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Numerical experiments for improvement in mesoscale simulation of Orissa super cyclone

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सार – 29 अक्तूबर, 1999 को उड़ीसा के तट पर आया महाचक्रवात उड़ीसा के अब तक के इतिहास का सबसे प्रचंड तूफान था जिसकी 250 कि.मी. प्रति घंटा की तीव्र गति वाली पवनों ने राज्य के 12 तटीय जिलों को तहस–नहस कर डाला। तूफान के स्थल से टकराने के पश्चात् 36 घंटे से भी अधिक समय तक पवनों की प्रचंडता बनी रही। इस तूफान से जान माल का काफी नुकसान हुआ। लगभग 10,000 लोगों की जानें गई। इस अध्ययन में तूफान के मेसोस्केल प्रतिरूप को बेहतर बनाने के लिए कुछ महत्वपूर्ण पहलुओं की जाँच हेतु व्यापक संख्यात्मक प्रयोग किए गए हैं। इन पहलुओं में गैर द्रवस्थैतिक गतिक, निदर्श क्षैतिज विभेदन और महत्वपूर्ण प्रत्यक्ष प्रक्रियाओं के प्राचलीकरण शामिल हैं। तूफान का 5 दिवसीय प्रतिरूप (123 घंटों के लगातार समाकलन) तैयार करने के लिए मेसोस्केल निदर्श एम. एम. 5 का उपयोग किया गया है।

इसमें समरूपी विभेदन (30 कि.मी.) और समरूपी समय श्रृंखला के साथ द्रवस्थैतिक (एच.एस.) तथा गैर द्रवस्थैतिक (एन. एस.) गतिकों के सहयोग से तूफान के प्रतिरूप में गैर द्रवस्थैतिकता के प्रभाव की जाँच की गई है। इस विधि से तूफान और विशेष रूप से इसकी तीव्रता का गैर द्रवस्थैतिक गतिकों के साथ सही प्रतिरूपण होता है। गैर द्रवस्थैतिक गतिकों के साथ 90 कि.मी., 60 कि.मी. और 30 कि.मी. के विभेदनों पर तूफान का प्रतिरूपण करते हुए निदर्श की संवर्धित क्षैतिज विभेदन की महत्ता की जाँच की गई है और तूफान के प्रतिरूपण में इसका प्रत्यक्ष प्रभाव देखा गया है।

महत्वपूर्ण प्रत्यक्ष प्रक्रिया वाले कपासी संवहन ग्रहीय परिसीमा स्तर (पी. बी. एल.) और विकिरण हेतु निदर्श में उपलब्ध प्राचलीकृत योजनाओं के बेहतर सम्भाव्य समन्वय का पता लगाने के लिए संख्यात्मक प्रयोग भी किए गए। सी. सी. एम. 2 विकिरण प्राचलीकृत योजना समेत ग्रेल कपासी संवहन और हाँग–पेन पी. बी. एल. योजना के साथ समन्वयन वाली योजना के अन्य परीक्षित योजनाओं की तुलना में सबसे बेहतर परिणामों का पता चला है।

ABSTRACT. The super cyclone that crossed Orissa coast on 29 October 1999 was the most intense storm in the history of Orissa with 12 coastal districts of the state were battered by winds reaching 250 kmph. The fury of winds continued for more than 36 hours after landfall of the storm. The storm caused huge damage to properties and nearly 10,000 people lost their lives. In the present study, extensive numerical experiments are conducted to investigate some important aspects that may lead to the improvement in mesoscale simulation of the storm. The aspects that are addressed here include non-hydrostatic dynamics, model horizontal resolution and parameterization of important physical processes. The mesoscale model MM5 is used to produce 5-day simulation of the storm.

The influence of non-hydrostaticity is investigated by simulating the storm with hydrostatic (HS) and non-hydrostatic (NS) dynamics at same resolution (30 km) and with same time step. The storm, in particular its intensity is better simulated with non-hydrostatic dynamics. The importance of increasing model horizontal resolution is investigated by simulating the storm at 90 km, 60 km and 30 km resolutions with non-hydrostatic dynamics and found to have perceptible impact in simulation of the storm.

Numerical experiments also are conducted to find the best possible combination of the parameterization schemes available in the model for the important physical processes cumulus convection, planetary boundary layer (PBL) and radiation. The combination of Grell cumulus convection and Hong-Pan PBL scheme along with CCM2 radiation parameterization scheme is found to provide the best result compared to the other schemes tested.

Key words – Super cyclone, Hydrostatic, Non-hydrostatic, Horizontal resolution, Cumulus convection, Planetary boundary layer and radiation.

1. Introduction

Tropical cyclones are one of the most devastating and deadliest meteorological phenomena worldwide. Conceived over warm tropical oceans and nurtured by the converging moisture, the mature tropical cyclones are associated with violent wind, torrential rainfall and storm surges. The Bay of Bengal is potentially energetic for the development of cyclonic storms and accounts for about 7% of the global annual total number of storms (Gray, 1968). Though, much weaker in intensity and smaller in size as compared to the cyclones of other regions, the Bay of Bengal cyclones, in particular, the post monsoon cyclones that cross east coast of India or Bangladesh are highly devastating. This is mainly due to dense populated coastal region, shallow bathymetry, nearly funnel shape of the coastline and the long stretch of the low-lying delta region embedded with large number of river systems. Timely and reasonably accurate prediction of track and intensity of these storms can save lot of lives and reduce damage to properties and therefore is of great importance.

There have been considerable improvements in the field of numerical weather prediction in last two decades and numerical weather prediction models are recently proved to be more successful in the operational tropical cyclone prediction as well. Much of this success is due to increase in computing resources, developments in numerical techniques, improved understanding of physical processes and improvements in observing systems, objective analysis and initialization. With increasing computing resource, in last half decade, the focus is on the use of high-resolution mesoscale models. As far as formulation of these models is concerned, the thrust is undoubtedly on relaxation of hydrostatic approximation.

The hydrostatic approximation holds good in systems with horizontal scale much larger than the vertical (Eckart, 1960). This does not necessarily mean that the use of hydrostatic dynamics is invalid in numerical model with horizontal resolution 10 km or higher. But, the weather system may be inadequately simulated (Mesinger, 1997). This may depend on the weather system as well. One major concern with the use of non-hydrostatic dynamics is the increase in number of prognostic variables and hence need of better computing resources. With rapid development in computing power, a number of fully non-hydrostatic models have been developed in recent past. The effect of non-hydrostatic dynamics in simulation of mountain waves under adiabatic conditions, moist convection, cold fronts etc. has been studied by a number of researchers (Clark, 1977; Durran and Klemp, 1983; Orlanski, 1981; Dudhia, 1993; and many others). However, the effect of non-hydrostatic dynamics in simulation of the Bay of Bengal cyclones has never been investigated and hence it is very important to look into this aspect. It can be mentioned here that a preliminary study (Mohanty *et al*., 2004) was conducted earlier to examine the capability of the modeling system in simulation of Orissa super cyclone.

The model horizontal resolution is an important issue in present day numerical weather prediction, particularly in tropical cyclone prediction. A regional model can capture the fine structure of the cyclones, if the model resolution is increased sufficiently. The topographic features and sub-grid scale physical processes are better represented with increase in horizontal resolution of the model. Further, all physical parameterizations in a numerical model are sensitive to model horizontal resolution.

It is well accepted that the physical processes play dominant role in the initiation and development of tropical weather systems unlike in the mid-latitude, where dynamical forcings are dominant. As far as development of tropical cyclones are concerned, cumulus convection; surface fluxes of heat, moisture and momentum; vertical mixing in the planetary boundary layer (PBL) and also radiative heating & cooling play important roles (Anthes, 1982). These physical processes cannot be resolved explicitly by the regional/mesoscale models at their current resolution and hence need to be parameterized in terms of large scale variables at the grid points. Though, a number of parameterization schemes are developed for implicit treatment of these important physical processes, these schemes have certain limitations (Zhang *et al*., 1994; Kuo *et al*., 1997) and are regime specific. Thus, it is important to find the suitability of these parameterization schemes and their combinations (for these processes) in simulating the Bay of Bengal cyclones.

