाले एन. सी. ए. आर. एम. एम. 5 को 5 दिन की अवधि के लिए समेकित किया गया है। इस अध्ययन के लिए प्रारम्भिक और परिसीमा की स्थितियों को एक अंश के अंतराल पर उपलब्ध हुए एन. सी. ई. पी. एफ. एन. एल. विश्लेषण आँकड़ों से लिया गया है।

यह प्रतिरूपित निदर्श 954 हैक्टापास्कल पर प्राप्त किए गए समुद्र तल के मध्य दाब और 58 मिनट प्रति सेकंड की अधिकतम पवनों के साथ उड़ीसा में आए महाचक्रवात की विकासात्मक स्थितियों को प्रस्तुत करता है। इस निदर्श से अनिवार्य अभिलक्षणों नामतः उष्ण क्रोड, केंद्र और केंद्र भित्ति प्रतिरूपण, हरीकेन क्रोड पवनों को प्राप्त किया गया है। यह निदर्श चक्रवात के स्थल भाग में प्रवेश करने के उपरांत उस स्थल के निकट 40 से.मी. प्रतिदिन की अधिकतम वर्षा का पूर्वानुमान लगा सकता है। यह निदर्श 24 घंटों में 120 कि.मी. त्रुटियों और 120 घंटों में 0 कि.मी. की कमी के साथ महाचक्रवात के पथ का एकदम सही आकलन प्रस्तुत करता है।

ABSTRACT. In this study NCAR MM5 with the cumulus parameterization scheme of Kain-Fritsch is used to simulate the evaluation of Orissa Super Cyclone for the period 25-30 October 1999. The NCAR MM5 with two-way nested horizontal domains of 90, 30 and 10 km are integrated for five days starting from 0000 UTC of 25 October, 1999. The initial and boundary conditions for this study have been taken from NCEP FNL analysis data available at 1° resolution.

The model simulation produces the development of the Orissa Super Cyclone with attained central sea level pressure of 954 hPa and maximum wind of 58 msec⁻¹. The essential characteristics such as warm core, eye and eye-wall simulation, hurricane core winds were obtained by the model. The model could predict a maximum rainfall of 40 cm/day near the landfall point. The model produces a very good estimate of track with errors of 120 km at 24 hours and decreasing to 0 km at 120 hours.

Key words – Cyclone, Convection, Mesoscale, Parameterization, Simulation.

1. Introduction

The physical and dynamical processes in the development and movement of the tropical cyclones are to be understood for better prediction. Direct observations of the tropical cyclones are not easily possible as they form and develop over the oceans and decay soon after the landfall. Despite these limitations, the general structure and the movement of these systems are well understood. However, no two cyclonic systems have the same identical characteristics, which show their variable nature. Reconnaissance flights are the only source of direct observations inside the tropical cyclones, where as remote sensing observations provide valuable information to monitor and help the prediction of individual storms.

The theories of formation of the tropical cyclones indicate the growth of small unstable waves through instability theory. The CISK mechanism proposed by Charney and Eliassen (1964), which is the cooperative interaction of the cumulus scale and cyclonic scale circulations, explains the mechanism of the growth of a small perturbation arising from persistent organised convection in a conditionally unstable environment over a small region to grow and develop in to a mature cyclonic storm under favorable atmospheric conditions. Gray (1968) identified the favorable atmospheric conditions as (i) low level cyclonic vorticity (ii) high mid-tropospheric humidity (iii) conditionally unstable atmosphere (iv) higher sea surface temperatures and (v) low vertical wind shear. The development of the

cyclone seems to be dependent on the combined affect of all these parameters. Quantitative prediction of the weather necessitates the use of numerical models. Mathematical equations of the atmospheric motion aided by suitable numerical methods are the basis of numerical weather prediction. Weather prediction models can be used for the tropical cyclone prediction provided they are designed to resolve the processes which contribute for their development and movement. Since CISK mechanism is important for the growth of the cyclones, numerical models should either resolve the cumulus scale explicitly or incorporate the physical processes through parameterisation. Explicit resolution of the cumulus processes require high horizontal resolution with 1-5 km grid spacing require large computational power. So the numerical models generally used the method of parameterisation of cumulus convection which facilitates horizontal resolutions depending on available computational resources. Different hypothesis were proposed to describe the convective processes. They are mainly based on empirical assumptions (Kuo, 1965, 1974); adjustment schemes (Betts and Miller, 1986) and mass flux schemes (Arakawa and Schubert, 1974; Emanuel, 1991; Kain and Fritsch, 1993, 2004). Simulation of tropical cyclones was attempted using Kuo scheme (Rosenthal, 1970a,b; Sundqvist, 1970a,b; Anthes, 1972); Arakawa and Schubert scheme (Bhaskar Rao and Ashok, 1999); Emanuel scheme (Bhaskar Rao 1997); Betts-Miller (Baik *et al.*, 1990). In the present study the cumulus parameterization scheme proposed by Kain (2004), an improvement of Kain and Fritsch (1993) is used to make a case study of one of the most intense and recent cyclone of north Indian ocean. Tropical cyclone predictions 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). In India, 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 Ramarao, 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 Ramarao, 2003)

Liu *et al.* (1997) gives a comprehensive review of the simulation of the tropical cyclones which 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 sensitive 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.

In this present study three nested domains with resolutions of 90, 30 and 10 km are used such that the innermost 10 km domain covers the region over which the cyclone intensified during the last three days *i.e.*, from 27-29 October, 1999; 30 km middle domain covers the Bay of Bengal region over which the cyclone was first

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	Kain- Fritsch 2 (KF2)		
PBL scheme	Medium Resolution Forecast (MRF)		
Explicit moisture scheme	Simple ice		

identified as a small low pressure system on 25; where as the 90 km outer domain covers large extended region on the four sides of the region of interest so as to simulate the atmospheric flow properly.

A brief description of the Orissa Super Cyclone taken up for this study is described in section 2; the details of the model used in this study are described in section 3; data and methodology are described in section 4 and the results and discussions are presented and discussed in section 5.