In addition, providing initial condition to the high-resolution mesoscale models is a challenge to the modelers and more so for tropical cyclone prediction. The tropical cyclones form in the data sparse region over the warm seas. Due to which, the location and intensity of the initial vortex is poorly represented in the large-scale analyses used to provide the initial condition for model integration. Thus, one needs to improve the initial vortex

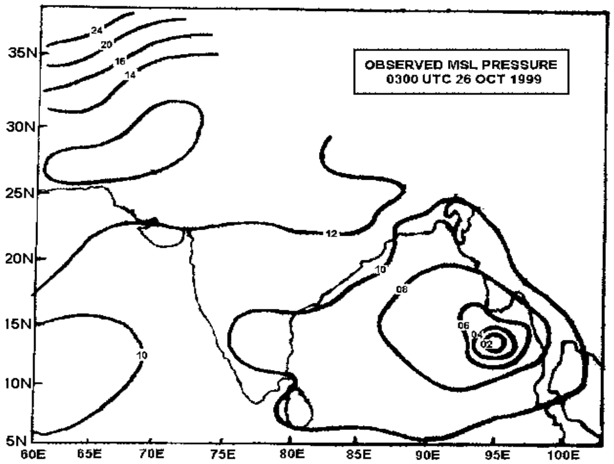


Fig. 1. Mean sea level pressure (in hPa) chart valid at 0300 UTC 26 October 1999 (Courtesy : IMD)

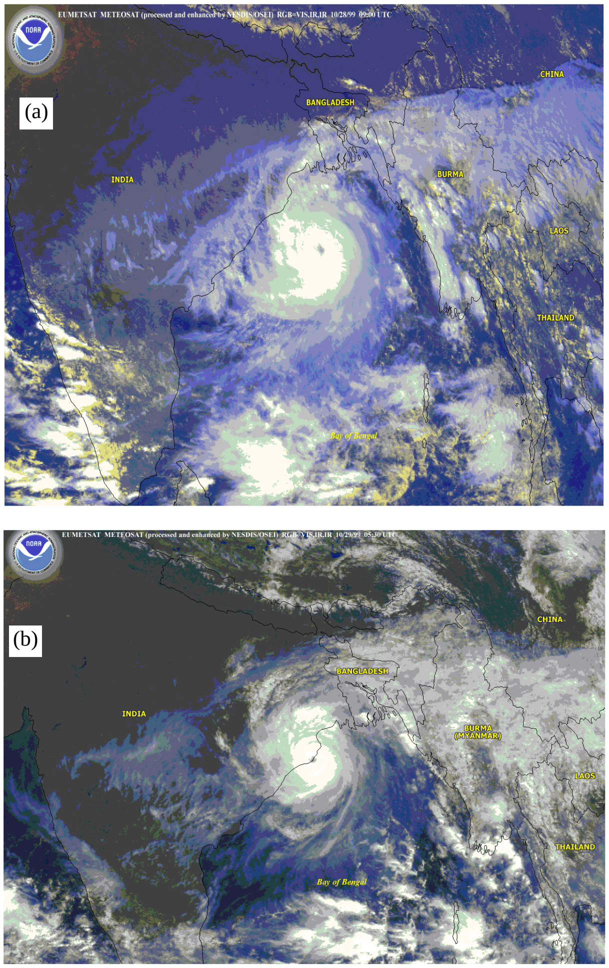
specification and hence the model initial condition. This can be achieved through assimilation of satellite derived meteorological parameters into the large-scale analysis and synthetic vortex initialization. It is another important and challenging problem in tropical cyclone research though beyond the scope of this paper.

In the present study, PSU/NCAR mesoscale model MM5 is integrated continuously for 123 hours (excluding 12 hours analysis nudging) to produce 5-day simulation of Orissa super cyclone. Numerical experiments are conducted to investigate the influence of non-hydrostatic dynamics and model resolution in simulating the storm and hence improving the forecast skill of the model. Extensive sensitivity experiments are performed to find the possible best combination of cumulus convection, planetary boundary layer and radiation parameterization schemes. In this respect, four cumulus convection, two PBL and two radiation parameterization schemes are tested.

Following introduction, synoptic features associated with Orissa super cyclone in provided briefly in section 2. Section 3 presents a short description of the model MM5, used in the study. Various numerical experiments conducted and data used are described in section 4. The simulation results and related discussions are provided section 5. Some broad conclusions/summary of the study are put forward in section 6.

2. Synoptic situation

The initial vortex of the storm was observed over the gulf of Thailand at 0000 UTC 24 October 1999 and is believed to be a remnant of the tropical cyclone 'TS992EVE' over the South China Sea. Moving westward across Malaysian Peninsula, it emerged in north Andaman Sea as a well-marked low-pressure area at 0000 UTC 25 October. It intensified into a deep depression by 1200 UTC of the same day and located near 12.5° N / 98.0° E. Moving in the west of northwesterly direction it intensified into a cyclonic storm by 0300 UTC 26 October and centered at 13.5° N / 95.0° E. The mean sea level pressure chart from IMD valid for this time is given in Fig. 1. This shows the storm with central SLP 1002 hPa and the closed isobars extended over a large area. By 0300 UTC 27 October, it intensified into a severe cyclonic storm with central SLP of 992 hPa (estimated). At this stage, it came under the influence of the upper level (200 hPa) ridge providing the outflow that helped in further intensification of the storm and is classified into a very severe cyclonic storm by 1500 UTC. By 0000 UTC 28 October, the upper level outflow came nearly over the center of the storm and led to further intensification of the storm. Moving in the same direction,



Figs. 2(a&b). Satellite pictures of the storm as obtained from EUMETSAT METEOSAT (*Courtesy* : NOAA Website) (a) at 0900 UTC 28 October 1999, (b) at 0530 UTC 29 October 1999

TABLE 1

Overview of the MM5 model used in the present study

Dynamics	Hydrostatic/Non-hydrostatic
Model domain	10° S - 31° N, 58° E - 110° E
Horizontal grid distance	90 km; 60 km; 30 km
Integration time step	180 sec; 120 sec; 60 sec
Map projection	Mercator
Horizontal grid system	Arakawa B-grid
Vertical co-ordinate	Terrain-following sigma co-ordinate 23 sigma levels (7 within boundary layer)
Time integration scheme	Leapfrog scheme (with time split technique)
Spatial differencing scheme	2nd order centered
Lateral Boundary condition	Time and inflow/outflow dependent (Hydrostatic)/relaxation (non-hydrostatic)
Top boundary condition	1. Rigid Lid (non-hydrostatic) 2. Sponge (hydrostatic)
Radiation parameterization	1. Dudhia’s long- and short-wave radiation 2. NCAR CCM2 radiation scheme
Surface layer parameterization	Multi-layer soil model
Cumulus parameterization	1. Anthes-Kuo 2. Grell 3. Kain-Fritsch 4. Betts-Miller
PBL parameterization	1. Blackadar 2. NCEP MRF
Microphysics	Simple ice scheme

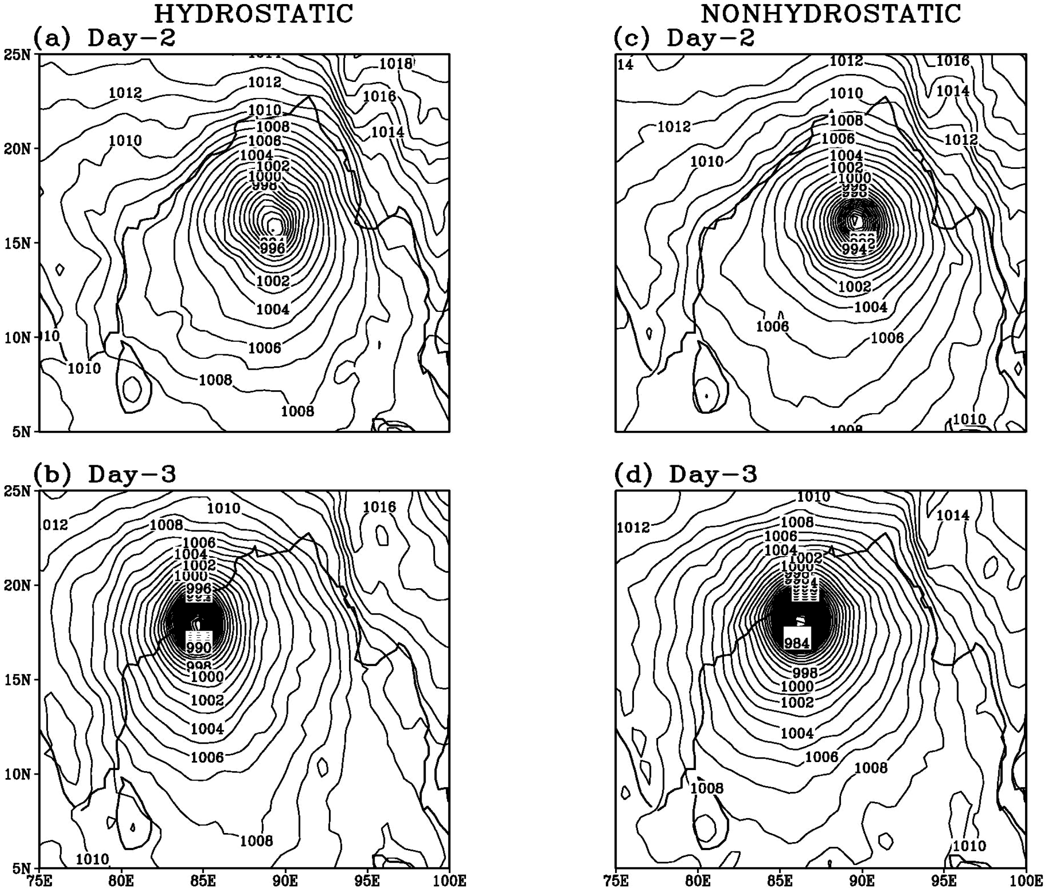
it further intensified into super cyclonic storm by 1800 UTC 28 October. The storm crossed Orissa coast close to south of Paradip around 0530 UTC 29 October. Fig. 2 shows the satellite picture of the storm at 0900 UTC on 28 October and at 0530 UTC 29 October as obtained from METEOSAT-5. After landfall, the storm is found to lay center around 20.5° N / 86.0° E by 0600 UTC 29 October (close to Bhubaneswar). It remained practically stationary at this location up to 0000 UTC 31 October. The storm maintained cyclonic intensity almost up to 1200 UTC 30 October. The super cyclonic storm caused exceptionally heavy rainfall over Orissa during 29-31 October 1999. Heavy rainfall was recorded on 1 November as well.