2. Description of Orissa Super Cyclone (1999)

The Orissa Super Cyclone, as referred by the India Meteorological Department (IMD), is the most intense cyclonic storm experienced over Bay of Bengal since the false point cyclone of 1885, with an estimated 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 intensity. The system continued to intensify and move westnorthwesterly 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 unusual 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° N, 86° 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. 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, Bhubaneshwar, Puri and Gopalpur respectively on 30 October and rainfall of 26, 36, 10, 12 and 15 cm at Paradip, Chandbali, Bhubaneshwar, Puri and Gopalpur respectively on 31 October. A storm surge of 6-9 m caused enormous damage inundating the coastal regions. At the end, the Orissa super cyclone caused extensive

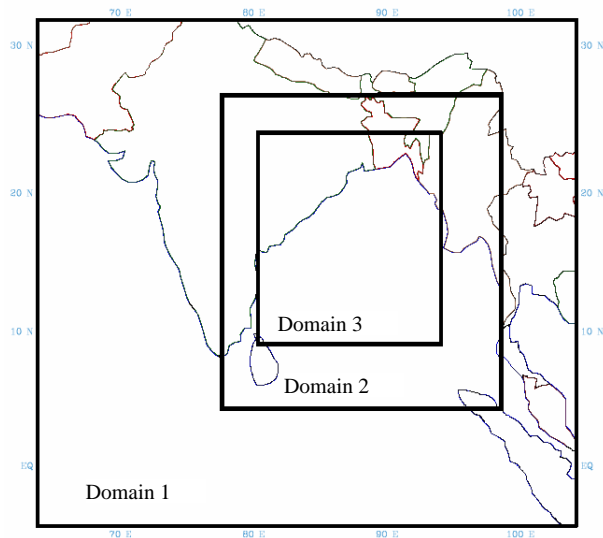


Fig. 1. Model domains with 90, 30 and 10 km resolutions

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 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. The details of the options used in this study are given in Table 1. The model is integrated for 120 hours starting from 0000 UTC of 25 October 1999.

NCAR MM5 provides the option to choose schemes for the physical processes of convection, planetary boundary layer, explicit moisture, radiation and soil structure. As the physical processes of convection, PBL and explicit moisture are important in tropical cyclone simulation, the MRF (Hong and Pan, 1996) scheme for PBL processes and simple ice (Dudhia, 1989) for explicit moisture have been chosen along with Kain-Fritsch scheme for cumulus convection so as to evaluate the performance of Kain-Fritsch scheme in comparison with

previous studies (Rao and Bhaskar Rao, 2003; Mohanty *et al.*, 2004).

4. Data and methodology

The initial conditions for the three model domains have been interpolated from NCEP FNL data available at $1^\circ \times 1^\circ$ degree 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 data. 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 the model results. The rainfall data during 25-30 October, 1999 are collected from Global Precipitation Index (GPI) rainfall data for comparison with model derived rainfall. The data are IR-based rainfall estimates which are an intermediate product of the Global Precipitation Climatology Project which is a WMO/WCRP effort (Janowiak and Arkin, 1991).

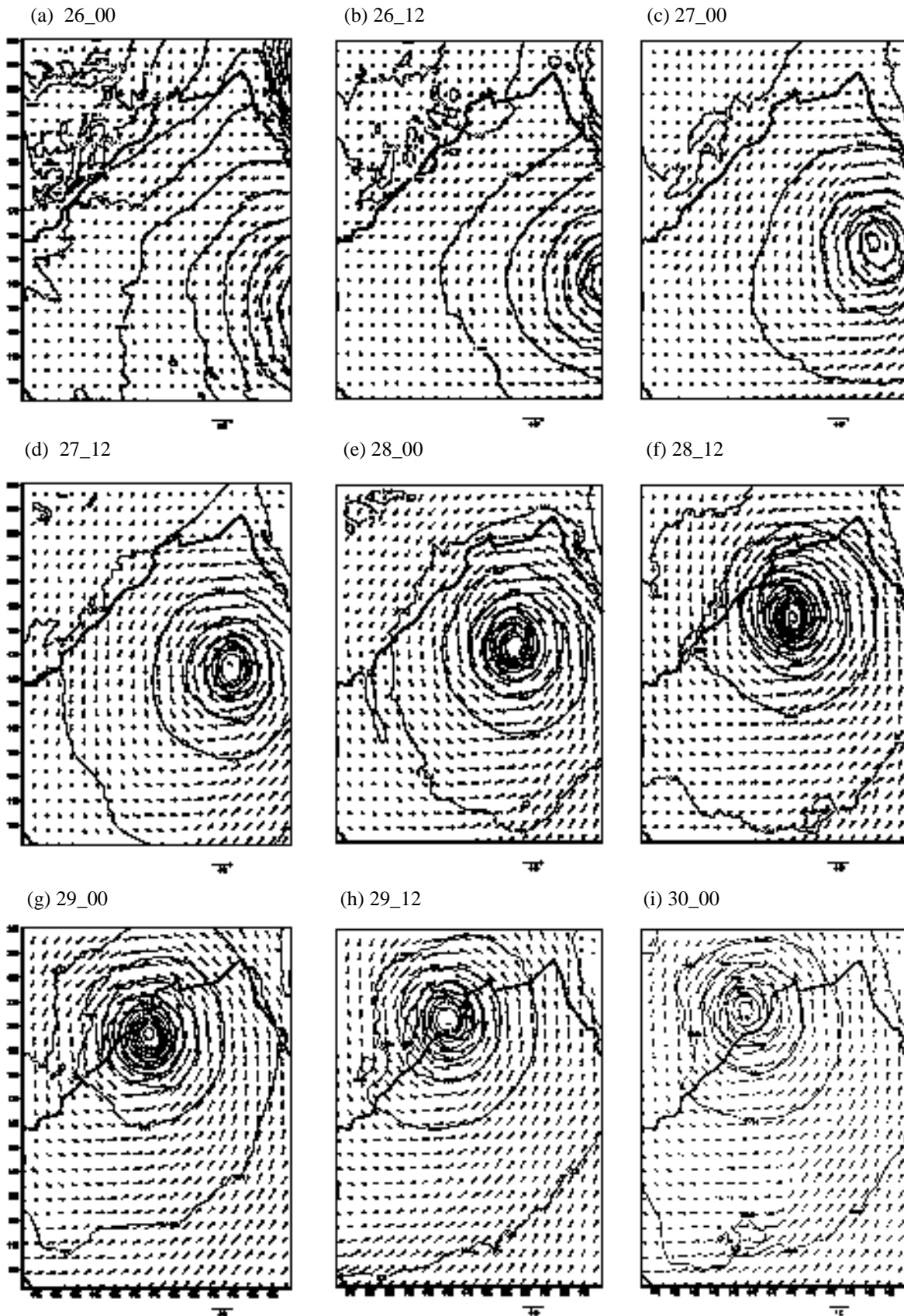
5. Results

In the present study NCAR MM5 is used to simulate the life cycle of the Orissa Super Cyclone, described in the previous section. The model is integrated for 120 hours starting from 0000 UTC of 25 October, 1999. Though different options for the parameterization of cumulus convection are available in the NCAR MM5, Kain and Fritsch (Kain, 2004) scheme, hereafter referred to as KF2, is chosen as it is one of the recently developed convection schemes based on mass flux hypothesis and not used in any of the cyclone simulation studies over north Indian Ocean so far.