Though, there was no recorded storm surge, a number of post-storm surveys carried out provide some estimate of storm surge associated with the storm. The National Center for Disaster Management (NCDM) estimated maximum storm surge of 7.95 m. Damage assessment survey by Ministry of Urban Development provides an estimated storm surge of 7.5 m. This apparently includes astronomical tide of 0.8 m at the time of landfall. Government of Orissa reported total sea level rise of 20 ft.

3. Model description

The mesoscale model MM5 developed at Pennsylvania State University (PSU)/National Center for Atmospheric Research (NCAR) is used in the present study. This is a primitive equation hydrostatic/non-hydrostatic model with pressure perturbation p', three velocity components (u, v, w), temperature T and specific humidity q as the main prognostic variables. Model equations are written in surface pressure weighted flux form in the terrain following sigma co-ordinate and solved in Arakawa B grid. Leapfrog time integration scheme with time splitting technique is used for integrating the model. It is to be mentioned here that version 3 onwards the modeling system supports non-hydrostatic dynamics only.

The most useful feature about the modeling system is its flexibility in terms of many options that are user specified. Setting these parameters to appropriate values, the model can be used for a wide range of applications. These include hydrostatic/non-hydrostatic dynamics, number of nests, nature of nesting, type of convection, PBL and radiation parameterization schemes etc. Another advantage with this modeling system is that it is a state-of-



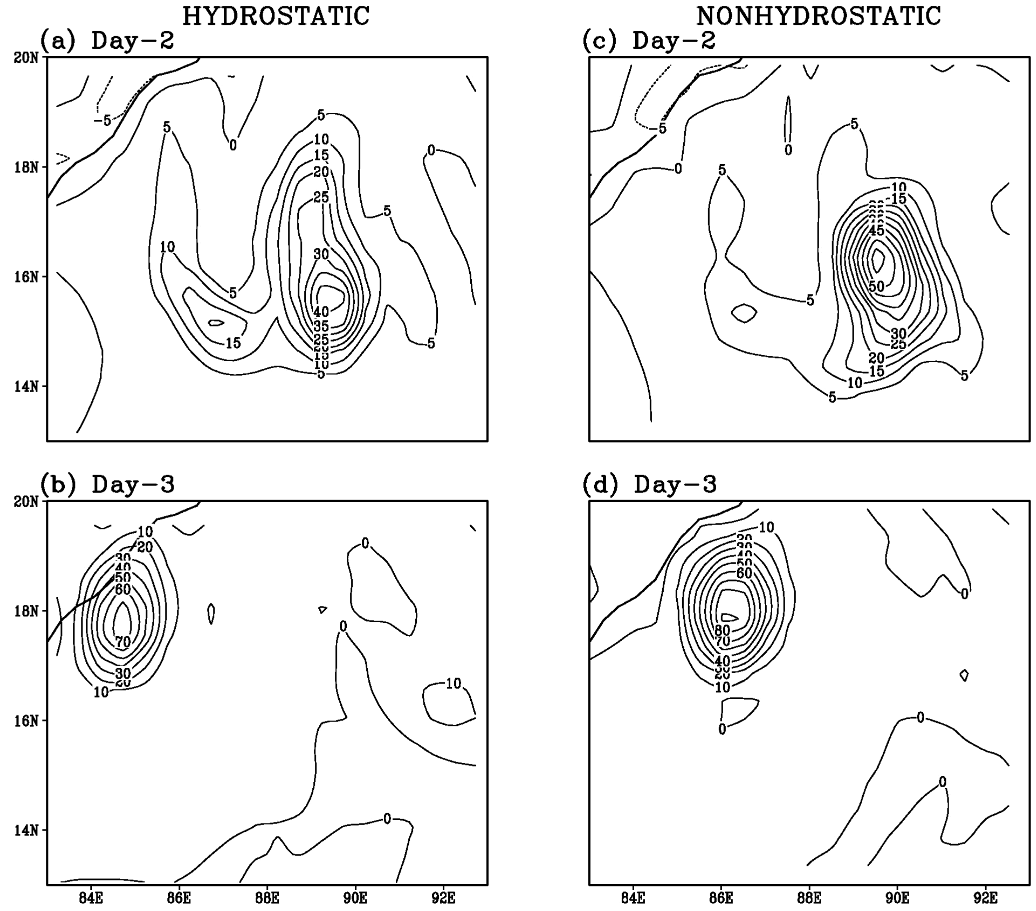
Figs. 3(a-d). Model simulated mean sea level pressure (all at 0000 UTC) with contour interval one hPa valid on (a) 28 October 1999 with hydrostatic dynamics, (b) 29 October 1999 with hydrostatic dynamics, (c) Same as (a) with non-hydrostatic dynamics, (d) Same as (b) with non-hydrostatic dynamics

the art model under continuous development. A detailed description of the model is available in Dudhia (1993) and Grell *et al.* (1995). The overview of the model used in this study is shown in Table 1.

4. Experimental design

The numerical experiments conducted to address the important aspects – non-hydrostatic dynamics, model resolution and selection of physical parameterization scheme are described in this section. All these aspects are discussed in the light of simulation of the super cyclone that crossed Orissa coast on 29 October 1999. The MM5 model described in the previous section is integrated up to 123 hrs producing 5-day simulation of the storm starting at 0000 UTC 26 October 1999. This helps to test the validity of the model forecast in 24, 48, 72, 96 and 120 hours. This is a relatively long integration as far as use of mesoscale model is concern but helped to avoid re-initialization of the model with coarse resolution global analysis. It can be mentioned here that the intensity of the storm is very poorly represented in the NCEP global reanalysis (central sea level pressure is always more than 1004 hPa; even on 29 October 1999) used to provide initial condition to the model. The influence of non-hydrostatic dynamics is investigated by integrating the model at 30 km horizontal resolution with hydrostatic (HS) and non-hydrostatic (NS) dynamics. To study the impact of horizontal grid spacing on forecast skill of the non-hydrostatic version the model, the storm is simulated with the model at 90 km and 60 km resolutions besides the simulations at 30 km.

To find a possible suitable combination of cumulus convection, PBL and radiation parameterization scheme among the schemes tested (four cumulus convection schemes, two PBL schemes and two radiation schemes), numerical experiments are conducted at two stages. In the first stage, a series of eight experiments are carried out with eight possible combinations of four convection and two PBL parameterization schemes along with CCM2 (2nd generation Community Climate Model) radiation scheme (Briegleb, 1992 and Kiehl *et al.*, 1994). The four convection schemes are Grell (Grell 1993), Betts-Miller

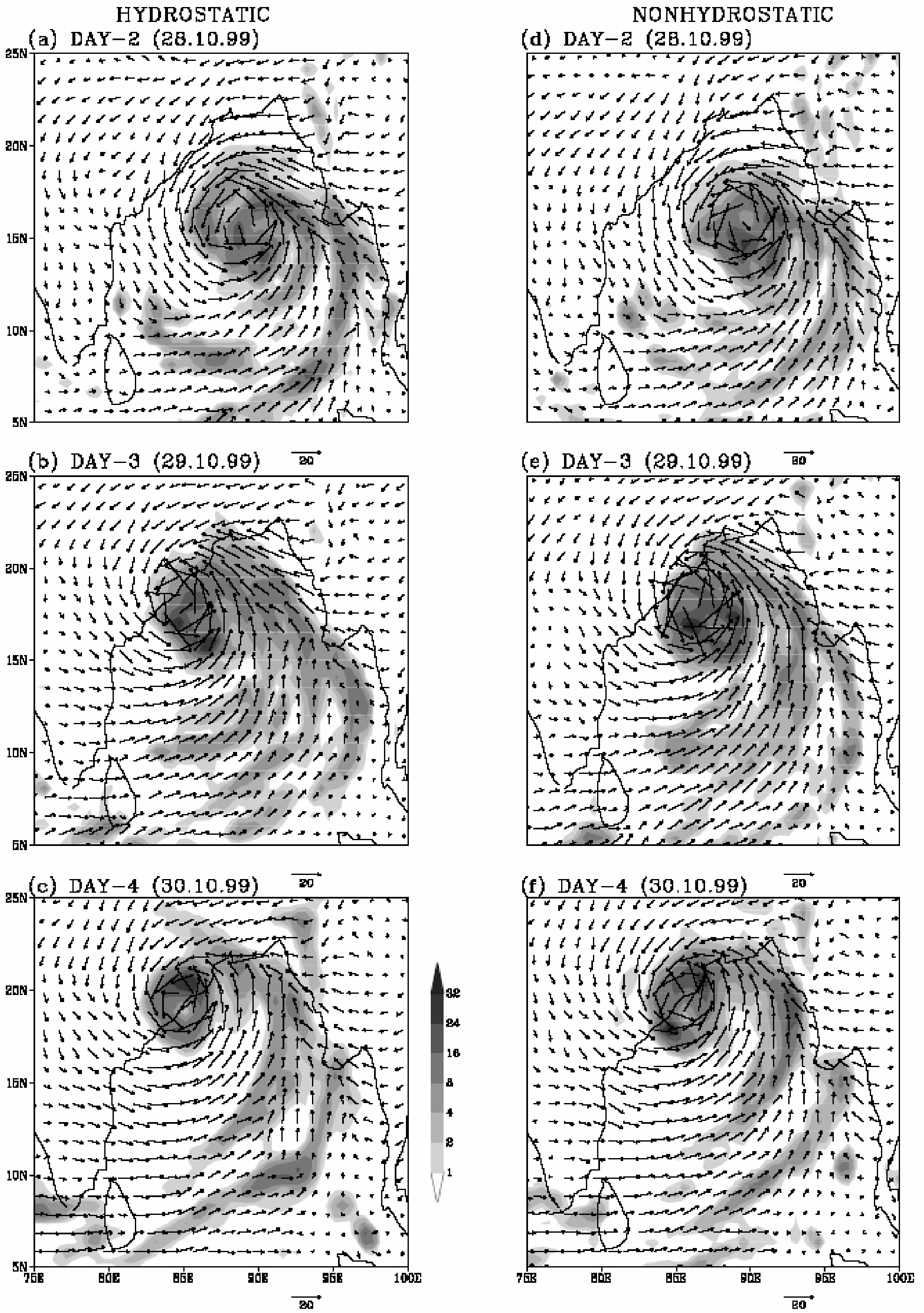


Figs. 4(a-d). Same as Figs. 3(a-d) but vertical component of horizontal vorticity (all at 0000 UTC) (in 10^{-5}sec^{-1}) with contour interval 5

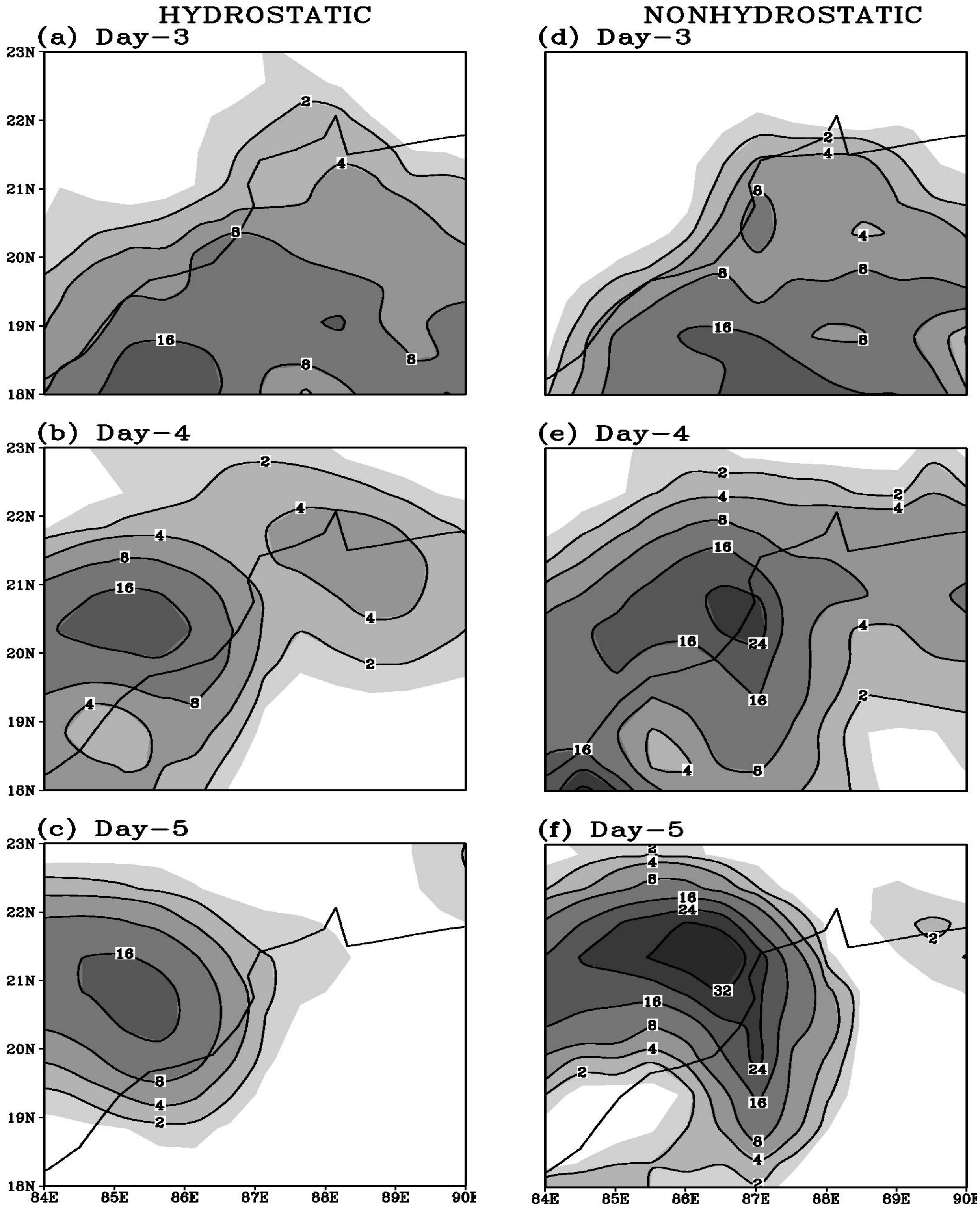
(Betts, 1986; Betts and Miller, 1986), Anthes-Kuo (Kuo, 1974; Anthes, 1977) and Kain-Fritsch (Kain and Fritsch, 1993), which hereafter referred as GR, BM, AK and KF respectively. Two PBL schemes are Blackadar (Blackadar, 1976, 1979; Zhang and Anthes, 1982) and Hong-Pan (Hong and Pan, 1996) as implemented in NCEP MRF model, which hereafter referred as B and M respectively. These schemes are selected, as these are the most widely used schemes in the mesoscale models. The experiments using MRF PBL scheme in combination with GR, BM, AK and KF convection schemes are referred as experiments M-GR, M-BM, M-AK and M-KF respectively. Similarly experiments using Blackadar PBL scheme in combination with GR, BM, AK and KF convection schemes are referred as experiments B-GR, B-BM, B-AK and B-KF respectively. In the second stage, one more experiment is conducted with the possible best combination of PBL and convection schemes obtained from the first stage along with Dudhia's (1989) long- and short-wave radiation scheme also known as Simple Cloud scheme (SC). All the experiments are conducted at 60 km model resolution to save computing time. For all these experiments, the model initial and boundary conditions are provided from NCEP reanalysis interpolated to model grids and the model is initialized through 12 hours (1200 UTC 25 October to 0000 UTC 26 October) nudging to the large-scale analysis.

5. Results and discussion

As discussed in the previous section, the model is integrated up to 123 hrs starting from 0000 UTC 26 October to 0300 UTC 31 October 1999 (last 3 hrs is for the verification of rainfall as the observed 24 hours accumulated rainfall is available at 0300 UTC). The simulation results are presented in this section along with verification analysis (analysis corresponding to the forecast time) and observations. The intensity of the storm is poorly represented in the reanalysis (figure not shown), which is attributed to its coarse resolution. The initial and subsequent positions of the storm are also in error



Figs. 5(a-f). Model simulated wind at 1000 hPa and 24 hours accumulated precipitation valid on (a) 28 October 1999 with hydrostatic dynamics, (b) 29 October 1999 with hydrostatic dynamics, (c) 30 October 1999 with hydrostatic dynamics, (d) Same as (a) with non-hydrostatic dynamics, (e) Same as (b) with non-hydrostatic dynamics, (f) Same as (c) with non-hydrostatic dynamics



Figs. 6(a-f). Model simulated 24 hours accumulated precipitation valid at 0300 UTC (in cm) (a) 29 October 1999 with hydrostatic dynamics, (b) 30 October 1999 with hydrostatic dynamics, (c) 31 October 1999 with hydrostatic dynamics, (d) Same as (a) with non-hydrostatic dynamics, (e) Same as (b) with non-hydrostatic dynamics, (f) Same as (c) with non-hydrostatic dynamics

TABLE 2

Observed/estimated (IMD) and model simulated central pressure drop (in hPa) in Orissa super cyclone and % (of observed) improvement with the use of non-hydrostatic dynamics

Time\Experiment	Forecast at 30 km Resolution				Non-hydrostatic				Observed/Estimated (IMD)
	Non-hydrostatic		Hydrostatic		60 km Resolution		90 km Resolution		
	FCST	FCST - OBS	FCST	FCST - OBS	FCST	FCST - OBS	FCST	FCST – OBS	
Day-1 (24 hours)	10 (10%)	00	09	-01	10	00	09	-01	10
Day-2 (48 hours)	23 (30%)	03	17	-03	20	00	14	-06	20
Day-3 (72 hours)	45 (13%)	-53	32	-66	31	-67	25	-73	98
Day-4 (96 hours)	25 (-7%)	11	24	10	19	05	20	06	14
Day-5 (120 hours)	15 (0%)	03	15	03	12	00	11	-01	12

TABLE 3

Vector displacement error (in km) in track forecast compared to the observed/best-fit track (IMD) in Orissa super cyclone and % improvement with non-hydrostatic dynamics

Time\Experiment	Verification analysis	Forecast at 30 km resolution		Non-hydrostatic	
		Non-hydrostatic	Hydrostatic	60 km resolution	90 km resolution
Day-1 (24 hours)	063	196 (21%)	248	181	155
Day-2 (48 hours)	111	157 (22%)	200	167	283
Day-3 (72 hours)	054	197 (37%)	314	155	272
Day-4 (96 hours)	228	137 (36%)	214	191	197
Day-5 (120 hours)	350	302 (29%)	426	323	402

* Initial positional error in NCEP reanalysis was 155 km and is reduced to 122 km in the process of model initialization using 12 hours analysis nudging technique

compared to its positions in the observed track. The initial positional error in the analysis was 155.3 km that is reduced to 122 km after initialization through 12 hours nudging to large-scale reanalysis.