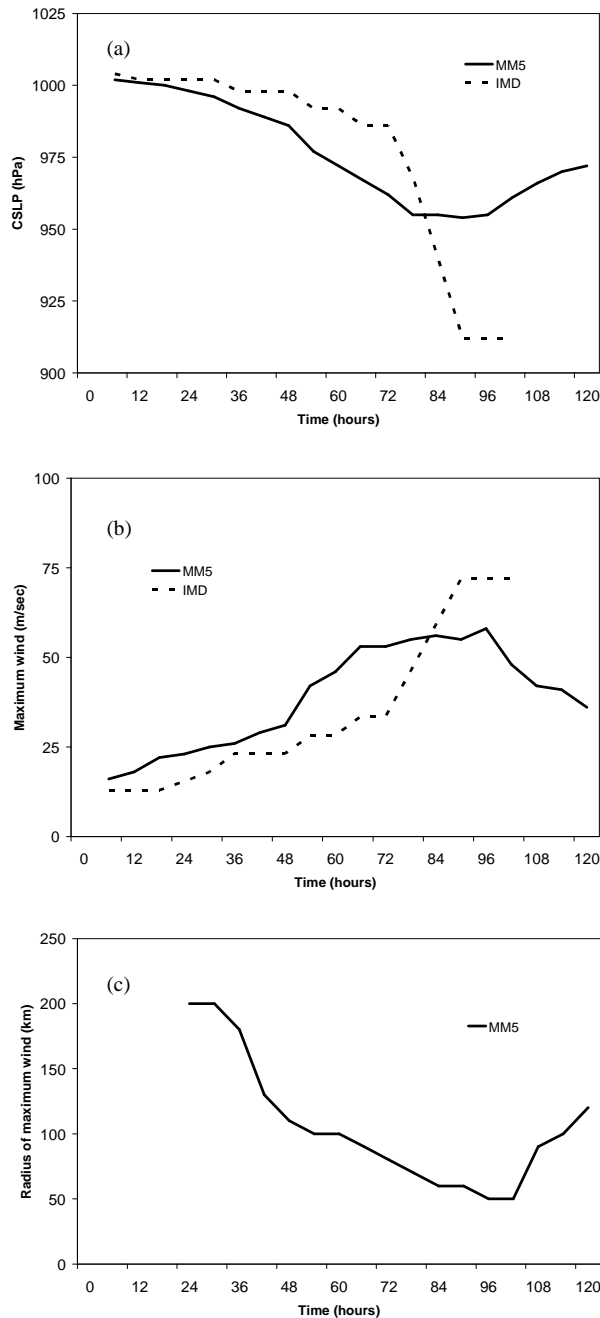
The evolution of the cyclone in terms of the sea level pressure (SLP), wind flow along with structure of the mature cyclone and the associated rainfall distribution are examined in detail. The movement of the cyclone and its final landfall point are analysed and compared with IMD reports.

5.1. Sea level pressure and winds at 925 hPa

As mentioned earlier, the inner most domain with 10 km resolution covers the cyclonic storm from 1200 UTC of 26 onwards and so the central sea level pressure (CSLP) distribution from 0000 UTC of 26 to 0000 UTC



Figs. 2(a-i). Distribution of sea level pressure (hPa) along with 925 hPa wind (m/sec)



Figs. 3(a-c). Time variation of model simulated and IMD estimates of (a) central sea level pressure (hPa), (b) maximum wind (msec^{-1}) and (c) model derived radius of maximum wind (km)

of 30 October are presented in Fig. 2. It is to be noted that the model simulates the stage of tropical storm at 0000 UTC of 26 October, gradually intensifying as severe cyclonic storm at 0000 UTC of 27 and very severe

cyclonic storm at 1800 UTC of 27. The shrinking of the storm area associated with its intensification are clearly noted from 0000 UTC of 26 till 0000 UTC of 28 October. Slight weakening of the storm just before its landfall and gradual weakening there after are also simulated. The time variation of the CSLP (Fig. 3) show gradual decrease from 0000 UTC of 25 up to 0000 UTC of 27 (17 hPa decrease in 48 hours); followed by rapid fall from 0000 UTC of 27 to 0600 UTC of 28 (31 hPa decrease in 30 hours); then a steady state from 0600 UTC of 28 to 0000 UTC of 29 (no pressure variation for 18 hours) and then gradual weakening from 0000 UTC of 29 to 0000 UTC of 30 (pressure increase of 17 hPa in 24 hours). This agrees with the reports of the IMD; noted in section 2, except that the model could not simulate the reported minimum CSLP of 912 hPa. Correspondingly time variation of the maximum wind (MW) show gradual intensification up to 0000 UTC of 27 (12 msec^{-1} increase in 48 hours); then rapid intensification from 0000 UTC of 27 to 0000 UTC of 28 (22 msec^{-1} increase in 24 hours), followed by a steady state for 24 hours (5 msec^{-1} increase in 24 hours) and then decrease of the wind speed (22 msec^{-1} decrease in 24 hours). The model simulated maximum wind is only 58 msec^{-1} as compared to 70 msec^{-1} of the IMD reports. The variation of the radius of the maximum wind (Fig. 3) shows the shrinking of the storm size up to 0000 UTC of 29 indicating the intensification of the storm followed by an increase of the radius of the maximum wind (RMW) corresponding with its dissipation. The above described features of the variation of CSLP, MW and RMW clearly indicate that the model could simulate the essential features agreeing with the observations. However it is noted that the model could not simulate the observed intensity of the Orissa Super Cyclone exactly.