5.1. *Hydrostatic vs. non-hydrostatic dynamics*

The model simulated mean sea level pressure (MSLP) with hydrostatic (HS) and non-hydrostatic (NS) dynamics is presented in the left and right panels respectively in Figs. 3(a-d). In all 5 days, NS simulation shows more intense storm than in HS simulation and the difference between intensities in these two simulations is very prominent on day-2 (48 hours) and day-3 (72 hours). Figs. 3(a&c) illustrate 48 hours forecast of MSLP valid at 0000 UTC 28 October (day-2) by HS and NS simulations respectively. The storm is with central SLP of 985 hPa and 991 hPa in the NS and HS simulations respectively compared to 986 hPa in the observation. On day-3, *i.e.*, at 0000 UTC 29 October, the NS and HS simulations show 963 hPa and 976 hPa central pressure respectively (Figs. 3(b&d). The corresponding estimated central SLP was 912 hPa. This indicates that the fast deepening of the storm between 28 and 29 October is better simulated using non-hydrostatic dynamics though the estimated lowest pressure was much lower (912 hPa) than the simulated one was with NS simulation. The vertical component of horizontal vorticity from NS and HS simulations valid for day-2 and day-3 is presented in Figs. 4(a-d). This clearly indicates initiation of stronger vertical velocity in the NS simulation. Relaxation of hydrostatic approximation helped in development of intense convection and thus favoring intensification of the storm.

On day-4 *i.e.*, at 0000 UTC 30 October, after landfall, the storm is found to be located at 19.7° N/ 85.0° E and 19.3° N / 84.4° E with central SLP of 982 hPa and 984 hPa respectively in NS and HS simulation

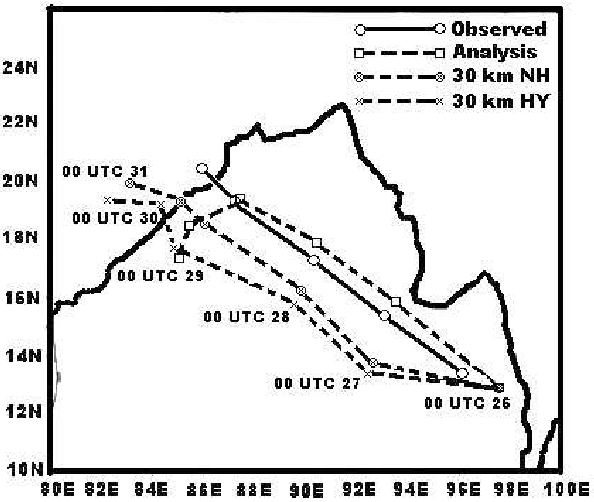


Fig. 7. The track of the storm during 26-31 October 1999 as obtained from model simulations, NCEP reanalysis and IMD observation / best-fit

(figure not presented). Though, the landfall is delayed in both simulations due to slow movement of the storm, the landfall point is better predicted in NS simulation. Further, the fast filling up of the storm as it approached the coastline is also better predicted in NS simulation compared to that in HS simulation. The pressure drop at the storm centre as obtained from NS and HS simulations are provided in Table 2. The values in the bracket give percentage improvement relative to hydrostatic simulation.

Figs. 5(a-d) shows model simulated wind vector at 1000 hPa with 24 hours accumulated precipitation from HS and NS simulations. This shows that the strength of the wind is also better simulated with non-hydrostatic dynamics. The spiral rain bands shows typical mesoscale structure as expected both from HS and NS dynamics. This also shows very heavy rainfall associated with such intense storm is well simulated by the model. As mentioned earlier, heavy rainfall was recorded over Orissa during 29-31 October and the model simulated 24 hours accumulated rainfall during this period is compared to the observed (IMD) rainfall in order to evaluate the model performance.

The 24 hours accumulated precipitation valid for day-3, day-4 and day-5 as obtained from HS and NS simulations are presented in Figs. 6(a-f). The magnitude of precipitation, which is closely related to the intensity of the storm, is also significantly better predicted in NS simulation. With the track of the storm, the precipitation band in the HS simulation is also shifted to the left. On day-3, though, the magnitude of maximum precipitation over Orissa was same in both simulations, in HS simulation the maximum precipitation was located around Bhubaneswar whereas in NS simulation it was near Chandbali area that closely matches with the observed one (figure not shown). On day-4, the NS simulation shows maximum precipitation of 26 cm very close to Bhubaneswar where maximum precipitation of 42.6 cm was recorded. The precipitation at Bhubaneswar in HS and NS simulations are 18 cm and 25 cm respectively. On day-5, NS simulation shows maximum precipitation of 39 cm around 21.3° N / 86.6° E compared to 36.3 cm observed around 20.7° N / 86.8° E. HS simulation shows 19 cm maximum precipitation in northwest Cuttack where observed precipitation was 25.4 cm. This clearly indicates that the rainfall associated with the storm is also significantly better simulated using non-hydrostatic dynamics.

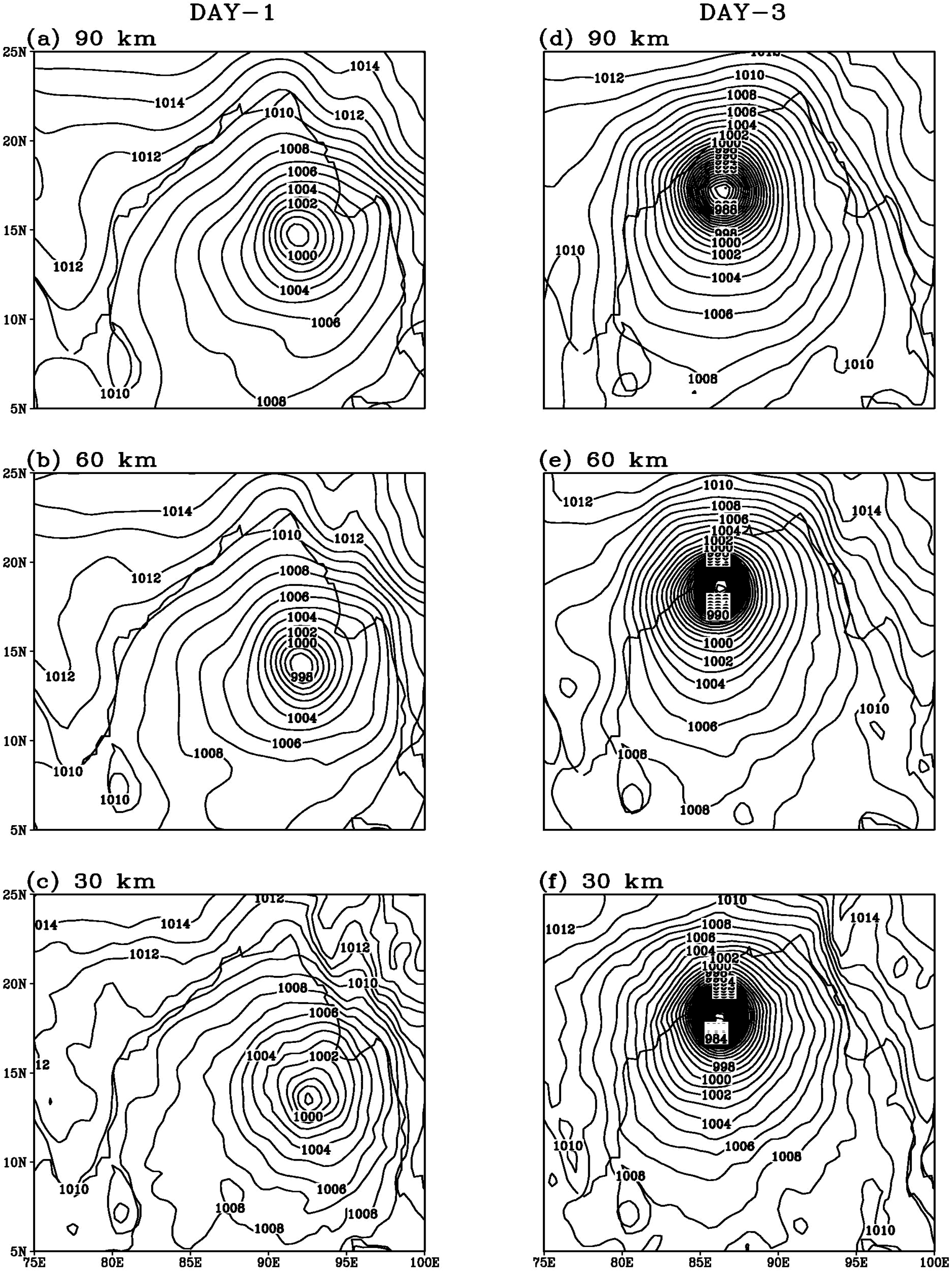
The model simulated (NS and HS) track of the storm is compared with the IMD observed track and the track obtained from NCEP/NCAR reanalysis. The track of the storm during 26-31 October with its location in every 24 hours is presented in Fig. 7. The vector displacement error in track forecast compared to the observed/best-fit track obtained from IMD is provided in Table 3, which indicates that the track of the storm is also better simulated with the relaxation of hydrostatic approximation.

The significant improvement in the simulation of track and intensity of the storm with the use of non-hydrostatic dynamics is in contrast to the results obtained by Dudhia (1993). In a similar study on a mid-latitude cyclone, he found no significant change in the track and intensity of the cyclone with inclusion of non-hydrostatic dynamics. This is due to less buoyant convective regime in mid-latitude cyclones, which was indicated by the fact that the convective precipitation in the said case was only about 1-2 % of the total precipitation. In the present case, there was intense convection and the convective precipitation had the major share in the total precipitation.

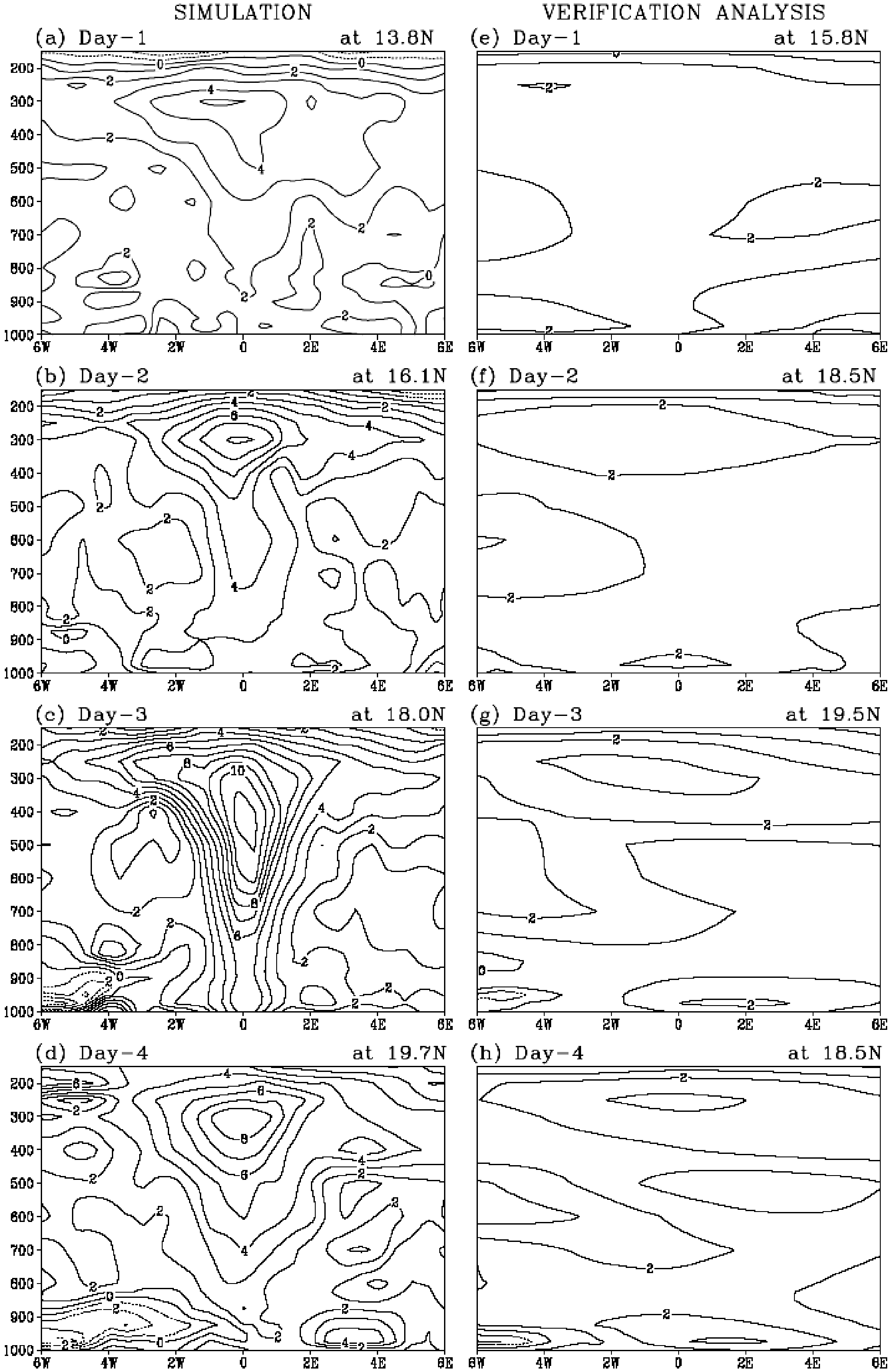
Kato (1997) found that with unaltered model physics, use of non-hydrostatic and hydrostatic dynamics provides significantly different simulation of moist convection at 20 km model resolution and the difference becomes more prominent at 10 km and 5 km model resolutions. The present results provide similar indication though the model is not tested at higher resolutions due to limited computing resources.

5.2. *Impact of horizontal resolution*

The results obtained from simulation of the storm at 90, 60 and 30 km model resolutions with non-hydrostatic



Figs. 8(a-f). Model simulated mean sea level pressure with contour interval one hPa (all at 0000 UTC) (a) valid on 27 October 1999 at 90 km model resolution, (b) same as (a) but at 60 km model resolution, (c) Same as (a) but at 30 km model resolution, (d)-(f) Same as (a)-(c) but valid on 29 October 1999



Figs. 9(a-h). Vertical cross section of temperature anomaly along with the central latitude of the storm (all valid at 0000 UTC) from (a) model simulation at 30 km valid on 27 October 1999, (b) same as (a) but valid on 28, (c) same as (a) but valid on 29, (d) same as (a) but valid on 30, (e) verification analysis valid on 27, (f) same as (e) but valid on 28, (g) same as (e) but valid on 29, (h) same as (e) but valid on 30