5.2. Divergence and vorticity

The distributions of divergence and vorticity corresponding to 850, 500 and 200 hPa are presented for three consecutive days *i.e.*, at 0000 UTC of 28, 29 and 30 October 1999. The distribution of divergence (Fig. 4) on 28, shows strong convergence at lower levels extending upto 500 hPa level and divergence dominates at upper levels. Spiral converging inflow into a concentric region at low levels reducing in intensity and extending to a wider region at mid tropospheric level is observed. Strong outflow dominates over a wide region in the upper troposphere. On 29 October, at the time just before landfall, convergence is present through the lower and middle tropospheres with divergent flow in the upper troposphere. At this time the convergent and divergent flows are weaker comparative to 0000 UTC of 28. At 0000 UTC of 30 October, about 18 hours after the landfall, convergence is still present in the lower and middle tropospheres but the spiraling inflow at lower

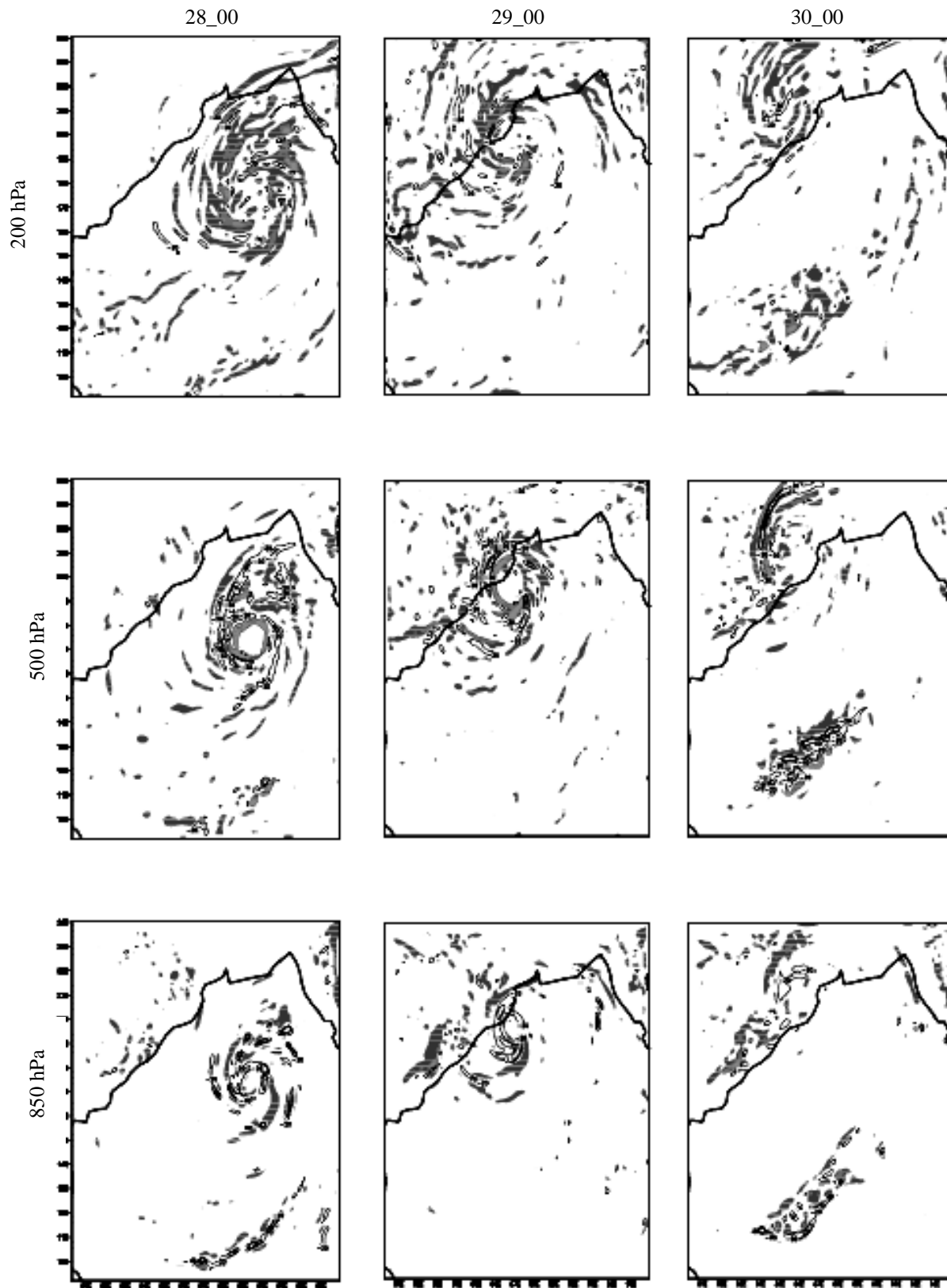


Fig. 4. Model derived divergence fields ($\times 10^5 \text{ sec}^{-1}$) for 850 hPa (bottom panel), 500 hPa (middle panel) and 200 hPa (top panel) levels at 0000 UTC of 28, 29 and 30 October 1999. Convergence fields are shaded and divergence fields are line contours

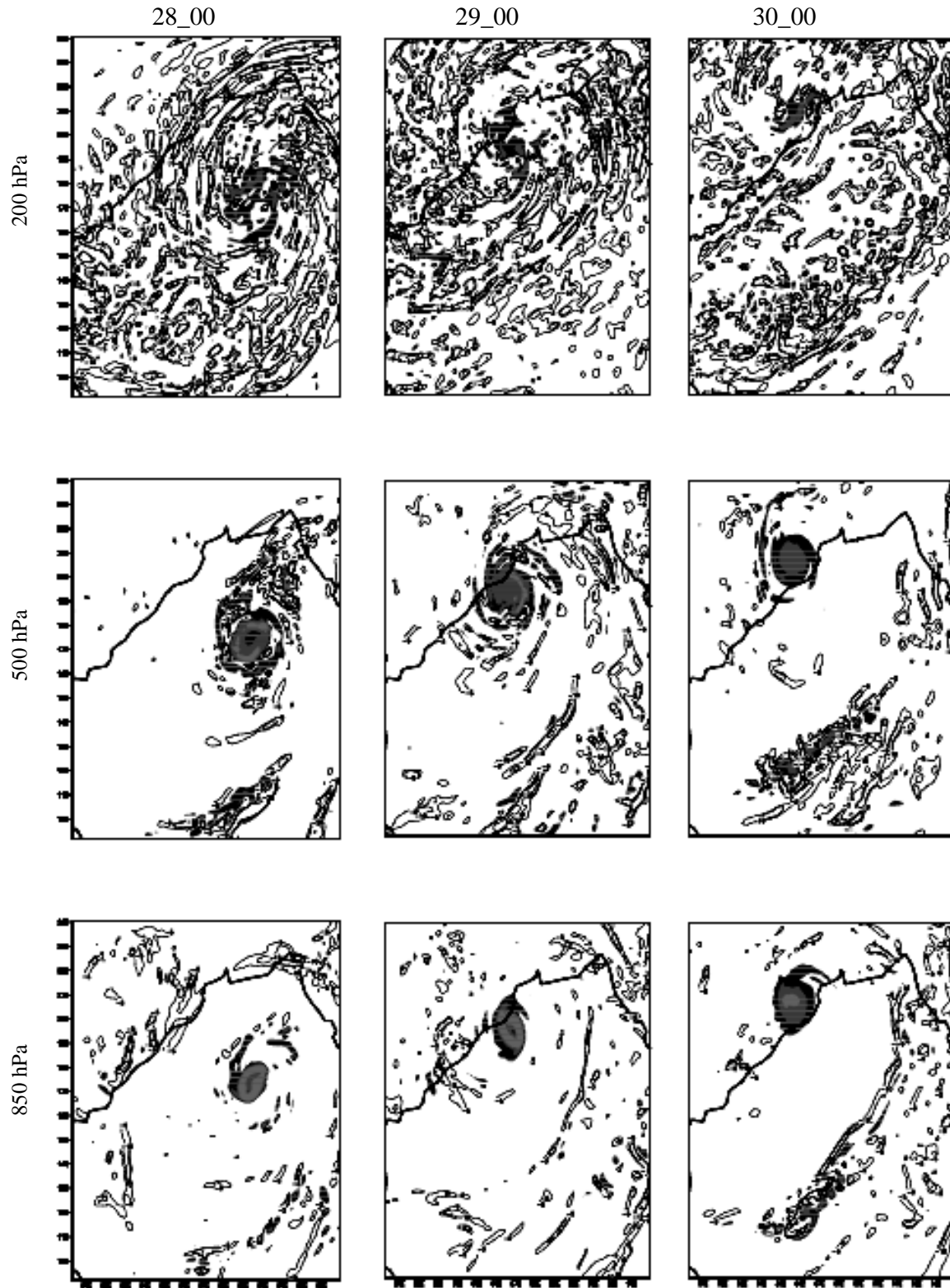
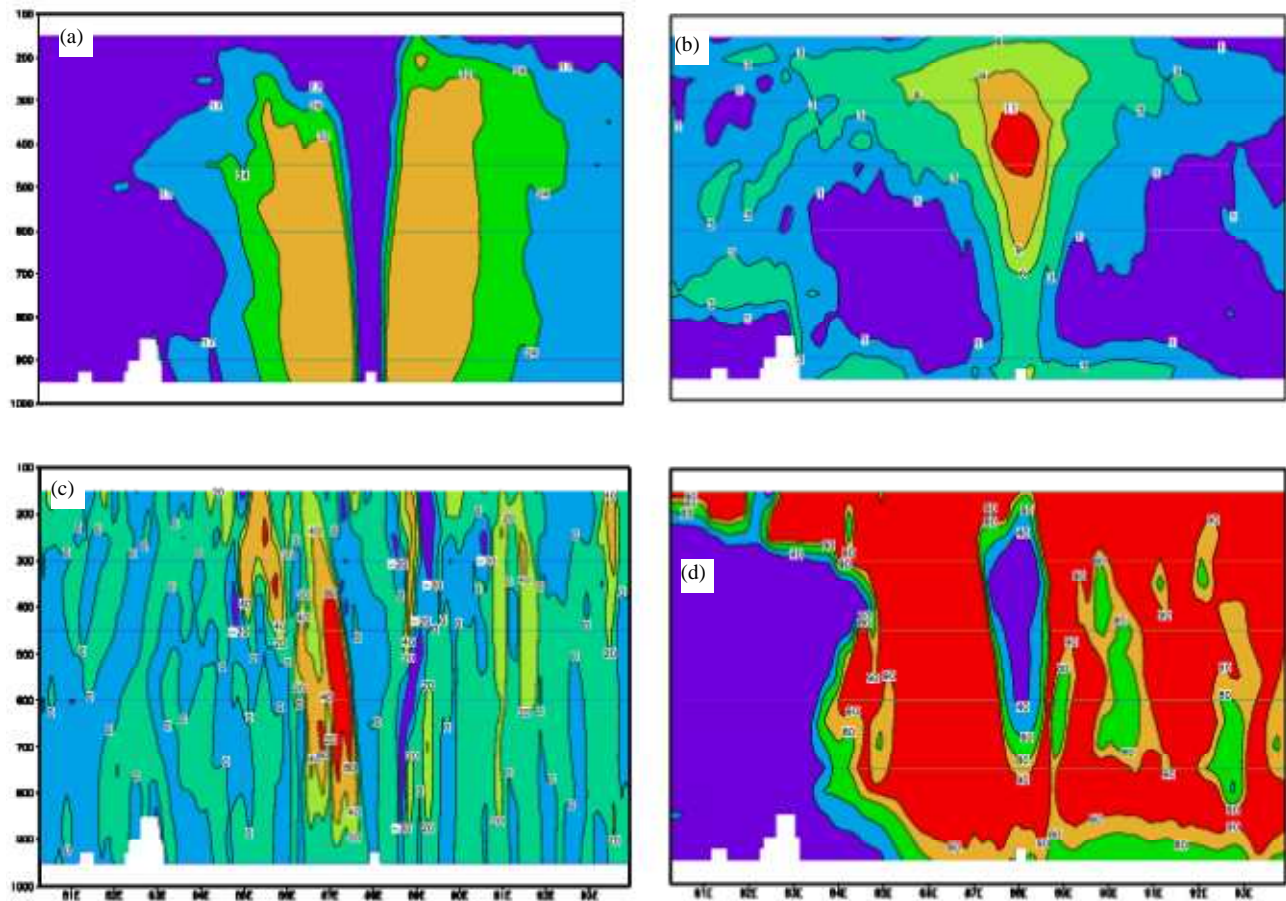


Fig. 5. Model derived vorticity fields ($\times 10^5 \text{ sec}^{-1}$) for 850 hPa (bottom panel), 500 hPa (middle panel) and 200 hPa (top panel) levels at 0000 UTC of 28, 29 and 30 October 1999. Positive values are shaded and negative fields are line contours



Figs. 6(a-d). Vertical section along 18.5° N at 1200 UTC of 28 October 1999 of (a) wind (m sec^{-1}), (b) temperature anomaly ($^{\circ}\text{C}$), (c) vertical velocity (cm sec^{-1}) and (d) relative humidity (%)