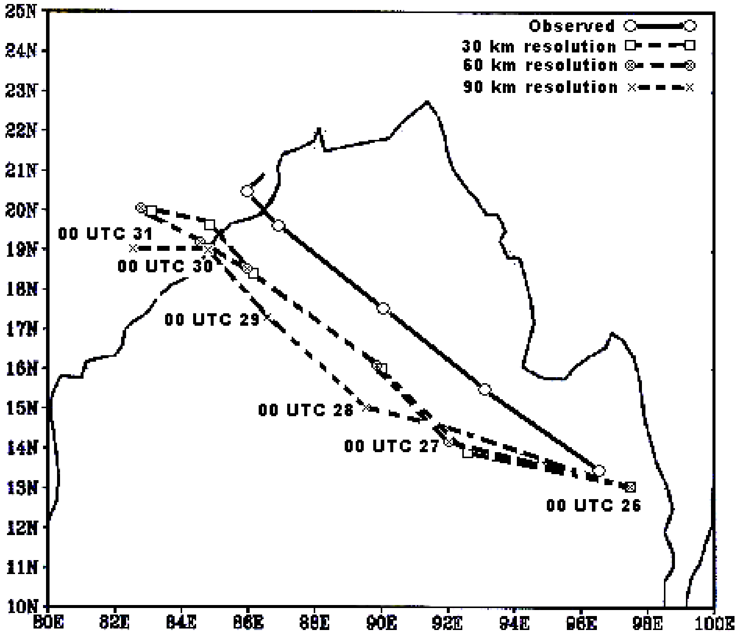


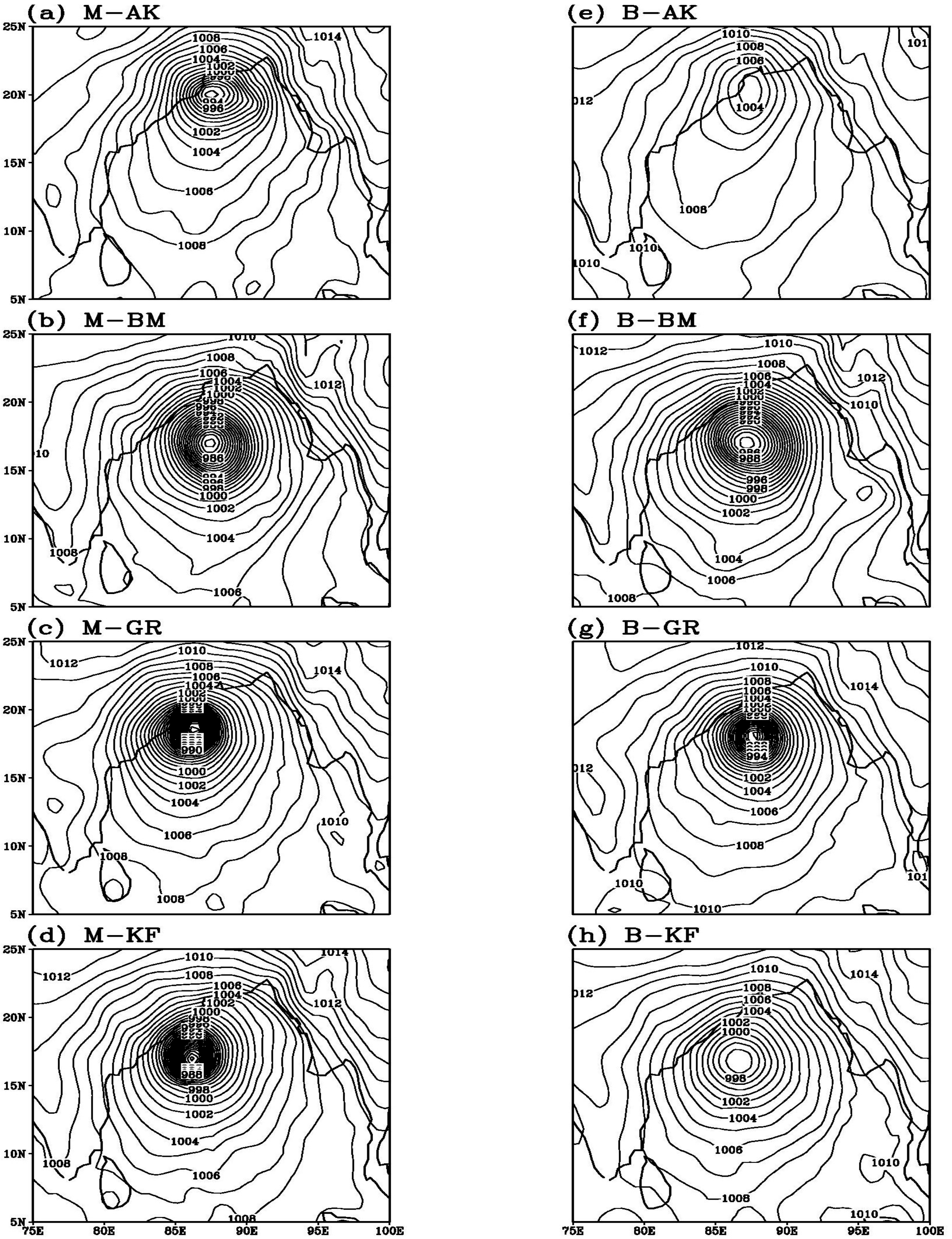
Fig. 10. The track of the storm during 26-31 October 1999 as obtained from model simulations at 90, 60, 30 km resolutions and IMD observation/best-fit

dynamics are presented in this section. It is to be mentioned here that the simulation results at 90, 60 and 30 km model resolutions are all interpolated to 0.5° resolutions for the shake of better comparison.

The model simulated (at 90, 60 and 30 km) mean sea level pressure valid on day-1 and day-3 is presented in Figs. 8(a-f). Model simulations show intense storm with strong pressure gradient whereas the verification analysis (figure not shown) shows weak storm extended over a larger area. As mentioned earlier, the intensity and location of the storm in the verification analyses is in large error due to its coarse resolution. Figs. 8(a-c), show MSLP valid at 0000 UTC 27 October (day-1) as simulated by 90, 60 and 30 km resolutions of the model. The storm is found to be with central SLP of 999 and 998 hPa respectively in 90, 60 and 30 km model resolutions compared to 998 hPa in the estimation. On day-2, the central SLP of the storm was 994, 988 and 985 hPa respectively in 90, 60 and 30 km model simulations (figure not presented) compared to 986 hPa in the observation. Figs. 8(d-f) illustrates model simulated MSLP valid on day-3 and the storm is with central SLP of 983, 977 and 963 hPa respectively in 90, 60 and 30 km resolutions of the model. The estimated central SLP was 912 hPa. This indicates that the intensity of the storm is better simulated with increasing model resolution and is well simulated by the model at 30 km resolution. Similar results obtained on day-4 and day-5 as well though the simulated storm is more intense than the observed one due to delayed landfall. The pressure drop on all the 5 days as obtained from model simulations and observation/estimation are provided in Table 2.

Though the trends of intensification and dissipation of the storm is well simulated by the model, the fast deepening of the storm between day-2 and day-3 is not well captured by the model. As pointed out by Yamasaki and Kurihara (Nagata *et al.*, 2001), the explosive deepening of cyclonic storms cannot be simulated by the eye-wall thermodynamics alone. It is important to resolve the downward motion at the center of the storm that contributes in deepening of the storms. This can be achieved with the use further higher resolution model.

Figs. 9(a-h) shows temperature anomaly (actual – mean) from model simulation at 30 km (non-hydrostatic) resolution and verification analysis (NCEP reanalysis which is used to provide initial and boundary condition to the model) valid at 0000 UTC 27, 28, 29 and 30 October 1999. The left panel shows the temperature anomaly from model simulation and right panel shows the same from verification analysis. This clearly shows that the warm core structure of the storm is very well simulated by the model with the core extended up to the lower level on intense stage (on day-3 *i.e.*, 29 October 1999) of the storm. This usual worm core structure of the storm is not observed in the coarse resolution (2.5° × 2.5° resolution) verification analysis as it can not well represent the intensity of the storm.



Figs. 11(a-h). 72-hrs forecasts of mean sea level pressure (in hPa) valid at 0000 UTC on 29 October 1999 with contour interval 1 hPa (a) Experiment M-AK (b) Experiment M-BM (c) Experiment M-GR (d) Experiment M-KF (e) Experiment B-AK (f) Experiment B-BM (g) Experiment B-GR and (h) Experiment B-KF

TABLE 4

Model simulated central pressure drop (hPa) in Orissa super cyclone with different combinations of parameterization schemes at 60 km resolution using non-hydrostatic dynamic

Experiments	Day-1 (24 hours)	Day-2 (48 hours)	Day-3 (72 hours)	Day-4 (96 hours)	Day-5 (120 hours)
Observed	10	20	98	14	12
M-AK-CCM2	07	10	15	09	08
M-BM-CCM2	07	12	24	34	17
M-GR-CCM2	10	20	31	19	12
M-KF-CCM2	06	11	28	25	16
B-AK-CCM2	05	05	05	02	01
B-BM-CCM2	08	12	22	32	20
B-GR-CCM2	07	11	25	24	17
B-KF-CCM2	06	08	12	18	19
M-GR-SC	09	17	30	15	08

The model simulated wind and 24 hours accumulated precipitation also shows that the intensity of the storm is better simulated at higher model resolution.