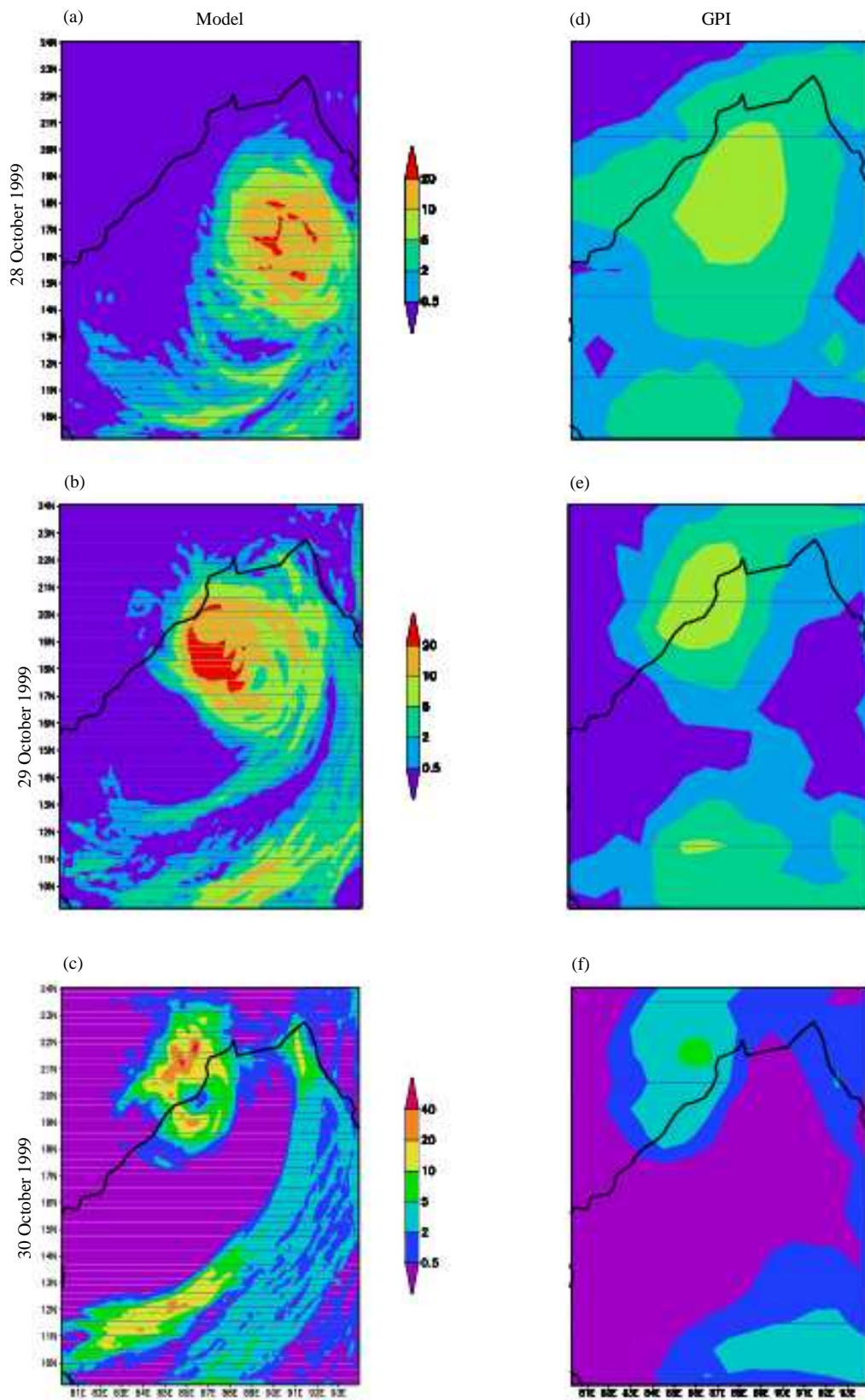
levels completely vanishes where as upper level divergence dominates the entire region. These features on 28 October, clearly indicating strong converging inflow in a narrow region at lower levels with associated divergent flow over a wider region at upper levels are the typical characteristics of a mature cyclonic storm. The features on 29 and 30 October indicate the beginning and continuation of the dissipation.

The vorticity distribution at 0000 UTC of 28 shows (Fig. 5) strong cyclonic vorticity at lower levels over a concentric region over north central Bay of Bengal. The cyclonic vorticity extends throughout the troposphere, gradually reducing from lower to upper levels. In the upper troposphere, anticyclonic vorticity over a wide region around central cyclonic vorticity region is noted. At 0000 UTC of 29, the cyclonic vorticity reduces its strength at all levels as compared to 28, but features of 28 persist on 29. On 30 October, after the landfall, the

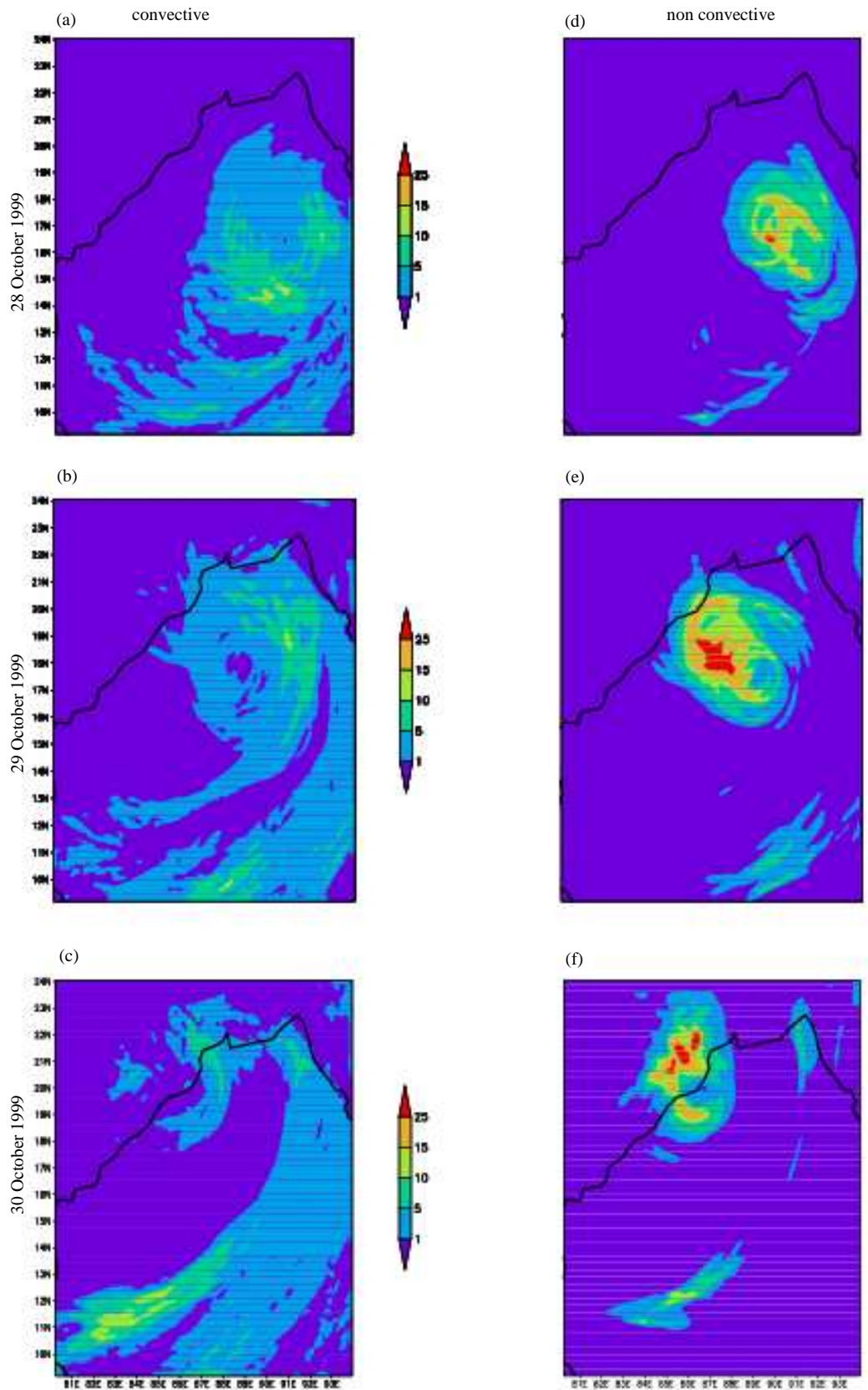
cyclonic vorticity in the lower troposphere reduces to half of that on 29, where as in the middle and upper troposphere same intensity of 29 prevails. These feature shows concentrated cyclonic vorticity at lower levels, slowly decreasing in intensity near and after the landfall and anticyclonic vorticity covering a wide region around the lower level cyclonic vorticity region in the upper troposphere.

5.3. Vertical structure

The longitude-height sections of the wind, temperature deviation, relative humidity and vertical velocity fields at 1200 UTC of 28 October, representing the mature stage of the cyclonic storm, are presented in Fig. 6. The wind field shows cyclonic strength winds throughout the troposphere extending up to 300 km on the western side and 500 km on the eastern side indicating asymmetries. Hurricane strength winds exceeding



Figs. 7(a-f). The model simulated rainfall rate (a,b,c) and GPI precipitation (d,e,f) in cm/day corresponding to 0000 UTC of (a,d) 28 October (b,e) 29 October and (c,f) 30 October 1999



Figs. 8(a-f). The model simulated convective precipitation (a,b,c) and non-convective precipitation (d,e,f) in cm/day corresponding to 0000 UTC of (a,d) 28 October (b,e) 29 October and (c,f) 30 October 1999

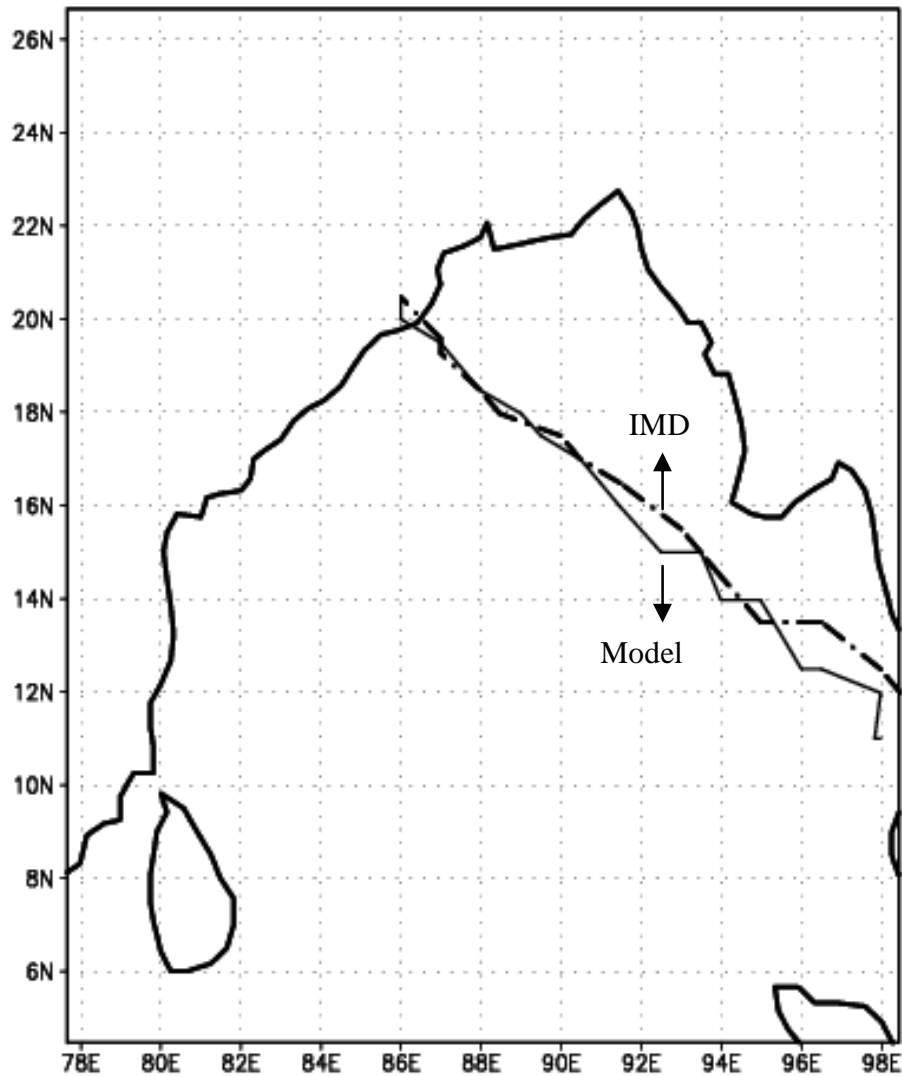


Fig. 9. Model simulated track positions along with IMD estimates

32 msec^{-1} are present within the 40–100 km radius up to 300 hPa level indicating a severe cyclonic storm. The temperature distribution shows warming of about 12° in the central region between 500–300 hPa levels. The warm core extends upward from 700 hPa level expanding outward up to 200 hPa level. The vertical velocity field shows weak downward motion is observed throughout the troposphere indicating subsidence and strong upward motion at a radius of 50 - 70 km, with a maximum of 50 cmsec^{-1} extending from 900–200 hPa levels. The vertical motions are strong on the westward side of the center. The relative humidity distribution shows dry region at the center between 850 to 200 hPa levels with moist saturated atmosphere in the lower troposphere extending upward around the central dry region.