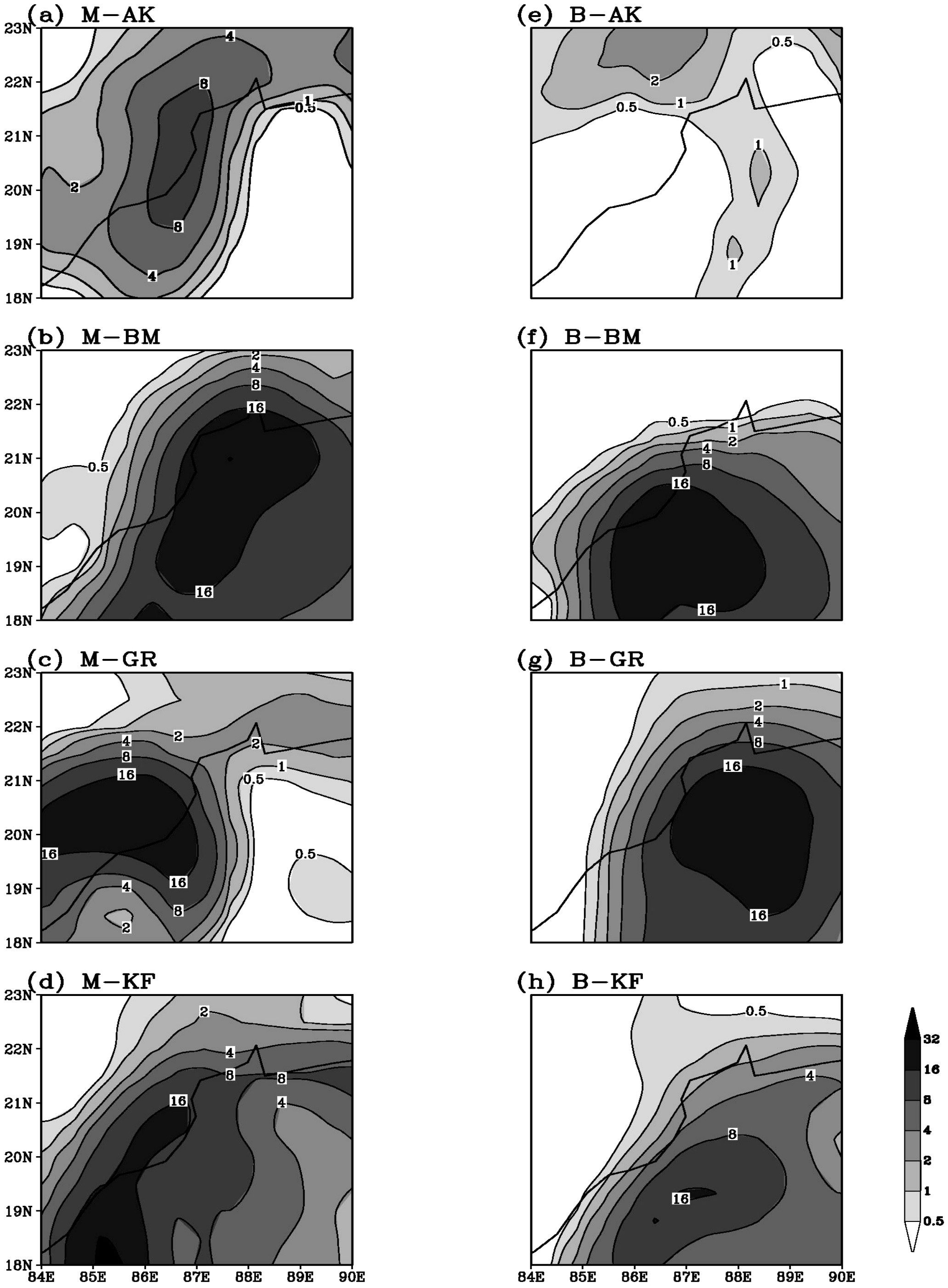
The tracks of the cyclone obtained from model simulations at different resolutions are compared with the observed track and is presented in Fig. 10. The track simulated by 30 km, 60 km and 90 km resolutions of the model are found to follow similar path with the one simulated by lower resolution are further away from the observed one. The displacement errors in track forecast at different model resolutions are provided in Table 3. It is evident from Table 3 that model resolution has relatively less impact on simulated track of the storm than on intensity. This is probably due to the fact that the movement of the storm is mainly governed by the large-scale steering flow that is well simulated even at relatively coarse resolutions of the model.

5.3. *Evaluation of PBL schemes*

The MSLP from all the eight experiments valid on day-3 *i.e.*, 29 October, when the storm was most intense is presented in Figs. 11(a-h). Left panel shows simulation results with MRF PBL scheme and right panel with Blackadar scheme. Comparison of the figures in the left panel to the corresponding figures in the right panel indicates that the intensity (central SLP) of the storm is better predicted by the MRF PBL scheme in combination with all convection schemes. The influence is minimum on BM convection scheme with pressure drop is improved by 2 hPa only. In combination with other convection schemes, it caused additional pressures drop in the range of 8-11 hPa *i.e.*, about 8-11% of the observed drop (98 hPa). In combination with GR, AK and KF convection schemes, the MRF PBL scheme reduces positional error of the storm as well in the range of 20-30%. Similar results obtained in other day simulations as well though the percentage of improvements is relatively less. The simulated pressure drop using all the possible combination of schemes in all 5 days is shown in Table 4. This shows that the location and intensity of the storm is better simulated with the use of MRF PBL scheme in combination with the GR, AK and KF convection schemes. Though, there is some improvement in the simulation results using BM convection scheme in combination with MRF PBL scheme, the improvement is not so prominent. The strength of the surface wind is also better simulated with the use of MRF PBL scheme.

The model simulated 24 hours accumulated rainfall with the eight combinations valid at 0300 UTC 30 October, the day after the landfall when maximum rainfall recorded over Orissa is shown in Figs. 12(a-h). This shows that the magnitude and distribution of simulated rainfall is also sensitive to the PBL parameterization scheme used in the model. The rainfall associated with the storm is improved even in the range of 12-15 cm (12 cm with GR scheme and 15 cm with KF) with some convection schemes. Similar results are obtained in simulation of 24 hours accumulated rainfall valid on day-3 and day-5 as well. The position and hence track of the storm is also better simulated with the use of MRF PBL scheme.

Better simulation results obtained using the MRF PBL scheme is probably due to stronger vertical mixing (non-local closure) allowed in this scheme. With the grid scale saturation of the boundary layer (which is obvious in presence of tropical cyclones), the strong vertical mixing will facilitate convection and hence intensification of the storm.



Figs. 12(a-h). Model simulated 24 hours accumulated precipitation (in cm) valid at 0300 UTC 30 October 1999 with logarithmic contour interval

5.4. *Evaluation of convection schemes*

A comparative study of the simulation results obtained using different cumulus parameterization schemes indicates that performance of the model is sensitive to cumulus convection schemes used in the model. On day-1, GR scheme provides relatively intense storm with central SLP 998 hPa (same as observed, with

MRF PBL scheme) compared other schemes. Similar results obtained on day-2 with central pressure drop varying up to 10 hPa from one scheme to other and GR scheme producing most intense storm with central SLP of 988 hPa compared to estimated SLP of 986 hPa. On day-3 [Figs. 11(a-h)], once again, GR convection scheme simulates most intense storm with central SLP of 977 hPa. It is found that AK scheme provides weakest storm. On day-4, GR and AK schemes show dissipation of the storm after landfall whereas BM and KF schemes show the storm still over sea with no sign of filling up. In fact, with BM and KF scheme (in combination with Blackadar PBL scheme) model simulation shows further intensification of the storm. Strength of the surface wind simulated by the model is also found to vary significantly with different convection schemes, which is again better simulated with the GR scheme. This shows that the intensity of the storm is better simulated with GR scheme.

As mentioned earlier, Figs. 12(a-h) shows model simulated 24 hours accumulated rainfall on day-4, using different cumulus parameterization schemes. It shows that the amount rainfall varies up to 17 cm from one cumulus convection scheme to another where observed maximum rainfall was 42.6 cm. Day-3 and day-5 simulation also shows similar results. This indicates that the model simulated rainfall is highly sensitive to the cumulus parameterization scheme used in the model. The amount of precipitation is simulated reasonably well by the model using GR, BM and KF schemes, with GR scheme providing rainfall matching more closely with the observed one. These results indicate that GR scheme in combination with the MRF PBL scheme is the most efficient combination as far as the overall performance of the model is concern. It is to be clarified here that though the location and movement of the storm is better simulated by AK scheme but the intensity is very poorly represented.

The sensitivity of the model forecast skill to the radiation parameterization scheme is examined using the most efficient combination of cumulus convection and PBL parameterization schemes *i.e.*, the M-GR combination. The comparative study of the results indicates that the model simulated location and intensity of the storms are sensitive to radiation and CCM2 radiation parameterization scheme provides better forecast of the storm compared to Dudhia's (Dudhia, 1989) short-wave long-wave radiation parameterization scheme.

6. Summary

The results obtained from extensive numerical experiments to address various aspects for improvement in mesoscale simulation of Orissa super cyclone is presented and discussed in the previous section. In the light of above discussions, the outcome of the study can be summarized as follows:

With unchanged model physics, the use of non-hydrostatic dynamics improved the simulation of track and intensity of the storm. In terms of pressure drop, there is 9% average (5 days) improvement in prediction of intensity of the storm. Relaxation of hydrostatic approximation allows stronger vertical velocity in highly buoyant convective regime and thus favors intensification of tropical cyclones through deep moist convection. There is significant improvement in prediction of track of the storm as well with average (5 days) error in track forecast compared to the observed (IMD) one is reduced by 29%.

Model horizontal resolution has significant impact on the simulation of intensity of the storm. The central pressure drop at peak intense stage of the storm is increased by 80% (25 hPa at 90 km to 45 hPa at 30 km resolution) as the model resolution is increased from 90 km to 30 km. The precipitation associated with the storm, particularly when it is over land, is better simulated at finer model resolution due to better representation of orography and localized mesoscale convection.

The forecast skill of the model at the resolutions used in the present study is sensitive to the cumulus convection and planetary boundary layer parameterization schemes. The radiation parameterization is also found to have perceptible impact on model simulation.

The Grell cumulus parameterization scheme with MRF PBL scheme provides the optimal combination of the schemes for simulation of the storm. The Anthes-Kuo cumulus parameterization schemes produce weak storm whereas the trends of intensification and dissipation of the storm is not well represented by Betts-Miller and Kain-Fritsch schemes.

Comparison of two radiation parameterization schemes (NCAR CCM2 and Dudhia's short- and long-wave) in association with MRF-Grell combination indicates that the intensity of the storm is better simulated using NCAR CCM2 radiation parameterization scheme.

Among the numerical experiments conducted, the non-hydrostatic simulation at 30 km model resolution provides the best forecast of both track and intensity of the storm. This emphasizes the use of further higher resolution non-hydrostatic model in prediction/simulation of explosively deepening storms.

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