The above described features clearly show hurricane winds around 40 km radius extending throughout the troposphere; vertical motion around central subsidence region; warm core extending from middle to upper troposphere and dry region at center surrounded by moist environment show the characteristics of eye and formation of the eye wall which conform with the established characteristics of an intense tropical cyclone.

5.4. Rainfall

The model derived rainfall rates (based on the rainfall during prior 24 hours) at 0000 UTC of 28, 29 and

TABLE 2

Track errors (km) of the model simulation

Time (hours)	24	48	72	96	120
Vector error (km)	124	78	55	11	0

30 October are analysed and compared with GPI data (Fig. 7). The total rainfall on 28 October shows concentrated rainfall over a radius of 200 km over the north central Bay of Bengal. The maximum precipitation obtained by the model is 30 cm/day. Contrastingly, GPI shows precipitation maximum of 8 cm/day over the northwest Bay of Bengal. The model simulates rainbands extending from the central core region towards southeast. Where as GPI shows concentrated rainfall across the Orissa coast. At 0000 UTC of 29, the rainfall region moved towards northwest Bay of Bengal. The model predicts maximum precipitation of 40 cm and rainbands extending southeast. At 0000 UTC of 30 October, about 18 hours after landfall, rainfall moves over inland across the Orissa coast. Rain bands extending towards southeast are predominant. The GPI shows decrease of rainfall region and concentrating over the land. These features indicate reasonable estimates of the rainfall rates and well simulated rainbands. However, rainfall seems to be more concentrated over the ocean region and underestimated over land.

The rainfall due to the grid-scale convection and sub-grid scale convection processes are also analysed and presented (Fig. 8) at 0000 UTC of 28, 29 and 30 October. As of the total rainfall described in the previous paragraph, it is observed that at the central core region of the cyclone *i.e.*, within 100 km radius, grid scale precipitation dominates, whereas rainfall around the peripheral region and rainbands are due to sub-grid scale convection. Since the present study uses 10 km resolution for the innermost domain, most of the convection in the central region could be resolved, where as in the outer regions sub-grid scale convection contributes.

5.5. Track of the cyclone

The model predicted movement of the Orissa Super Cyclone along with the IMD reported positions are presented in Fig. 9. The locations of the center of the Orissa super cyclone are plotted at 12 hour interval

starting from 0000 UTC of 25 up to 30 October 1999. It is to be noted that the initial position in the model analysis is different from the IMD reports, as NCEP FNL analysis is used as available at 1° resolution without any assimilation or a bogus vortex.

The model predicted track of the storm has deviation during the first two to three days of integration with in an error of 124 - 55 km and nearly coincides there after. The vector errors at 24 hour interval are given in Table 2. It is observed that the model has an error of 124 km at 24 hours, slowly decreasing to 0 km at 120 hours. The initial high errors may be due to the difference in the location at the initial time step (*i.e.*) 0000 UTC of 25 October and the subsequent decrease of error may be attributed to a good simulation of the environmental flow patterns which influence the movement of the cyclone. The model simulated central sea level pressure, maximum wind and the track using Kain-Fritsch scheme as reported in this study are noted to be better than those of Mohanty *et al.*, (2004) and Rao and Bhaskar Rao (2003) reporting minimum CSLP of 963 and 962 hPa using Grell scheme. However a number of case studies have to be performed before arriving at any conclusion.

6. Summary and conclusions

The present study is carried out to examine the hypotheses proposed by Kain – Fritsch (Kain, 2004) for parameterization of convection through a simulation study of the Orissa Super Cyclone. As convection processes play an important role in the intensification and movement of tropical cyclone, the KF2 scheme is chosen to represent sub-grid scale convection processes along with MRF (Hong-Pan, 1996) for planetary boundary layer and simple ice scheme (Dudhia, 1989) for explicit moisture. The case study of Orissa super cyclone is chosen as it is the most intense cyclone ever recorded over the north Indian Ocean. The reports show the system as a low pressure on 25 October and gradually intensified as a tropical cyclone by 28 and then rapid intensification for 12 to 18 hours attaining the stage of Super Cyclone. The movement of this cyclone was a near straight track towards northwest following the climate normal. These features make it an ideal case study for model validation.

The model derived sea level pressure distribution show the gradual intensification of the system during the first 2 to 3 days and then rapid intensification for about 24

hours agreeing with the observations. However the rate of rapid intensification is underestimated and could not be predicted truly. The model could predict the minimum CSLP as 954 hPa and the maximum wind as 58 msec^{-1} , both underestimated, as compared to the IMD reports of 912 hPa and 70 msec^{-1} respectively. The shrinking of the cyclone size associated with the intensification and its expansion after landfall is simulated.

The features of the divergence and vorticity fields at the mature stage of the storm are well simulated. Strong convergence in a concentric region at lower levels and wide spread divergence at upper levels at the mature stage; gradual weakening of the low level convergence after the landfall are simulated. Cyclonic vorticity extends throughout the troposphere with its maximum at lower levels on 28 October; persisting throughout the troposphere with reduced intensity on 29 and then reducing by 50% from the landfall time to 0000 UTC of 30 October.

The model simulated cyclone structure shows core of hurricane winds within 40-100 km radius and extending throughout the troposphere. A warm core extending from 3 km expanding outward up to 12 km is obtained. The vertical velocity field shows subsidence at the center surrounded by vertical motion extending throughout the troposphere. Beyond 200 km radius, weak alternating upward and downward motions exist. The model atmosphere shows dryness at the center between 3 to 12 km levels surrounded by highly moist near saturated environment within the 200 km radius.

The model derived rainfall shows reasonable estimates slightly more than the GPI estimates, as GPI estimates have limitations to predict high rainfall intensity. The model predicted area of precipitation lag the GPI location. The model simulates the formation of rainbands extending towards southeast, which indicates the model capability to simulate the mesoscale convective systems. The distribution of grid scale and sub-grid scale precipitation indicate that grid scale precipitation is a major contributor for the precipitation over the cyclone region where as sub-grid scale precipitation dominates the outer peripheral region.

The model could predict the movement agreeing with the observations with the initial errors of 120 km at

24 hour and decreasing thereafter coinciding with the observations after 72 hours.

The results show that KF2 scheme for cumulus convection give better simulation as compared to Grell. The present study indicates that the Kain-Fritsch convection parameterization scheme gives reasonable prediction of convection associated with a development and movement. The numerical study also emphasis the use of NCAR MM5 supporting the earlier studies. This is only a preliminary study using KF schemes and requires more case studies to arrive at definite conclusions.

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